

EVOLUTION OF THE SOUTHERN SAN JOAQUIN BASIN AND MID-TERTIARY "TRANSITIONAL" TECTONICS, CENTRAL CALIFORNIA

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Abstract. A Cenozoic tectonic and sedimentary history is proposed for the Southern San Joaquin Basin (SSJB) and Tehachapi Mountains that evolved adjacent to the plate margin off central California. Seismic reflection, borehole, field, biostratigraphic, and paleomagnetic data are integrated into geologic and fault structure maps, cross sections, and geohistory plots and are analyzed with previous work in the region to develop a model relating the sequence, timing, and distribution of complex, tectonically linked events. The largely buried structures and strata in the SSJB preserve an unusually complete record of the mid-Tertiary transition from convergent to transform plate boundary as well as the regional transition to contraction during the Pliocene. Significant structural relief, existing across both extensional and contractile features, is preserved in the subsurface and an active fold-thrust belt propagates basinward along the margin of the U-shaped Tejon embayment. The Cenozoic evolution of the SSJB reflects the regional deformation of central California as different tectonic events followed each other along the adjacent North American plate margin. Five Oligocene-Miocene basin phases are identified in the SSJB: (1) late Oligocene/early Miocene extensional subsidence, with high- and low-angle normal faulting, accompanied by volcanism and deposition of coarse syntectonic conglomerates; (2) middle Miocene uplift; (3) later mid-Miocene transtensional subsidence to lower bathyal depths; (4) alternating subsidence and uplift until the late Miocene; and (5) flexural subsidence due to Pliocene to Recent contraction. Reconstructions of mid-Tertiary California place the southern San Joaquin/Tehachapi extensional terrane as a paleotectonic block located between the Western Mojave terrane (then to the east) and the Western California terrane (then to the south and west). Regional extension occurred during a long transition period between convergent and transform boundaries along the North American plate margin. Significant slip along the San Andreas transform postdates this extensional event. Its origin apparently coincided with a regional middle Miocene uplift event, indicating that the San Andreas fault is younger than previously supposed. The Tertiary SSJB has subsided due to extension/transtension, crustal tilting, and thrust-related loading. The Maricopa Subbasin floor is likely composed of ensimatic and mafic rocks like those along the west side of the Sierra Nevada and locally has subsided beyond 12 km. In contrast, the relatively stable Tejon embayment, underlain by Sierran crystalline crust, achieved its maximum subsidence in the Miocene. Since Pliocene time, the SSJB has filled and continued to deepen after the basin was tectonically shut off from the Pacific Ocean.

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Paper number 91TC02871.
0278-7407/92/91TC-02871\$10.00

INTRODUCTION

Different tectonic settings have prevailed in southern California during the Cenozoic; however, the sequence, timing, and transition between regional events are not fully understood. Many California basins preserve a record of these events, despite significant overprinting. These basins opened, filled, subsided, and were deformed in variable settings while, at times, bodily translated and rotated [e.g. Crowell, 1987]. Wide varieties of subsurface data, including multifold seismic reflection and borehole data, and field access to exposed portions of the basins, provide an opportunity to reconstruct their polycyclic histories. As these basin histories unfold, it appears that existing plate-scale models constructed to explain their origin are not entirely consistent with information concerning the timing and regional distribution of tectonic events, as discussed below.

Recent geological and geophysical work in the southern Sierra Nevada addressing Mesozoic paleogeographic problems, including a CALCRUST deep-crustal seismic profile, identified the need for new investigations of the structure and Cenozoic history of the SSJB [Sams and Saleeby, 1988] (P. E. Malin et al., Evidence for crustal-scale tilting beneath the Tehachapi Mountains and Tejon embayment, submitted to *Journal of Geophysical Research*, 1990). Furthermore, an unusually complete record of the structures and strata necessary to unravel part of the Cenozoic history of southern California exists in the southern end of the basin. Therefore the Tejon embayment, a topographic depression located at the southern end of the SSJB, 40 km south of Bakersfield was selected for study (Figures 1 and 2). Our paper presents new field and subsurface data and describes the structure and tectonic evolution of the SSJB over the past 30 m.y. as different tectonic events followed each other along the plate margin. The relationships between the local structural styles, the transitions between them, and the sequence and timing of relevant regional events are examined.

Two basic problems underlie this study: (1) the nature and timing of major transitions between Cenozoic tectonic events along the North American plate margin and (2) how changes at the plate scale are expressed in adjacent basins. Thus the geologic history of the SSJB described in this paper has implications for (1) regional tectonic history and paleogeography of southern and central California; (2) how tectonic events follow one another along rapidly changing plate margins; and (3) Cenozoic evolution of petroliferous California basins.

DATA AND METHODS

Data bearing on the subsurface of the shallow central Tejon embayment along with field exposures of the basement rocks and Cenozoic strata that rim its margins provide a means for studying the history of the SSJB, other portions of which are beyond the reach of boreholes and conventional seismic profiling. For the basin analysis, subsurface data from seismic reflection profiles and several hundred boreholes from the alluviated basin were integrated with field data from the uplifted basin margins. Borehole data include electric logs, dipmeter logs, biostratigraphic data, well histories, and velocity surveys. Structural mapping and analysis of the tectonic history were accomplished through interpretation of 17 industrial seismic profiles and a CALCRUST seismic survey; construction of borehole and seismic-based structural cross sections and stratigraphic diagrams; and compilation of geologic maps [Dibblee, 1973; Bartow and Dibblee, 1981], with new mapping and field observations in critical areas. Access to good exposures is limited by vegetation and few fresh roadcuts.

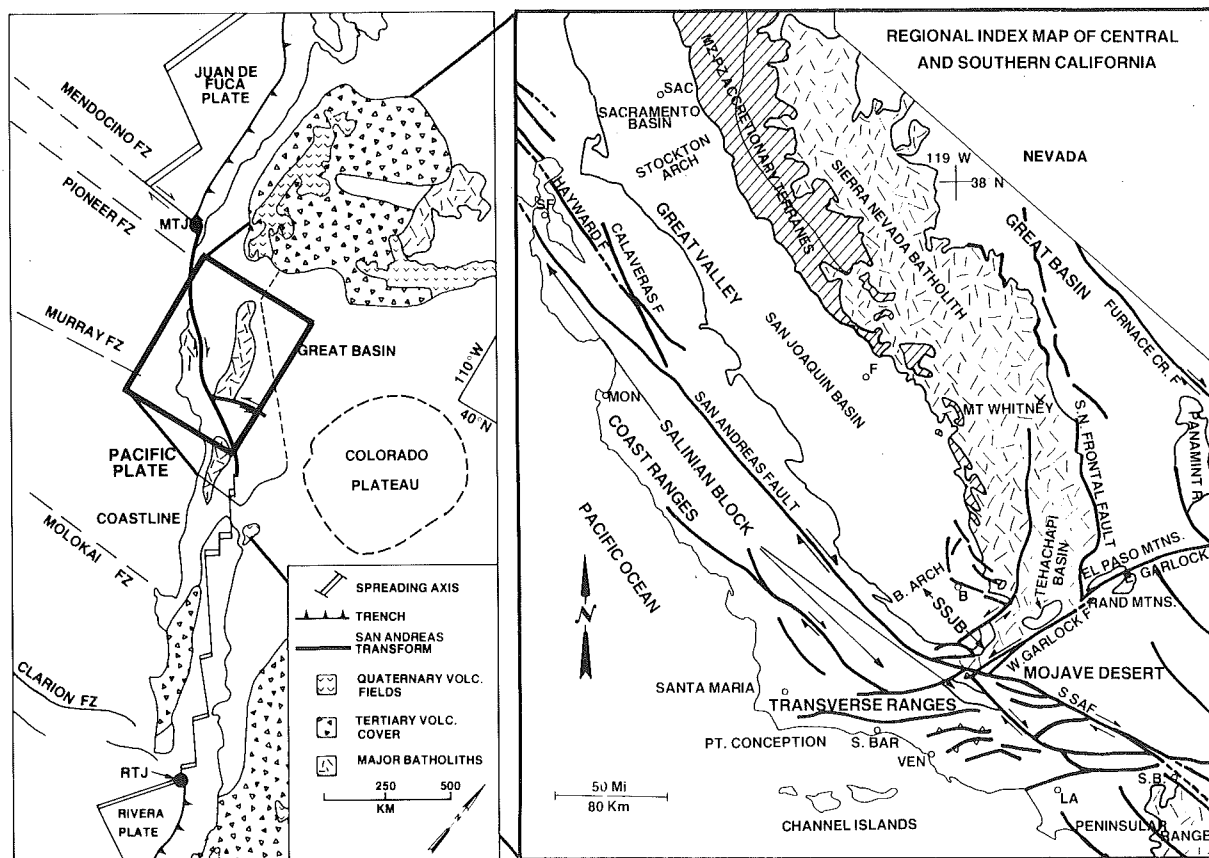


Fig. 1. Regional setting of the southern San Joaquin Basin. Left diagram modified after Dickinson and Snyder [1979] and Atwater and Severinghaus [1989]; right diagram (located in rectangle on left) is modified after Goodman [1989]. Hatched areas are accretionary terranes composed of ensimatic rocks and ophiolitic fragments along the western Sierra Nevada that extend south into study area. Juan de Fuca and Rivera plates are remnants of the mainly subducted Farallon plate. Offshore faults are not shown. Abbreviations are B, Bakersfield; F, Fresno; S.B., San Bernardino; S. Bar, Santa Barbara; Ven, Ventura; SF, San Francisco; Mon, Monterey; LA, Los Angeles; S SAF, southern San Andreas fault, S.N., Sierra Nevada; FZ, fracture zone; and MTJ/RTJ, Mendocino/Rivera Triple Junctions.

In order to better understand basin subsidence history, paleobathymetric and biostratigraphic information were derived from detailed, proprietary industrial paleontological reports of many of the boreholes. These data were compared with paleoenvironmental schemes that relate ancient assemblages to modern marine homeomorphs [Ingle, 1981; Lagoe, 1984; Bandy and Arnal, 1969] or that utilize seismic stratigraphy and facies analysis [H. Olson and R. Bloch, written communication, 1988] to determine paleobathymetry. This information was combined with measured thicknesses of lithologic units from specific wells into geohistory diagrams, two of which are presented in this paper.

REGIONAL TECTONIC HISTORY AND BASIN EVOLUTION

Atwater [1970] first related the on-land history of the San Andreas transform fault in California to the marine record of magnetic anomalies in the Pacific Ocean. This work provided evidence for the mid-Tertiary change in plate boundary type, that is, from a north trending convergent plate boundary offshore to a lengthening transform located onshore in southern California. In the former setting, the remains of the

Farallon Plate were subducted under the North American Plate beginning roughly at the latitude of present-day northern Mexico [Stock and Molnar, 1988]. After spreading and subduction ceased, the Pacific plate generally moved (and continues to move) north with respect to the North American plate in the transform setting [Atwater and Molnar, 1973]. These plate models predict that this transition took place during late Oligocene time. A major uncertainty is the nature, kinematics, timing and duration of this transition, and its relationship with regional geology. Unfortunately, the marine magnetic record for the time interval 28.5 Ma to 17 Ma is somewhat ambiguous, as discussed below [Atwater, 1989; Stock and Molnar, 1988].

Within this general plate tectonic framework, the origin and rapid subsidence of fault-bounded California basins have both been related to the approach of the Pacific-Farallon spreading ridge to the western margin of North America [Nilsen, 1984], or to crustal extension associated with the lengthening San Andreas transform. General models for this extension include North America overriding the East Pacific Rise [Menard, 1960] and progressive shearing of a wide margin between the Pacific and North American plates [Atwater, 1970]. A related model links the time-space distribution of localized basin extension and volcanism to the northwestward migration of the unstable

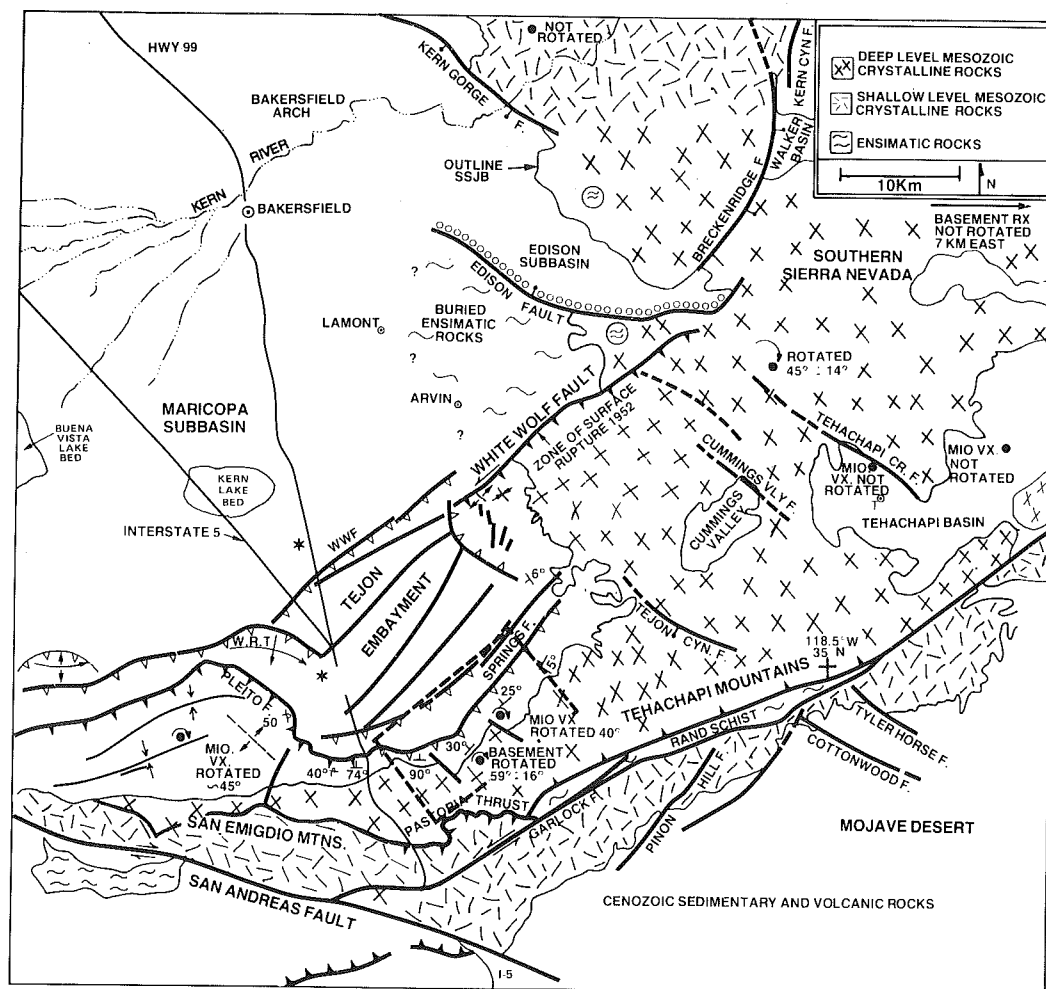


Fig. 2. Index map to the southern San Joaquin Basin and southern Sierra Nevada. Barbs represent blind thrusts (open) and exposed thrusts (closed). Heavy dots indicate sites of published paleomagnetic results, and stars indicate geohistory sites discussed in the text. Dashed rectangle shows location of Plate 1. Abbreviations are T, Tehachapi (town); Mio. VX, Miocene volcanic rocks; W.R.T., Wheeler Ridge Thrust; F, fault; WWF, White Wolf fault; CYN, canyon and CR, creek.

Mendocino Triple Junction (MTJ, Figure 1) [McKenzie and Morgan, 1969; Blake et al., 1978; Dickinson and Snyder, 1979; Fox et al., 1985]. In this model, pull-apart basins are created and then subside under a transtensional setting of oblique-slip and normal faulting coupled with volcanism, while the San Andreas system evolves from its nascent offshore position to its present inboard trace [Crowell, 1974, 1987]. Specifically, it has been proposed that the Neogene history of the SSJB has been controlled by the migration of the MTJ and by subsequent wrench tectonics along the SAF system [Bartow, 1987; Harding, 1976].

On the other hand, the timing of localized extension and volcanism does not show a clear northward reduction in age over the past 30 Ma [Stanley, 1987]. Regarding the SSJB, Goodman et al. [1989] suggested that late Oligocene-early Miocene basin subsidence, normal faulting, and syntectonic volcanic flows, and coarse clastic deposits were all part of regional mid-Tertiary extension that cannot be explained solely by triple junction instability (see also Tennyson [1989] and Davis and Lagoe [1988]). The subsequent late Tertiary transition from general extension to contraction in a direction normal to the San Andreas fault has resulted in substantial

shortening and structural overprinting that has obscured this mid-Tertiary record. This paper presents new insights into these two transitions and attempts to synthesize this information with previous studies from the region.

REGIONAL SETTING

In the active tectonic setting, the SSJB and southern Sierra Nevada are transitional locales residing between Great Basin extension to the east and transpression along the Pacific-North American plate boundary to the west. The Sacramento-San Joaquin Basin is divided into several smaller subbasins by west trending arches (Figure 1). The SSJB is situated south of the Bakersfield Arch and just north of the intersection of the San Andreas and Garlock faults, with 315 and 64 kms of Neogene strike-slip, respectively (Figures 1 and 2) [Crowell, 1979; Carter, 1987]. The deep crustal-level rocks of the Tehachapi Mountains that project under the Tejon embayment crop out in scattered exposures. There, tectonic elements curve sharply from a regional southern Sierran N-NW trend to an E-NE trend near the Garlock fault [Sharry, 1981], which separates the deep-crustal southern Sierras from less deformed granites of the

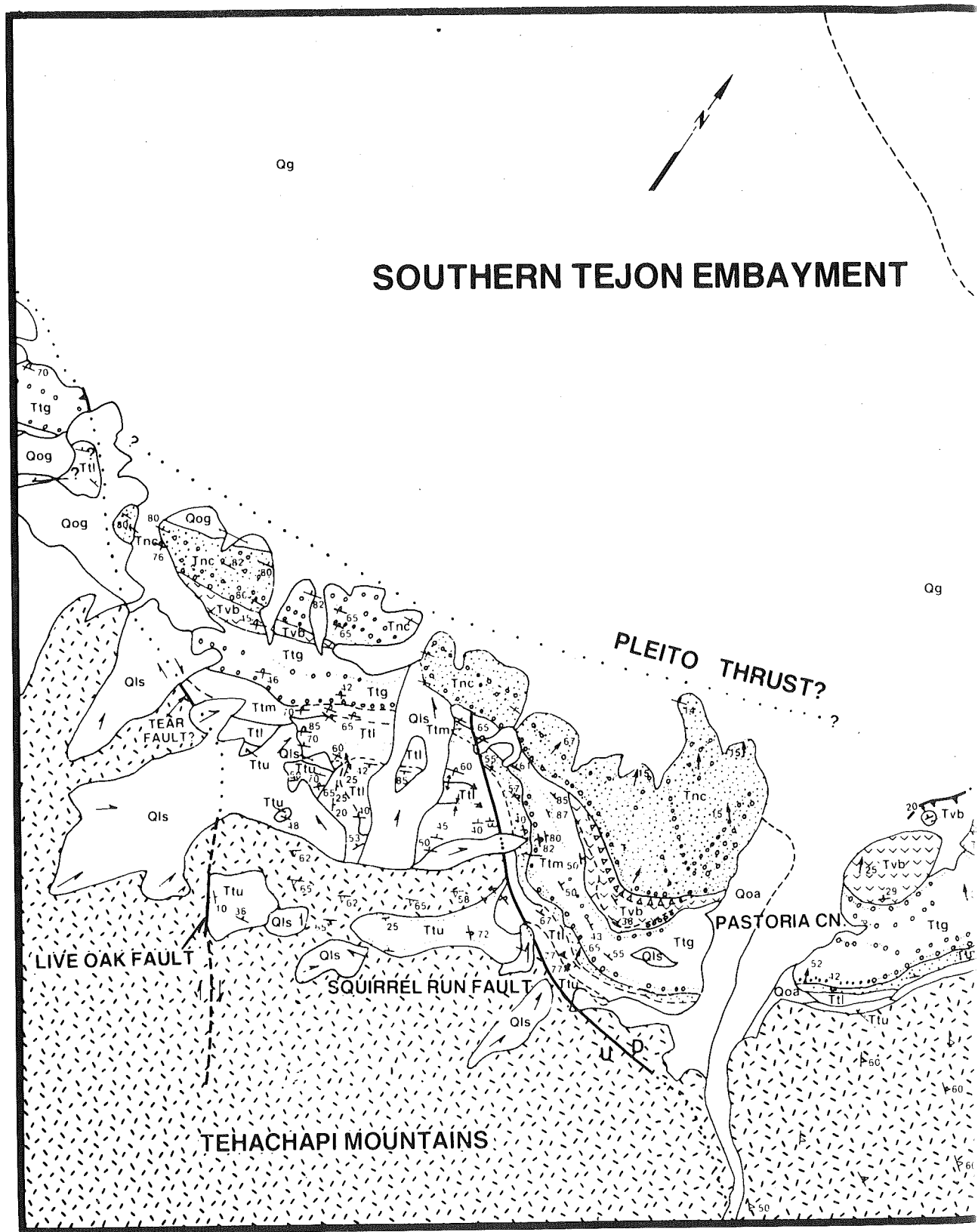
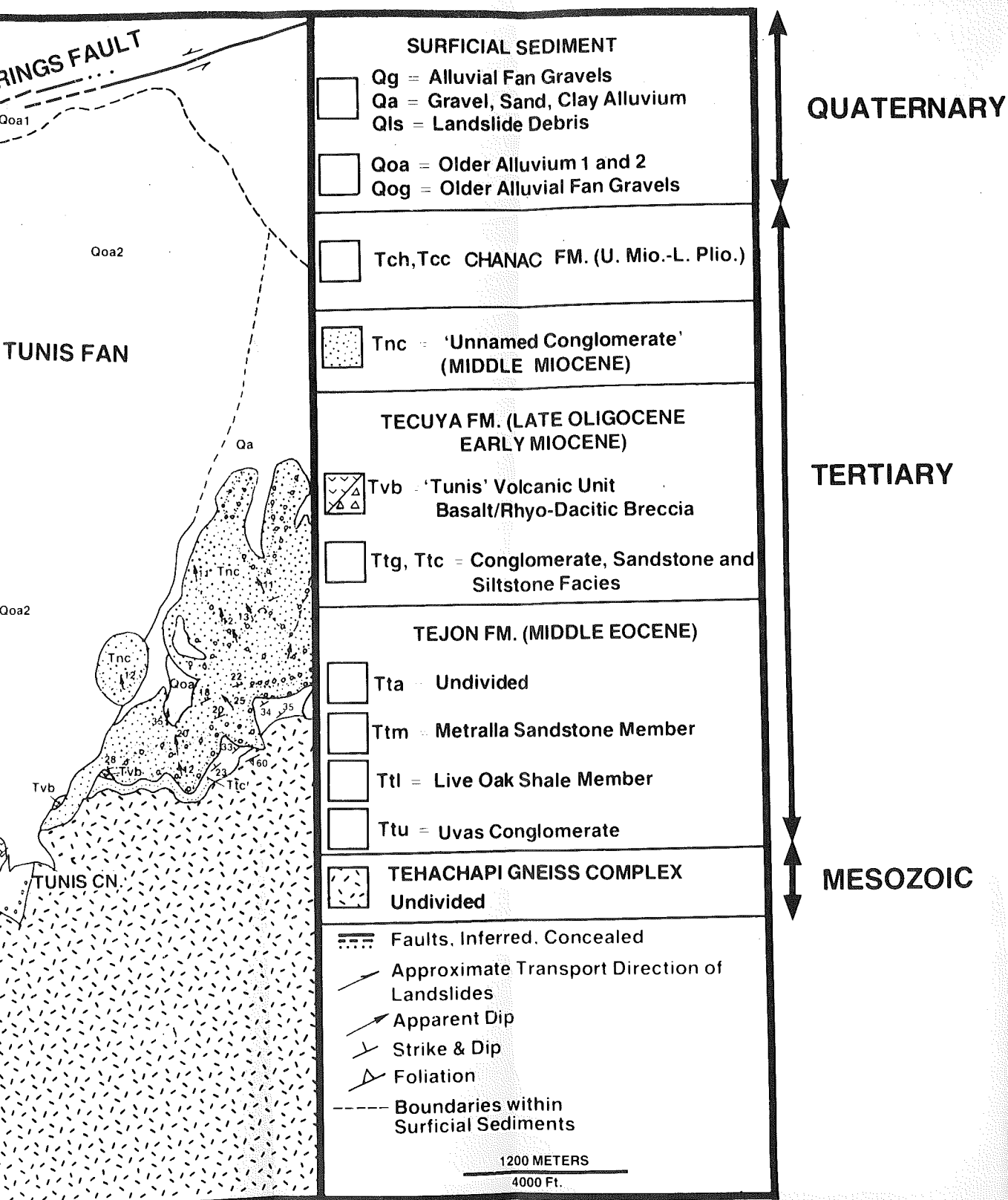
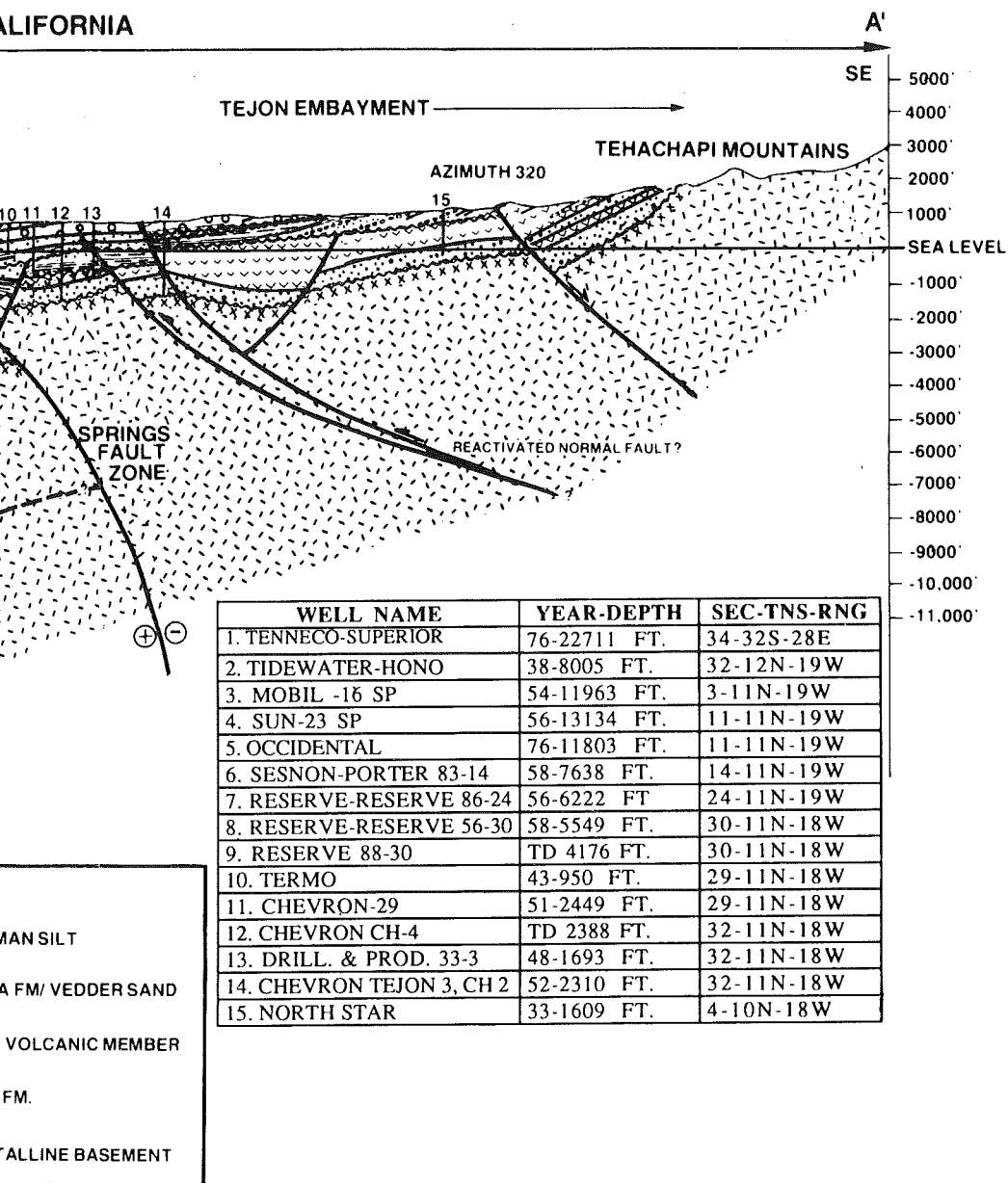


Plate 1. Geologic map along the southern margin Southern San Joaquin Basin showing striking normal faults that were active in the mid-Tertiary, overlapped by a mid-Tertiary marine rocks. This Eocene pinchout line can be extended north into the subsurface.



and Goodman [1989]. Along this margin is a series of NW
 unconformably overlain by onlapping middle Eocene

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nts. The White Wolf fault is a reverse fault with associated folding on its
from seismic reflection data on shelf. The patterns shown in the legend only

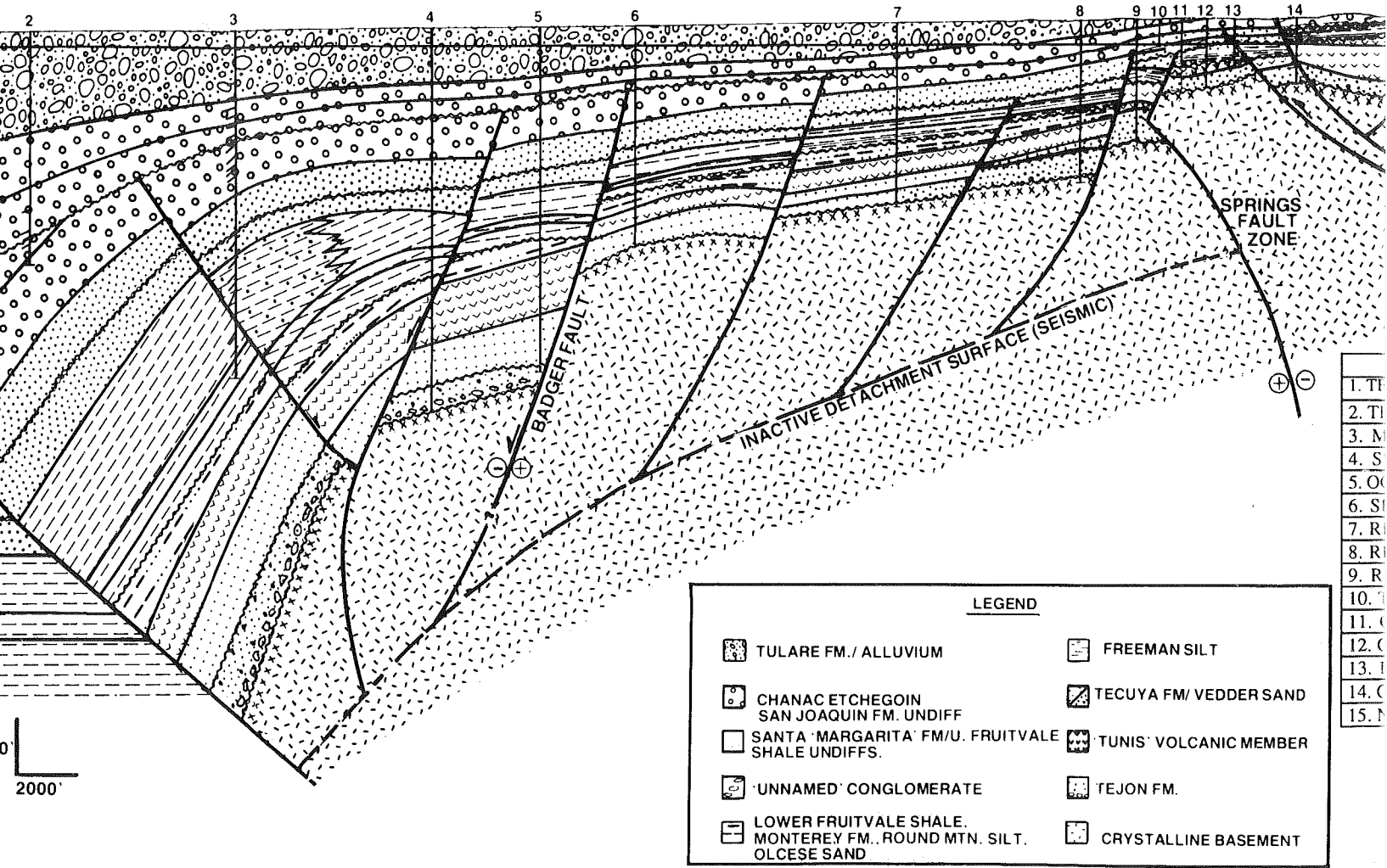
STRUCTURAL CROSS SECTION TEHACHAPI FOOTHILLS-SOUTHERN SAN JOAQUIN BASIN, CALIFORNIA 16.3 MILES/26.1 Km

TEJON EMBAYMENT

TEJON

AZIMUTH 347 | AZIMUTH 350

~325



' constructed from field, borehole, and seismic data (located on Figure 5). Tick marks on boreholes show dipmeter data constraints. The White Wolf fault es towards the fault tip. The high-angle Springs fault is overprinted by shallow-dipping thrusts. Detachment surface projected from seismic reflection dat graphic facies (see Figure 4).

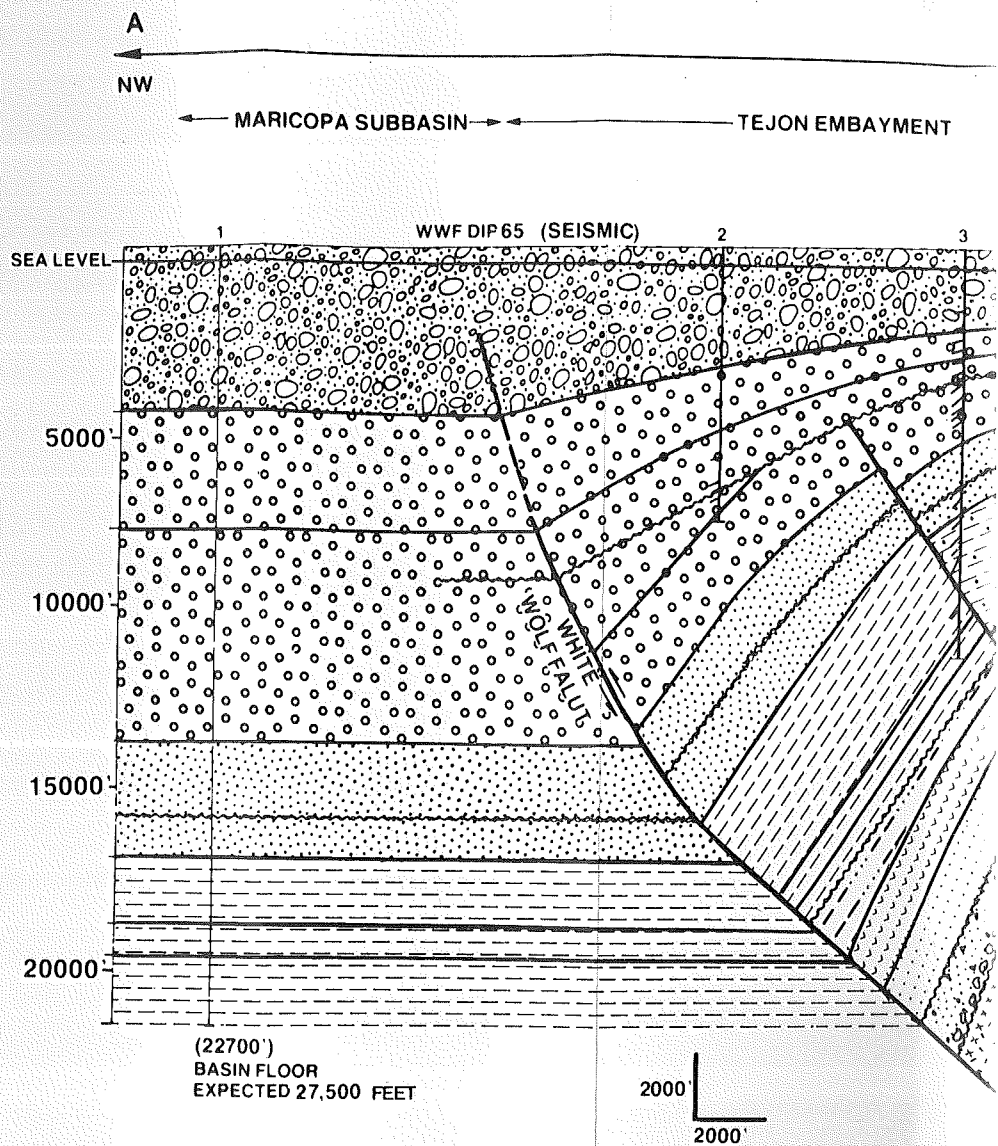


Plate 2. Structural cross section A-A' constructed from field, borehole, and seismic data. The hanging wall. Vertical offset decreases towards the fault tip. The horizontal scale generally approximate the lithostratigraphic facies (see Figure 4).

Mojave block. The Garlocks's two branches bound the Rand Schist complex (Figure 2). The seismically active, fold-thrust belt along the south side of the SSJB is a mirror image to the fold-thrust belt on the north side of the Los Angeles Basin, on opposite sides of the SAF (Figure 1) [Namson and Davis, 1988].

The Tejon embayment is bounded to the east and south by the crystalline rocks of the Tehachapi Mountains and to the southwest by the imbricated and folded Tertiary sedimentary rocks of the San Emigdio Mountains [Davis and Lagoe, 1988]. The oblique-slip White Wolf fault system (WWF) separates the Tejon embayment from the south end of the 10 to 12 km-deep Maricopa Subbasin (MSB; Figure 2). Thus within a distance of some 20 km there is 14 km structural relief along the top basement unconformity. The inferred regional boundary between Sierran crystalline rocks and metasedimentary, metavolcanic and ultramafic accretionary rocks is based on both field and drill core studies of the basement complex (Figures 1 and 2) [Ross, 1987a, b; Sams and Saleeby, 1988]. Analysis of borehole data suggests that metaigneous rocks beneath the southeastern MSB probably represent subsurface equivalents to exposures of ensimatic and ultramafic rocks along the west side of the Sierran batholith [Ross, 1987b]. In contrast, most of the boreholes in the Tejon embayment have encountered crystalline "granitic, dioritic, or gneissic" rocks (as recorded in well reports) that are assumed to be subsurface projections of exposed metatonalites and gneissic rocks in the Tehachapi Mountains. The Tejon embayment and Wheeler Ridge are penetrated by hundreds of boreholes and have produced over 125 million barrels of oil.

GEOLOGY OF THE SOUTHERN END SAN JOAQUIN BASIN

Overview of Basin History

An historical outline of the southern SSJB is provided in this overview before structural geology and stratigraphy are described in more detail. The subsidence history and basin phases are best illustrated by representative geohistory plots of boreholes in the basin (Figure 3; sites located in Figure 2). The geohistory models suggest that the large-magnitude subsidence and uplift events have a large thermotectonic imprint (see also DeCelles [1988]). The sequence and timing of these events are consistent with stratigraphic and structural relationships discussed below.

Paleogene. Forearc basin deposits related to late Mesozoic/early Tertiary subduction and the related Sierran magmatic arc underlie much of the Great Valley [Ingersoll, 1988]. However, south of the Bakersfield Arch, the Great Valley Sequence has not been recognized. The oldest Tertiary rocks identified in the SSJB are mid-Eocene marine sediments. It appears that an early Eocene regional uplift event completely removed from the SSJB the tilted Paleocene marine and nonmarine sediments found in the Goler Basin, 100 km to the NE [Cox, 1987]. This early Eocene, and especially Late Cretaceous-Paleocene, uplift was responsible for the unroofing and removal of up to 30 km of vertical section from the southern Sierran magmatic arc ('mid' to late Cretaceous age [Sharry, 1981] (D.A. Pickett and J.B. Saleeby, Thermobarometric constraints on the depth of exposure and conditions of plutonism and metamorphism at deep levels of the Sierra Nevada batholith, California, submitted to *Journal of Geophysical Research*, 1991)). The oblong Sacramento-San Joaquin Basin developed mostly on the older Cretaceous forearc basin. It consisted of a shallow shelf bounded by a fluvial and coastal plain to the east and a submarine slope to the west [Nilsen, 1984]. It is significant that in the Tejon embayment,

middle Eocene strata of the Tejon Formation unconformably overlie the deep-level crystalline basement complex and record a marine transgression towards present-day east [Nilsen, 1987].

After middle Eocene subsidence, followed by late Eocene-early Oligocene uplift, the SSJB again subsided tectonically (Figure 3) [DeCelles, 1988; Goodman, 1989; Davis and Lagoe, 1988]. By late Oligocene time a sufficiently deep marine basin had subsided to lower bathyal depths, with a steep basin margin, considerable relief, and several depocenters [Hirst, 1988]. It is remarkable that these deep-marine deposits locally overlie widespread Oligocene red bed deposits [Nilsen, 1984]. Geohistory modeling suggests several kilometers of subsidence of SSJB floors in late Oligocene/early Miocene time (Figure 3), related to regional extension beginning in the late Oligocene, as discussed below.

Miocene. Subsidence and deep-marine conditions, coupled with high- and low-angle normal faulting at Tejon embayment, continued into early Miocene time. At this time, the SSJB experienced submarine and subaerial volcanism. Submarine channels derived from the steep, irregular Tejon embayment margin probably sourced submarine fans, now buried deeply under the MSB [Macpherson, 1978; Hirst, 1988]. Following the rapid subsidence associated with the late Oligocene to early Miocene extension, there was significant but short-lived uplift associated with tilting and folding in late early to middle Miocene time (Figure 3) [Graham, et al., 1989; Loomis and Glazner, 1986]. This event was immediately followed by rapid middle Miocene deepening that was widespread in the San Joaquin Basin (Figure 3) [Graham and Williams, 1985]. Periods of uplift and fault-related subsidence apparently alternated until late Miocene time when relative stability and shallow marine environments prevailed again [Goodman, 1989].

Pliocene to Recent. The transition from general extension to contraction most likely occurred in early Pliocene time, as discussed below. Since then, thrusting and folding along the southeastern, southern, and western basin margins have exhumed the basement and Tertiary section, while the central Tejon and, notably, the MSB continued to subside. Figure 3 shows the great contribution of sediment loading to the subsidence of the MSB in the past 10 m.y., in contrast to the earlier subsidence history. The precise timing of the large-scale overprinting and uplift remains elusive because of the poorly understood, largely nonmarine Pliocene to Recent stratigraphy. Due to regional shortening and rapid thrust-related uplift at this time, the central portions of former Miocene deep-marine subbasins have evolved into arid, intermontane foreland depressions, with significant topographic relief at the basin margins. Here, older strata are eroded and sediment is redeposited into depressions, as an active fold-thrust belt migrates basinward, normal to the orientations of the nearby San Andreas and Garlock fault traces [Goodman, 1989; Davis and Lagoe, 1988].

Stratigraphy: Basement Rocks and Cenozoic Basin Fill

The Tehachapi gneiss complex is considered to be the exposed floor of the southern Sierra Nevada batholith. It consists mainly of heterogeneous mafic to felsic igneous and metaigneous rock dated between 120 and 110 Ma, including rocks resembling metamorphic granulites in texture and composition [Ross, 1985; Sharry, 1981; Saleeby et al., 1987; Sams and Saleeby 1988]. Igneous emplacement and metamorphism took place between 25 and 30 km [Sharry, 1981; D.A. Pickett and J.B. Saleeby, submitted manuscript, 1991]. North of the WWF, the Cenozoic strata of the southeastern MSB are probably underlain by mafic Paleozoic and Mesozoic rocks and other rocks of transitional or oceanic affinity, as discussed below (Figure 4).

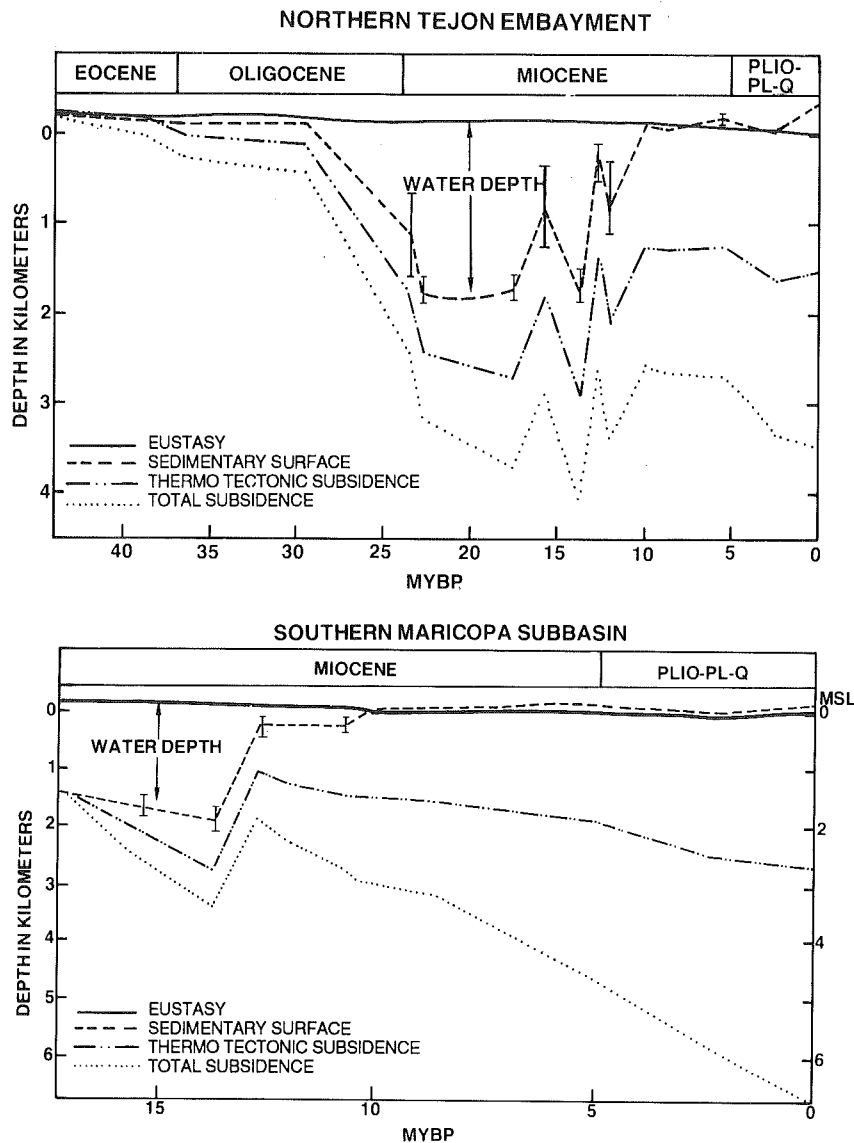


Fig. 3. Geohistory diagrams based on borehole data from central Tejon embayment and southern Maricopa Subbasin (MSB; sites are located in Figure 2) constructed according to an Airy isostasy model. Four different curves are shown, with the sea level curve of Haq et al. [1987] at the top and the bottom curve representing total subsidence since middle Eocene time. Paleobathymetry is based on proprietary paleontology reports, with error bars. Present measured stratigraphic thickness is shown at time = 0. Most subsidence in Tejon embayment can be related to late Oligocene to late Miocene tectonic events, whereas the MSB subsided rapidly since late Miocene time mainly due to the sediment load. Plio-Pl-Q is Pliocene-Pleistocene-Quaternary. Modified from Goodman [1989].

Cenozoic stratigraphy is characterized by rapid vertical and horizontal facies changes, especially within the Neogene section, with numerous unconformities that record the removal of thick sections of strata along the basin margins (Figure 4; see also Bartow and McDougall [1984], Olson, et al. [1986], Bartow, [1987], and DeCelles [1988]). The Eocene Tejon Formation unconformably overlies the Tehachapi gneiss complex south of the WWF. Overlying Eocene shallow marine sandstone, siltstone, and shale are Oligocene-Miocene volcanic rocks, coarse sandstones, and a variety of conglomerates that interfinger down-dip with well-sorted, fine- to medium-grained marine sandstones and shales (Figure 4). Within the study area, the lower Miocene "Tunis Volcanics"

include stacked vesicular basaltic flows, dacite flows, lapilli and lithic tuffs, graded pyroclastic deposits, coarse rhyodacitic breccias, and intrusive dikes. The volcanic unit reaches a maximum thickness of more than 600 m under the Tejon embayment, and it has been dated at 22.7 Ma by whole rock Ar^{40}/Ar^{39} ratios (date by L. Snee, U.S. Geological Survey; J. Plescia, written communication, 1986). Thus, since these volcanic rocks can be readily identified at the surface, as well as on seismic reflection and well log data, the unit is an important time marker.

The younger Miocene section changes facies within a few kilometers of the basin margins (Figure 4). For example, dominantly coarse-grained, nonmarine deposits of the Bena

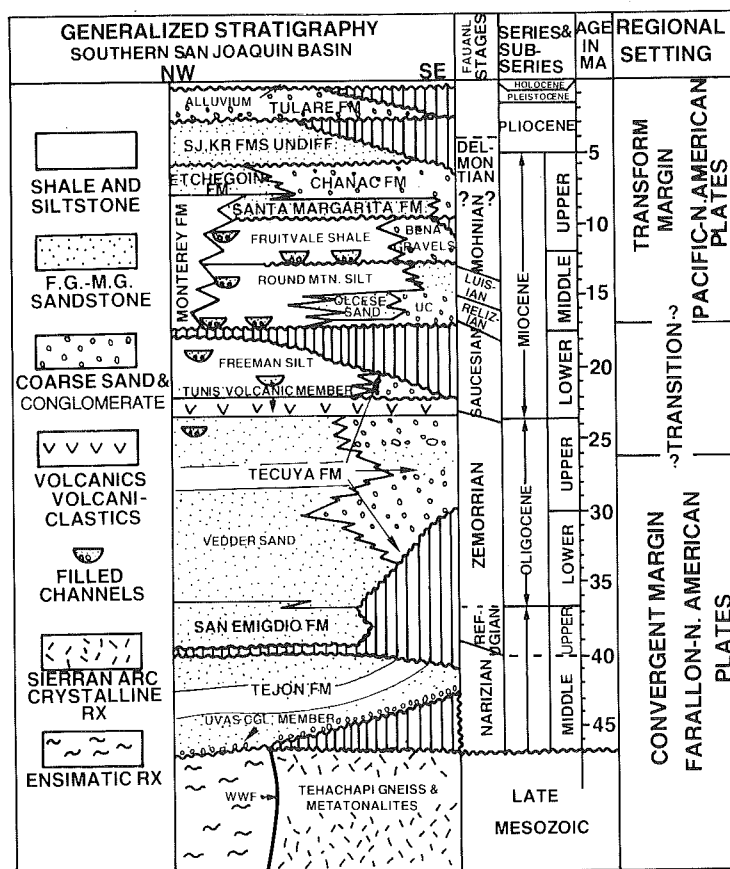


Fig. 4. Generalized stratigraphic column for the southern end of the San Joaquin Basin. Lithostratigraphic units are depicted versus time, California foraminiferal stages [after Kleinpell, 1938], and generalized regional settings. Abbreviations are SJ, San Joaquin Formation; KR, Kern River Formation; UC, Unnamed conglomerate; WWF, White Wolf fault; RX, rocks; CGL, conglomerate and F.G.-M.G., fine to medium grain. Vertical lines indicate eroded section. Compiled from Bartow and McDougall [1984], Bartow [1987], DeCelles [1988], Nilsen [1987], Olson et al. [1986] and Goodman [1989].

gravels, Unnamed conglomerate [Dibblee, 1973], and Olcese sand crop out along the basin margins, and are coeval with shallow and deeper marine facies of the Olcese sand, Round Mountain silt, Fruitvale shale, and Monterey Formation shales located downdip in the subsurface. Numerous paleochannels incised into the fine-grained Miocene strata of deep water marine origin. Their coarse-grained fill can be recognized in the subsurface by their electric log character and by their chaotic signature on seismic reflection lines [Hirst, 1988]. Moving up section, the Santa Margarita Formation at Comanche Point consists of a basal, single cobble-rich layer, probably a transgressive lag deposit, overlain by fossiliferous sandstone of shallow marine origin. New strontium isotope analyses of shell material suggest an age of approximately 8.5 Ma for the Santa Margarita Formation in the study area [J. Schultz, University of California, Santa Barbara, written communication, 1989]. The upper Miocene/lower Pliocene Chanac Formation is composed of poorly sorted and interbedded cobble conglomerate, pebbly arkosic sandstone, and shale. The lower Chanac is the nonmarine facies equivalent to the marine and transitional facies of the Santa Margarita Formation, which the Chanac Formation ultimately overlies (Figure 4). The Plio-Pleistocene section consists of coarse alluvial fan and fluvial sediments that interfinger with shallow marine shelf, restricted marine, brackish-water, and lacustrine

deposits in the center of the SSJB [Bartow, 1987]. These basin center deposits indicate a gradual shoaling of the section there.

Major Unconformities

Middle Eocene shallow marine sandstones and siltstones of the Tejon Formation unconformably overlie the deformed Cretaceous quartzofeldspathic gneisses (at Edmonston Pumping Station; Plate 1). Thus the deep crustal rocks were unroofed and emplaced near sea level before about 45 Ma, as discussed above. In addition to this pre-middle Eocene nonconformity and the enormous amount of erosion that it represents, there are also late Eocene/early Oligocene, middle Miocene, upper Miocene (Mohnian), and Pliocene-Pleistocene angular unconformities that are especially prominent along the basin margins.

A significant mid-Miocene unconformity in the study area (about 16-17 Ma in age) is exposed along the southern and eastern basin margin. The Unnamed conglomerate overlaps, along strike, late Oligocene/early Miocene-aged normal faults, volcanic and clastic facies of the Tecuya Formation, the Tejon Formation, and crystalline basement (Plate 1). The Unnamed conglomerate is the oldest unit to contain clasts of the Rand Schist. East of Comanche Point, mid-Miocene conglomeratic

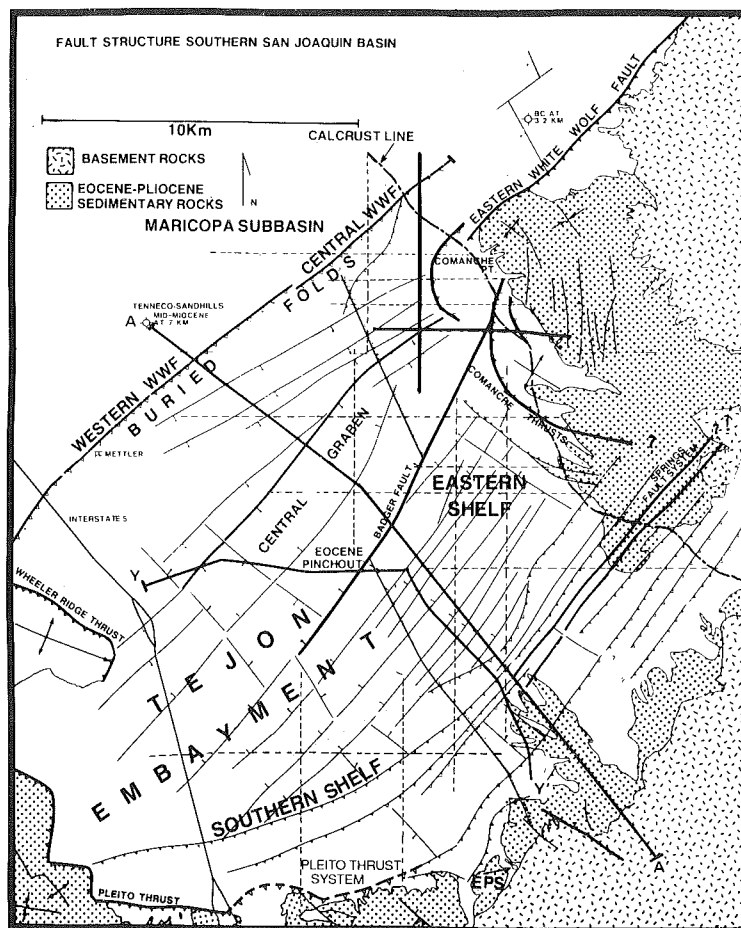


Fig. 5. Composite fault structure map of the southern end SSJB based on seismic reflection grid (dashed lines oriented oblique to structural grain), borehole data, and geologic maps. Thrusts symbols are as in Fig. 2. High-angle faults are shown with bars on downthrown side. Most faults are buried and are mapped at the top of the lower Miocene volcanic unit. The trace of the exposed eastern White Wolf fault system (WWF) is based on ground rupture in 1952, whereas the buried western segment trace is projected from subsurface data. EPS is Edmonston pumping station and BC is Basement Complex. A-A' and Y-Y' are cross sections shown in Plate 2 and Figure 9. The other two thick lines are seismic profiles shown in Figures 6 and 7. The trace of the Eocene marine pinchout is based on surface geology, biostratigraphic data, and electric log correlations.

sandstones and boulder conglomerates unconformably overlie gneissic basement rocks. When combined with the subsidence history of the central embayment discussed above (Figure 3), the mid-Miocene unconformity appears to represent significant uplift and erosion in the SSJB (see also Loomis and Glazner [1986]). There are at least two younger Miocene unconformities: one near the base of the Mohnian Stage and another at the base of the Santa Margarita Formation (Figure 4). There are also several Pliocene to Recent unconformities. An angular unconformity within the Chanac Formation apparently overlaps the majority of the normal faults in the central embayment, discussed below, and suggests that the local transition from extension to contraction occurred in the early Pliocene.

Structure of the Tejon Embayment and Boundary Faults

The Tejon embayment is a U-shaped topographic basin whose north, open side is defined by the buried White Wolf fault (Figure 2). The structural framework consists of (1)

inactive high-angle normal and oblique-slip faults with at least three different orientations, (2) low-angle faults imaged on seismic data, (3) thrust faults that ring the basin, and (4) oblique to reverse-slip faults that lie subparallel to the Garlock fault. The structural styles reflect both extensional and contractional histories (Figure 5; Plate 2). Both Comanche Point and Wheeler Ridge are thrust-fault-cored anticlines that rise above the flat valley floor (Figure 5) [Goodman et al., 1989; Medwedeff, 1988]. In between are older, largely buried NE and NW trending, high-angle structures with dominantly normal separation. The fault sets all lie in close proximity to one another, and their relative histories are discussed below.

We found that bed thicknesses throughout the section (Plate 2) are not preserved due to (1) significant expansion of strata and structural relief across Oligocene/Miocene growth faults, (2) abrupt changes in stratal thicknesses and depositional facies away from the basin margins, (3) significant erosional unconformities, and (4) the likelihood of material moving in and out of the plane of section. The latter imbalance is due to (1) a component of strike slip along the faults in the shallow section and (2) Neogene clockwise rotations in this area.

Central Embayment structure. The most continuous structures in the Tejon embayment are the buried, NE striking, high-angle faults and central graben (Figure 5). The NW striking faults exposed along the southern basin margins have buried equivalents that appear as cross faults to the buried NE striking set. The Badger fault forms the southeast margin of the central graben and dips 60° to 70°NW (Plate 2). There is 1-2 km of vertical separation of the top crystalline basement surface across this structure. We propose that this fault had an oblique-slip history because of about 4 km right-lateral separation of the Eocene pinchout surface. The Springs fault lies subparallel to both the White Wolf and Garlock faults and is adjacent to a series of subparallel thrust faults that evidently merge with the Pleito Thrust system to the west. The Springs fault is an active high-angle fault rooted in the middle crust, on the basis of seismic data, with evidence for oblique slip [Goodman and Malin, 1988; Bartow, 1984] (Plates 1 and 2). It is marked at the surface by a linear escarpment and by a series of springs in the Tejon Hills, where Recent gravels are offset [Harris, 1954]. The Springs fault itself becomes entangled with the SE dipping Pleito thrusts along its western end (Figure 5 and Plate 1).

Along the eastern and southern shelves of Tejon embayment are relatively small, high-angle, NE striking faults with mainly normal separation (Figure 5). Seismic data suggest that these high-angle faults sole at depth into a series of reflective, low-angle structures that dip to the northwest [e.g., Goodman, 1989, figure 7]. As the sense and magnitude of separation across the former faults is not consistent, the former structures may share the oblique-slip history of the Badger fault. The basin floor deepens abruptly northwest of the Badger fault. Here, there is significant expansion of wedge-shaped Oligocene and younger strata into the central graben and deep-marine Miocene biofacies are present (Plate 2). The basin floor drops dramatically across the WWF into the MSB. The central graben narrows to the NE, where it is truncated by the Comanche Thrust system (Figures 5 and 6).

There are a number of contrasts between the NW and NE striking faults. The NW striking faults generally dip less steeply than the NE striking faults and are locally truncated by the NE striking faults [Goodman, 1989]. In the southern Tejon embayment, the NW striking normal faults dip about 45°, whereas the NE striking faults dip at about 70°, at shallow depths. The NW striking faults show significant vertical offset of the lower Miocene and Paleogene sections (Plates 1 and 2) analogous to the east striking Edison fault north of the WWF (Figure 2). With regard to their timing, the NW striking faults are overlapped at the middle-Miocene unconformity by the Unnamed conglomerate, whereas the NE striking faults generally offset this unconformity surface and younger section (Plates 1 and 2 and Figure 6). Other workers have claimed that these faults, south of the WWF, were inactive after early Miocene time [Davis and Lagoe, 1988].

Structure of the Basin Margins. The basin margins are structurally complicated from contractional overprinting. Along the eastern margin of Tejon embayment, strata dip gently westward, whereas moving west along the southern margin toward Pastoria Canyon, strata become progressively sub-vertical to overturned along the S-SE dipping Pleito fault (Plate 2). The youthful Wheeler Ridge, western Pleito, and Comanche thrust systems that rim the Tejon embayment lie between zones of normal faults which they have locally exhumed and truncated (Plates 1 and 2; Figure 5; east end Figure 6). Other basement-involved, buried reverse faults in the foothills are indicated by a recent CALCRUST reflection line, and have also played a major part in the recent uplift of the Tehachapi and San Emigdio Mountains (P. E. Malin et al., submitted manuscript, 1991).

The Pleito fault is the major active structure along the south border of the SSJB and is responsible for considerable deformation in the San Emigdio Range [Namson and Davis, 1988]. The Pleito fault forms an escarpment bounding the eastern San Emigdio foothills (SW corner of Figure 5). East of Grapevine Canyon, the Pleito thrust system consists of multiple strands: one that generally separates Tertiary rocks in the western Tehachapi foothills from flat-lying alluvium on the valley floor, and several buried strands that are evident on seismic reflection data. Despite a subtle surface expression, movement along the Pleito fault system has produced considerable deformation in the Tehachapi foothills. Just west of Pastoria Canyon, gneisses and tightly folded middle Eocene to middle Miocene strata lie on the hanging wall, while moderately north dipping strata compose the footwall block (Plate 2). The Pleito system merges with faults lying parallel to the Springs fault to the east, where folding of the Tertiary section is less intense.

South of the Pleito fault are several NW striking faults with apparent right-lateral offset in plan view (Squirrel Run, Live Oak, and Tunis faults in Plate 2); they were originally mapped as strike-slip cross faults by Hoots [1930]. Across these poorly exposed fault surfaces, the sedimentary and volcanic components of the Tecuya Formation are generally thicker and coarser. On the downthrown block of the Tunis fault, the Tunis Volcanic Member is almost 300 m thicker than on the upthrown block. The older Tecuya Formation conglomerates, with boulder-sized clasts of locally derived basement debris, are present only on the hanging wall. These moderately dipping structures are interpreted to be normal-growth faults, as discussed below [see also DeCelles, 1988]. Some of these same stratigraphic relationships are observed across faults with net reverse separation and can be attributed to reactivation of older normal faults (Plate 2).

White Wolf Fault System. The definition and slip history of the WWF is controversial [Hill, 1955; Webb, 1981; Ross, 1986; Stein and Thatcher 1981; Davis and Lagoe, 1988; Goodman, 1989]. From steep escarpments near Comanche Point and to the northeast (surface rupture occurred during the oblique-reverse, M 7.5 Arvin-Tehachapi and related Kern County earthquakes in 1952 [Bartow and Dibblee, 1981]), the trace of the buried WWF is traditionally continued southwest across the flat San Joaquin Valley floor and then beneath Wheeler Ridge, where it becomes entangled with the Wheeler Ridge Thrust system (Figure 5). Our work focused on the central WWF segments east of Wheeler Ridge. Here, vertical offset of the top basement surface exceeds 3 km (downthrown side to the northwest [Bartow, 1984]). Lying subparallel to the WWF is a series of normal faults with similar NE strike orientations (Figure 5) which have not been active since middle Miocene time. Northwest of these faults, the buried central WWF forms the boundary between the folded strata in the northern Tejon embayment and the relatively flat-lying strata of the southern MSB (Figure 7 and Plate 2). On the basis of limited well and seismic data, the buried central WWF system is composed of south dipping segments that are offset more than 2 km horizontally to the northwest from the exposed eastern segment (Figure 5). Thus the eastern segment of the WWF is more closely related to the east dipping Comanche Thrust, as they combine to elevate high-standing Comanche Point, than to the higher-angle segments to the west.

The evolution of the WWF is important because it reflects the extensional and contractional histories of the region [Goodman, 1989]. Previously, Davis and Lagoe [1988] portrayed the WWF structure as a folded normal fault, underlain by flat, active thrusts that underlie Wheeler Ridge and the San Emigdio mountains. Seismic and borehole-based cross sections depict the WWF dipping 60°SE, with only the

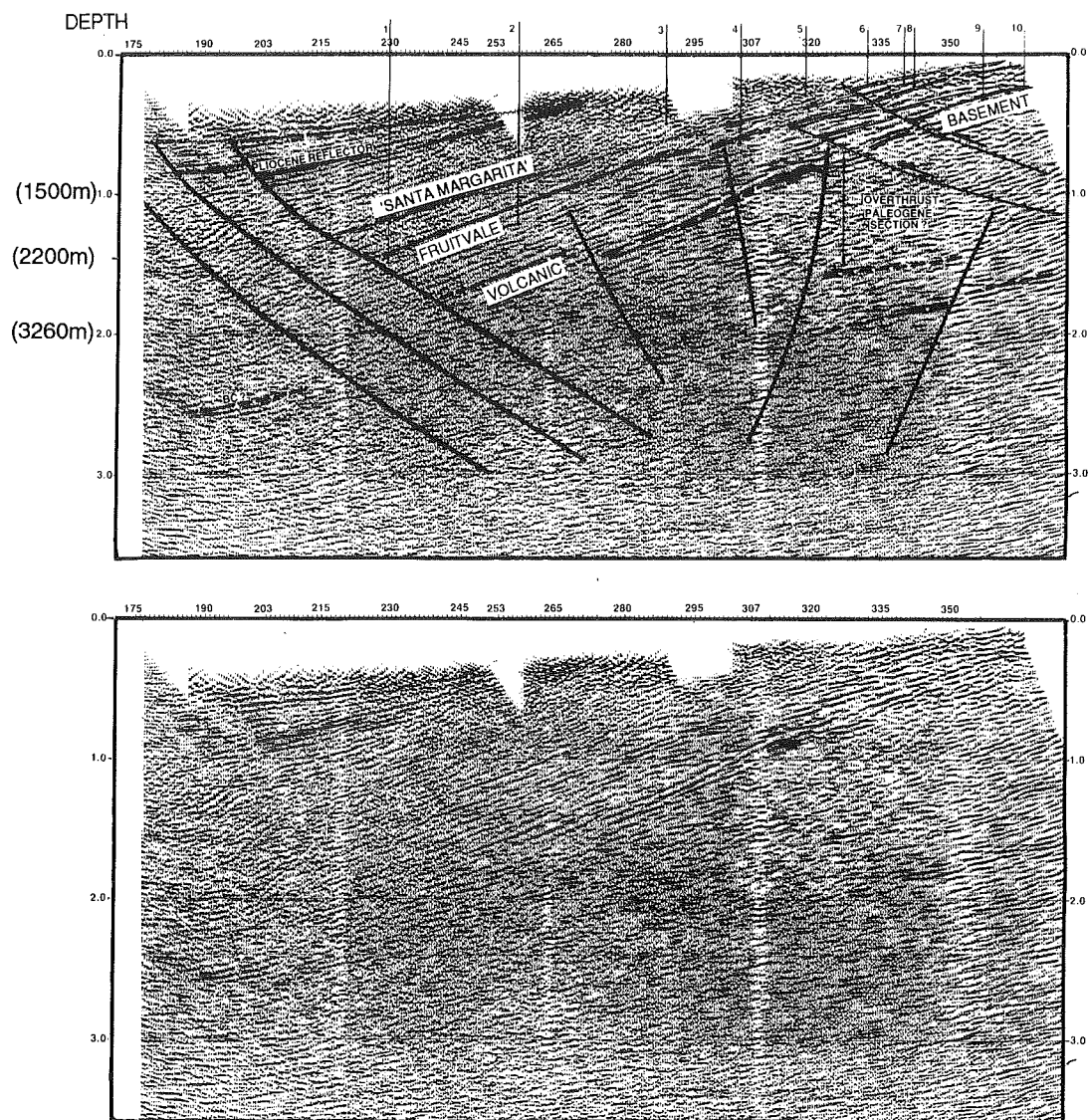


Fig. 6. E-W seismic profile from the northern Tejon embayment (located in Figure 5) depicting both extensional and contractional features. Oligocene-Miocene oblique-normal faults overprinted by late Neogene thrusts. Boreholes and total depth, in feet, as follows: 1, Arco-SP, 7605 (2319 m); 2, Exxon-Preszler, 6000 (1829 m); 3, Exxon-Tejon, 2495 (761 m); 4, Hall-Baker, 3257 (993 m); 5, Cannon, 1360 (415 m); 6, Wa-Mc-Co, 1041 (317 m); 7, Gould-Claire, 1295 (395 m); 8, Lubking, 1082 (330 m); 9, Gould-Tejon, 1285 (392 m); 10, T&E-Tejon, 1047 (319 m). Length of section is 5.8 km.

Tejon section south of the WWF tightly folded (Plate 2). Our cross sections differ from previous interpretations [e.g., Davis and Lagoe, 1988] in that the thick stratal section, north of the WWF in the MSB, is not solely related to normal-growth faulting. In our interpretation, higher rates of subsidence and sedimentation in the MSB, during periodic Pliocene to Recent vertical movement along the WWF, is the greatest factor causing the present large vertical separation of Miocene and older strata between the Tejon embayment and MSB [see Medwedeff, 1988]. Above the buried fault surface, the young, thick section in the MSB apparently onlaps folds in the northern Tejon embayment (Plate 2).

Figure 7 provides a seismic image of the strata north and south of the WWF. On the front limb of the anticline, lying against the main fault surface, strata dip too steeply to be

properly imaged, unlike the gently dipping back-limb syncline (Figure 7). Data from six boreholes lying near the profile have been projected into the section. Boreholes 1-3 penetrate a section lying completely within the Tejon embayment, whereas wells 4 and 5 penetrated beneath the WWF and bottomed in the southernmost MSB. Well 4 apparently encountered the Santa Margarita Formation (upper Miocene) and Fruitvale shales at least twice, and bottomed in middle Miocene strata. Well 5 also penetrated the Santa Margarita Formation in the hanging-wall of the WWF and again penetrated the upper Miocene, fossiliferous marine section in the footwall, according to well log annotations. North of the WWF, well 6 penetrates an undeformed, unrepeat stratigraphic section where the top of the Santa Margarita Formation lies below 4 km. There is about 2.5 km vertical

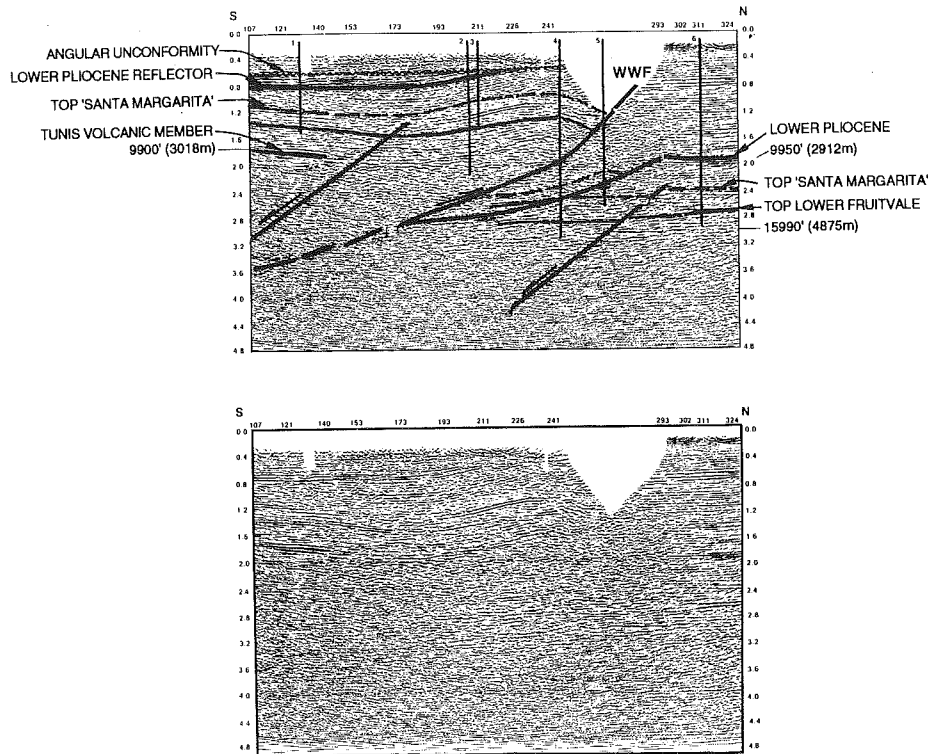


Fig. 7. N-S seismic profile (located on Figure 5) crosses oblique to the trace of the buried segment of the White Wolf fault system (WWF) and inactive subparallel faults. Fault-generated anticline in Tejon embayment contrasts with thick, flat-lying Pliocene section in MSB. Lower Pliocene reflector on Tejon side is truncated at an angular unconformity related to movement along WWF. Boreholes, total depth, in feet, and strata at bottom as follows: 1, Arco-SP, 7605 (2319 m), middle Miocene; 2, M&G-Valpredo, 10500 (3201 m), Oligocene; 3, Oil Scout-Tejon, 7008 (2136 m), middle Miocene; 4, MCOR-Shell, 17653 (5832 m), Luisian-Relizian; 5, Transamerica-Rexroth, 12892 (3930 m), upper Miocene megafossils; and 6, Texas-Argent 1, 15223 (4641 m), Luisian-Relizian. Vertical exaggeration is ~ 0.54 for upper 3 s. (two-way travel time) north of WWF and is ~ 0.67 for upper 2 s. south of WWF. Section is 7.6 km long; there is a data gap at canal.

separation of the Santa Margarita sandstone and Fruitvale shale across the WWF segment in Figure 7, unlike the segment depicted in cross section A-A' farther west (Plate 2). The latter section shows little or no reverse separation of upper Miocene and younger strata. Apparently, there is a progression of increased deformation of the shallow section towards the east along the segments of the WWF, culminating with recent surface rupture involving crystalline basement NE of Comanche Point.

Davis and Lagoe (1988) claimed that the WWF has always dipped to the north and was the important basin-bounding fault, facilitating the deepening of the MSB since the mid-Miocene. In their interpretation, the WWF presently dips to the north at 1 km depth and deeper, with only the upper portion passively rotated by deep thrusting to its present south dipping configuration. Although there must have been a north dipping normal fault bounding the deep MSB during the Miocene, their requirement that this structure evolved into the present-day WWF is inconsistent with the data at hand. On the basis of the similar orientation of nearby faults, we propose that the WWF has dipped south since the Miocene when it was part of the oblique-normal fault set that strikes NE (Figure 5). In this model, the south dipping WWF was reactivated as a reverse fault in the Pliocene. Since most of the thick strata in the MSB is upper Miocene to Recent in age, it appears that the MSB continued to subside during thrusting

along the WWF and related folding in the northern Tejon embayment.

Paleomagnetic evidence for crustal rotations. Published paleomagnetic results suggest that the Tehachapi Block, which includes the western Tehachapi Mountains and the Tejon embayment, has rotated clockwise as have other large southern California blocks [Luyendyk et al., 1985; McWilliams and Li, 1985]. Scattered paleomagnetic sampling and analysis suggests substantial Cenozoic clockwise rotations of the crystalline basement: about 45° northwest of Tehachapi Basin and about 60° near the southern end of the SSJB east of Grapevine Canyon (Figure 2; near pumping station in Plate 1) [Kanter and McWilliams, 1982; McWilliams and Li, 1985]. In contrast, the southern Sierras show no evidence for rotation at about the latitude of Bakersfield (east end Figure 2). Significant rotation of the Tehachapi Block is consistent with the physiographic trend of the southern Sierras. Furthermore, numerous penetrations of Sierran crystalline rocks beneath the Tejon embayment suggest that it is not underlain by the ancestral Sierran forearc, despite being at the southern end of the San Joaquin Valley.

The timing and scale of these Late Cretaceous to Recent rotations are only defined by limited sampling of different volcanic units in the San Joaquin and Tehachapi basins (Figure 2). The 16-18 Ma Miocene volcanic rocks at Tehachapi Basin, have not been rotated where basement rocks are rotated [Kanter

and McWilliams, 1982; McWilliams and Li, 1985]. In contrast, the 23 m.y. old basalts are rotated between 30° and 40° clockwise in the Tejon embayment [Plescia and Calderone, 1986], and 44° clockwise in the San Emigdio Mountains farther west [Graham et al., 1990].

Therefore it is probable that a large proportion of the clockwise rotations occurred during the early Neogene in the study area. It has been assumed that regional rotations ended not later than 16 Ma on the basis of the Tehachapi Basin data [McWilliams and Li, 1985; Golombek and Brown, 1988]. Given that slightly younger (20 m.y. old) volcanic rocks are rotated in the Mojave Desert, this would imply that about 40° of rotation occurred in a 2 to 4 m.y. time span regionally. As an alternate solution, we speculate that the Miocene clockwise rotations continued west of Tehachapi Basin, including Tejon embayment, beyond 16 Ma [Goodman, 1989]. This requires a structural boundary immediately southwest of the Tehachapi Basin, discussed below. More information is needed to better document the size and shape of the rotating pieces composing the Tehachapi Block and to understand how these rotations were accommodated in the SSJB north of the WWF.

Low-Angle faults. The Edison fault provides field evidence for mid-Tertiary low-angle normal faulting in the SSJB (Figures 2 and 8) [Dibblee and Warne, 1988]. The north dipping Edison fault separates the pre-Cenozoic basement rocks to the south from thick sections of coarse Oligocene and Miocene sediments in the Edison subbasin. Fault dips range from 22° up to 60° near the WWF, with a maximum displacement of more than 1.5 km at its western end. Several feet of mylonite, gouge, and crushed rock are present along the (now overgrown) fault surface [Dibblee and Chesterman, 1953] (Figure 8). In particular, the south-tilted late Oligocene to early Miocene Bealville fanglomerate is present only on the downthrown side of the Edison fault [Dibblee and Warne, 1988], similar to the relationship between the Tunis fault and Tecuya Formation conglomerates discussed above. The Bealville boulder fanglomerate consists of locally derived Sierran granodioritic basement clasts up to 3 m in diameter. Thus the mid-Tertiary Edison fault is the same age as the exposed NW striking normal faults in the Tejon embayment. Gently dipping seismic reflectors within the crystalline basement are imaged in industrial and CALCRUST seismic data along the eastern shelf of the Tejon embayment [Goodman, 1989, figure 7]. Here, high-angle NE striking faults sole down onto these low-angle structures. The latter structures are interpreted to be mid-Tertiary low-angle normal faults that accommodated the Oligocene and Miocene extension discussed below.

Summary: Structural evolution. Using the geological and geophysical observations described above, we propose the following history that reconciles these data sets. Before up to 40° of post-early Miocene clockwise rotations, N-S/E-W striking normal fault sets (e.g., Edison fault) originated during late Oligocene/early Miocene extension and significant tectonic subsidence. These faults demonstrate substantial expansion of the mid-Tertiary age section but provide little evidence for significant reactivation after middle Miocene uplift and erosion. The NE striking faults, on the other hand, were episodically active during most of the Miocene. It appears that abrupt tectonic subsidence in middle Miocene time was accompanied by reactivation of older normal faults, such as the Badger fault, and the opening of the central graben. In other words, faults striking north in late Oligocene and early Miocene time were likely active during and after rotation to their present NE striking orientations (Figure 5). The presently NW striking faults also were bodily rotated to their present configurations but apparently were not properly oriented for reactivation during the mid-Miocene basin

deepening. CALCRUST-U.S. Geological Survey reflection and refraction data show general structural continuity in the middle to lower crust [Goodman et al., 1989]. This observation, and the evidence for rotations in the upper crust, implies that the upper crust is mobile and is delaminated from the lower crust in the Tehachapi Block. It further suggests that much of the regional deformation did not involve the entire crust and was facilitated by shallow-dipping, upper crustal and midcrustal decollement structures (P.E. Malin et al., submitted manuscript, 1991). Under the active strain pattern, thrust-cored anticlines like Wheeler Ridge and Comanche Point have broken through the valley floor. Over the past few million years, the long-lived WWF structure was reactivated as a complexly segmented, SE dipping thrust, causing folds and uplift in the Tejon embayment and Tehachapi Mountains while the MSB has continued to subside to the north. The Pleito, Wheeler Ridge, and WWF thrust systems lie subparallel to the San Andreas and Garlock strike-slip faults north of where the latter two structures intersect. While these thrusts have no demonstrable physical connection to the master strike-slip faults, they apparently represent the contractile portion of transpressional motion north of this junction [e.g., Zoback et al., 1987].

SEQUENCE AND TIMING OF MIDDLE AND LATE TERTIARY TECTONIC EVENTS IN THE SSJB

The syntectonic thickening of sedimentary and volcanic rocks across normal to oblique-normal faults, the fault offset of Miocene unconformities, and the subsidence history of the basin all indicate that there have been several episodes of late Oligocene to late Miocene extension in the SSJB (Figure 3 and Plate 2). As a result, the stratigraphic section in the central graben is many times thicker than the section along the basin margin (Figure 9). Northwest of the basin-rim thrusts and Springs fault system, there is a progression of fault-bounded, down-dropped, basin-thickening blocks towards the center of Tejon embayment. These faults apparently were not active until late Oligocene time. Owing to numerous erosive submarine canyons, syntectonic sedimentation and volcanism, and oblique-normal faulting, there are very abrupt facies and thickness changes within late Oligocene and Miocene strata (Figure 9).

The late Oligocene/early Miocene (mid-Tertiary) extensional event includes relatively low angle, normal-growth faulting, basalt flows, coarse volcanic breccias, igneous dikes, locally derived boulder fanglomerates, and rapid thermotectonic subsidence. Magnetostratigraphic sampling of the early Miocene volcanic flows near the NW striking Tunis fault provides some information on relative timing [Hirst, 1986] (Plate 1). Only normally polarized fields can be identified on the upthrown western side, whereas the thicker volcanic section on the downthrown side contains reversely polarized fields overlain by the normally polarized fields [Hirst, 1986]. Thus faulting must have been roughly synchronous with the extrusion of the volcanic flows, as is also suggested by the orientation of the dike rock subparallel to the normal faults (Plate 1). The syntectonic conglomerates that bracket the "Tunis Volcanics" contain a variety of clast types. They contain metasedimentary and metavolcanic clasts, as found in Eocene and lower Oligocene conglomerates, but also record the first influx of locally derived tonalitic and gneissic cobbles and boulders, similar to rocks that crop out today in the Tehachapi Mountains [Goodman, 1989].

Therefore, the evidence suggests that sufficient structural relief existed during this extensional event such that the deep-level rocks of the Tehachapi Range were eroded and were locally distributed as high-energy sedimentary deposits. The

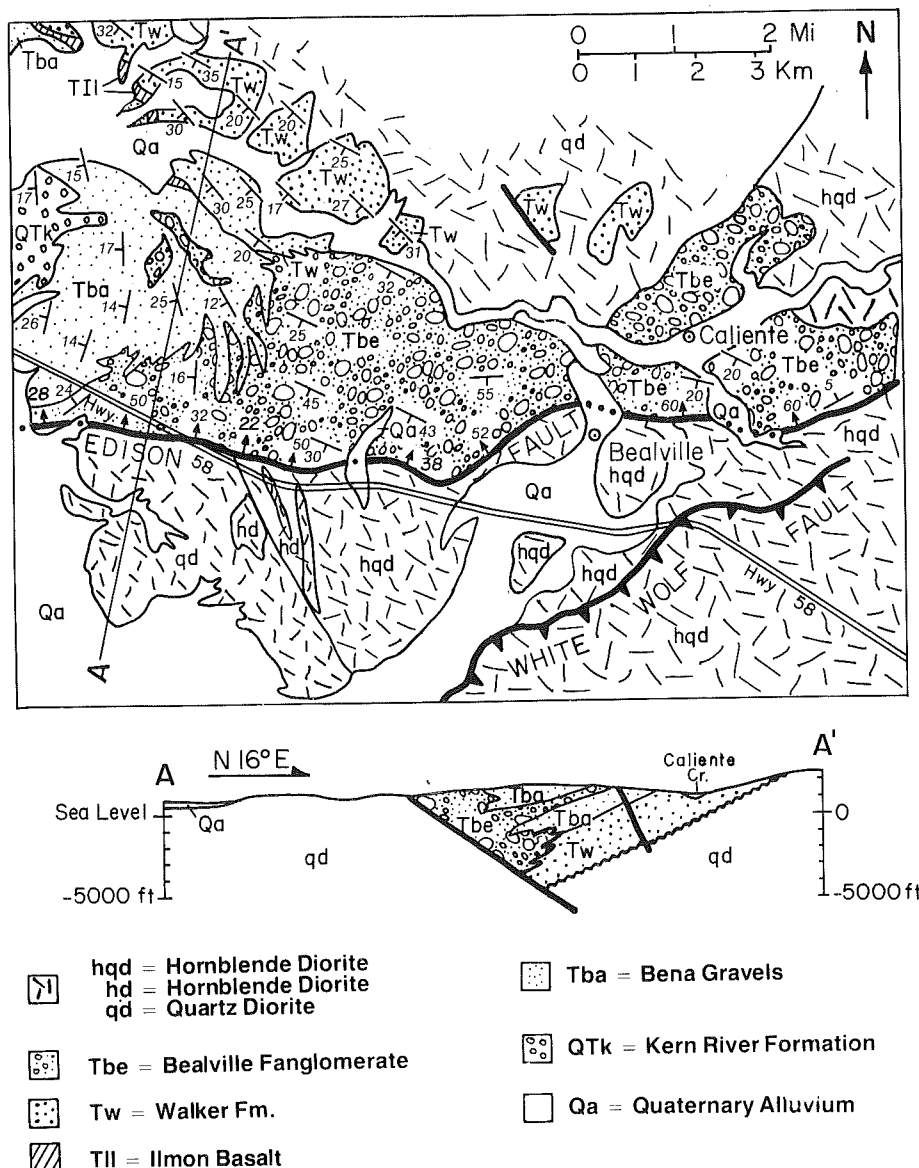


Fig. 8. Map and cross-sectional views of the Edison fault area (modified after Dibblee and Warne [1988]). Dip of Edison fault varies along strike from 22° to 60° south near the White Wolf fault. South-dipping, late Oligocene-early Miocene Bealville fanglomerate was deposited along the fault where it overlies upper Eocene to lower Miocene Walker Formation, which consists mainly of Sierran-derived arkosic sandstone and conglomerate. Note exposures of early Miocene Ilmon Basalt.

paleomagnetic relationships, as well as the differences in thickness and facies of the Tecuya Formation across these faults, cannot be explained by differential uplift and erosion during middle Miocene uplift. If that were the case, the older, reversely polarized flows but not the normally polarized rocks would be present on the upthrown block of the Tunis fault.

The middle Miocene uplift event marked a significant, temporary reversal of mid-Tertiary subsidence in the SSJB (Figure 3). Conglomerate clasts immediately above the associated angular unconformity are very different from those in the Tecuya Formation. Apparently, the Mesozoic Rand Schist was first exposed in the vicinity at this time, and the lower Miocene volcanic unit was locally exposed [Goodman, 1989]. The regional distribution of Pelona-Rand-Orocopia schist clasts in mid-Miocene conglomerates [T. Dibblee,

personal communication, May 1989] suggests that this mid-Miocene uplift was regional in extent.

The SSJB reached its maximum ocean depths [Bandy and Arnal, 1969] later in the Miocene. The paleobathymetry and the thickness of Luisian strata indicate that sedimentation rates in the Tejon embayment did not keep pace with rapid basin subsidence. Miocene subsidence and uplift events alternated until after 10 Ma (Figure 3), with the approximately 16-17 Ma, 12.5 Ma and 10 Ma uplift events tied to unconformities identified in the Tejon embayment (Figure 9 and Plate 1). Some of the NE striking faults were episodically active throughout the Miocene, with significant vertical offset (Figures 6 and 9). Therefore we propose that the middle to late Miocene thermotectonic subsidence was, in part, facilitated by the normal or oblique-normal reactivation of existing faults.

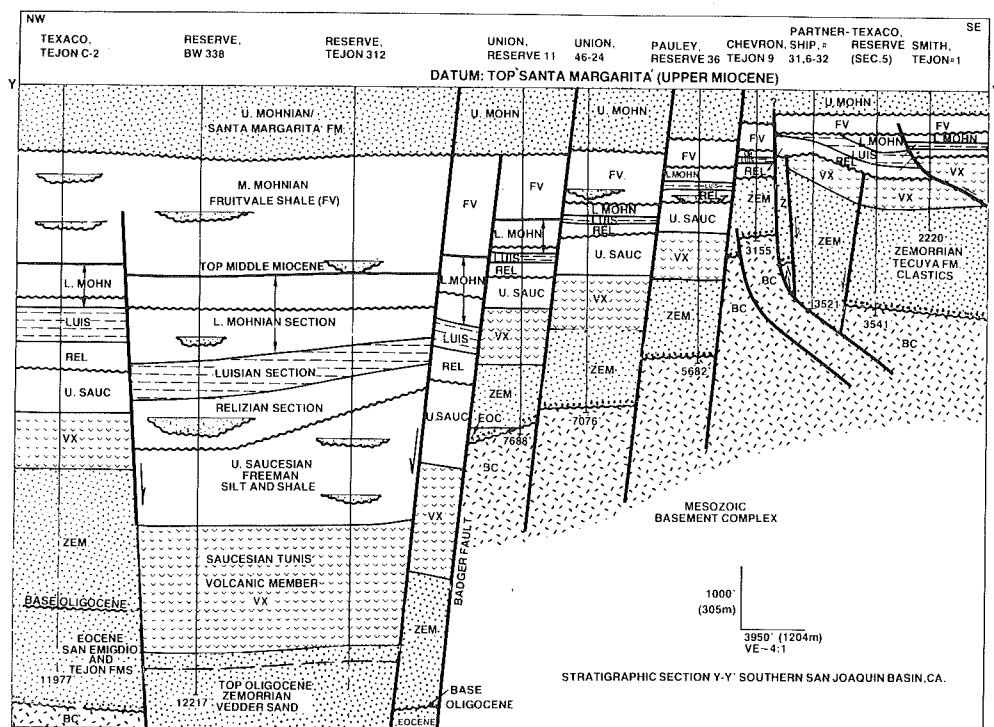


Fig. 9. Stratigraphic section Y-Y' (located on Figure 5) with some generalized lithofacies given. Section is thin in SE, along the thrust basin margins. NW striking normal faults uplifted as seen on seismic. The NE striking faults, including the central graben, were episodically active from the late Oligocene to the late Miocene. Lenses represent coarse-grained submarine canyon deposits. VE, vertical exaggeration; U, M, L, upper, middle, lower; Mohn, Mohnian; Luis, Luisian; Rel, Relizian; Sauc, Saucian; Z and Zem, Zemorrian and BC, Basement complex.

Subsurface data suggest that the oblique-normal faults are overlapped by an unconformity that lies within the upper portion of the Chanac Formation; thus places the transition between extension and contraction no earlier than early Pliocene time (e.g., Plate 2).

The relative stability of the Tejon embayment over the past 10 m.y. is in marked contrast to the remarkable subsidence of the MSB. In the latter subsidence, a middle Miocene marker has subsided by more than 7 km due to (1) normal faulting until earliest Pliocene time and (2) flexural subsidence due to the post-early Pliocene thrusting along its margins and syntectonic high sedimentation rates (Figure 3).

EARLY MIOCENE PALEOGEOGRAPHY OF THE SSJB AND SOUTHERN SIERRA NEVADA

The mid-Tertiary history of the SSJB and southern Sierra Nevada can be placed in the context of regional geology by undoing the Neogene clockwise rotations of the Tehachapi Block and strike-slip along the San Andreas and Garlock faults. The present day regional geology and structure for the SSJB and Sierra Nevada are depicted in Figures 1 and 2. Figure 2 also shows the magnitude of clockwise tectonic rotations, as well as locations of volcanic and crystalline rocks known to be unrotated, based on paleomagnetic data. A late Miocene reconstruction of this region (not shown) must account for approximately 60 km of left slip on the Garlock fault, which probably did not become a left-lateral fault until after 10 Ma, well after the rotations ended [Carter, 1987; Loomis and Burbank, 1988]. Restoring this amount of slip along the

Garlock fault moves the southern Sierran/Tejon block to the east and aligns the deep crustal level Tehachapi gneisses, metatonalites and Rand schists with similar deep-level terranes in the north central Mojave Desert and Rand Mountains (Figures 1 and 2). The next step backward in time accounts for the 40° clockwise rotation of the Tehachapi Block, assuming that the WWF and the western Garlock fault are rotated structures. This leads to the early reconstruction shown in Figure 10, where early Miocene normal faulting was synchronous with the extrusion of the Tunis Volcanic Member in the SSJB.

In this reconstruction, the early Miocene SSJB/Tehachapi extensional terrane depicted in Figure 10 linked the Mojave and Western California extensional terranes. The Western California extensional terrane, defined by the restoration of volcanic centers and basin fragments along strike-slip faults [Stanley, 1987], lay immediately to the south and west of the SSJB. Directly east of the SSJB/Tehachapi area lay the E-W trending Mojave extensional terranes, which underwent N-S extension in the mid-Tertiary (Figure 10) [Dokka, 1989]. At this time, the largest normal fault sets in the SSJB/Tehachapi area generally trended E-W, sandwiched between the north striking, subparallel Garlock and WWF-Kern Canyon fault systems. The restored E-striking faults include the Tejon Canyon fault, a prominent lineament that presently separates the Bear Valley Springs Tonalite to the northeast from the deep-crustal Tehachapi Gneiss Complex [Sams, 1986], the Tehachapi Creek fault, and the Tunis fault. In this mid-Tertiary reconstruction, the Tehachapi Creek Fault is aligned with the low-angle Edison normal fault (Figures 2 and 10). The north striking cross faults, shown schematically in Figure

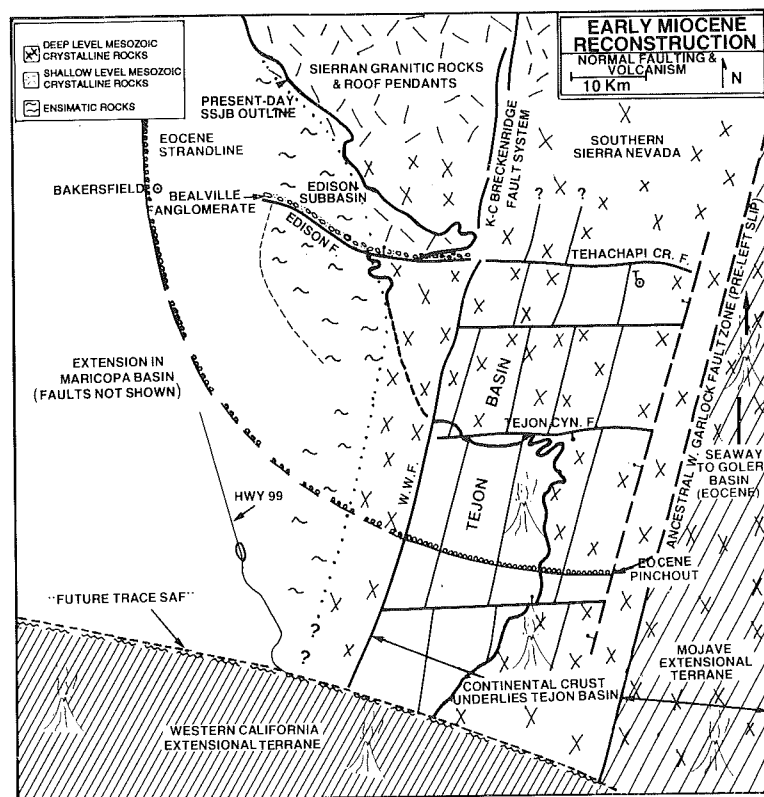


Fig. 10. Early Miocene reconstruction of the study area (about 22-23 Ma). About 60 km left slip on the Garlock fault and then 40° clockwise rotation have been restored from the present-day map (Figure 2), using a vertical axis of rotation between the White Wolf and Breckenridge faults. Pre-San Andreas fault (SAF) regional extension was synchronous with volcanism (volcanic centers shown schematically). The restored western Garlock fault separated the Southern San Joaquin Basin extensional terrane from the Mojave extensional terrane to the east. The southern end (prerotation coordinates) of this extensional belt was subsequently displaced over 300 km NW along the SAF [Stanley, 1987] ("future trace SAF" is shown in its present location with respect to Bakersfield which is arbitrarily held fixed as a reference point). Thus the SSJB terrane extended farther south than is indicated. The dotted line is the inferred boundary between continental crust immediately underlying the Tejon embayment and transitional crust which probably underlies the deep Maricopa Subbasin. Arrow shows location of inferred Eocene seaway that linked the Tejon embayment and Goler Basin.

10, were later reactivated during the mid-Miocene deepening of the SSJB, as the Tehachapi Block rotated clockwise.

The ancestral WWF was colinear with the Kern Canyon-Breckenridge fault system and may have shared a pre-early Miocene history including Late Cretaceous and Cenozoic dextral slip [Moore and duBray, 1978; Busby-Spera and Saleeby, 1990]. Furthermore, if the ancestral western Garlock fault was active in the early Miocene, it served as a north striking transfer fault between the SSJB/Tehachapi extensional terrane and the Mojave extensional terranes to the east. Later in the Miocene, the western Garlock structure itself was bodily rotated into an orientation favorable for the well-documented late Miocene to Recent left-slip. Projecting the reconstruction of this area to the Paleogene, we observe that the Eocene marine pinchout trends roughly N-S along the SSJB east of what is now Bakersfield [Bartow, 1987], then curves to an approximately E-W trend across what is now the Tejon embayment (40° rotation of middle Eocene pinchout shown in Figure 5 is accounted for in Figure 10) [Goodman, 1989]. Our restoration predicts that a Paleogene seaway, or embayment of the Pacific Ocean, transgressed eastward over eroded Sierran crust. This inferred, inland marine seaway provides an

explanation for the recent discovery of Paleogene marine rocks in the Goler Basin [Cox, 1987]. If this seaway reached as far to the northeast as the Goler basin, it submerged large portions of the deep-level Tehachapi gneiss complex, as did the Tejon Formation, and probably submerged portions of the Mojave Block. The seaway would have been breached during late Eocene/early Oligocene contraction, with Neogene tectonic events further isolating the SSJB from the Goler Basin and destroying most of the Paleogene marine record east of the Tejon embayment [Goodman, 1989; Graham et al., 1990].

IMPLICATIONS FOR REGIONAL TECTONICS

Timing of Regional Events, Onshore California

The sequence and timing of tectonic events in the SSJB displays some striking similarities with other areas of southern and central California (Figure 11). The SSJB is only one of a series of mid-Tertiary basins distributed over a latitudinal distance of several hundred kilometers with thick marine and localized nonmarine clastic deposits (e.g., Cuyama, Soledad,

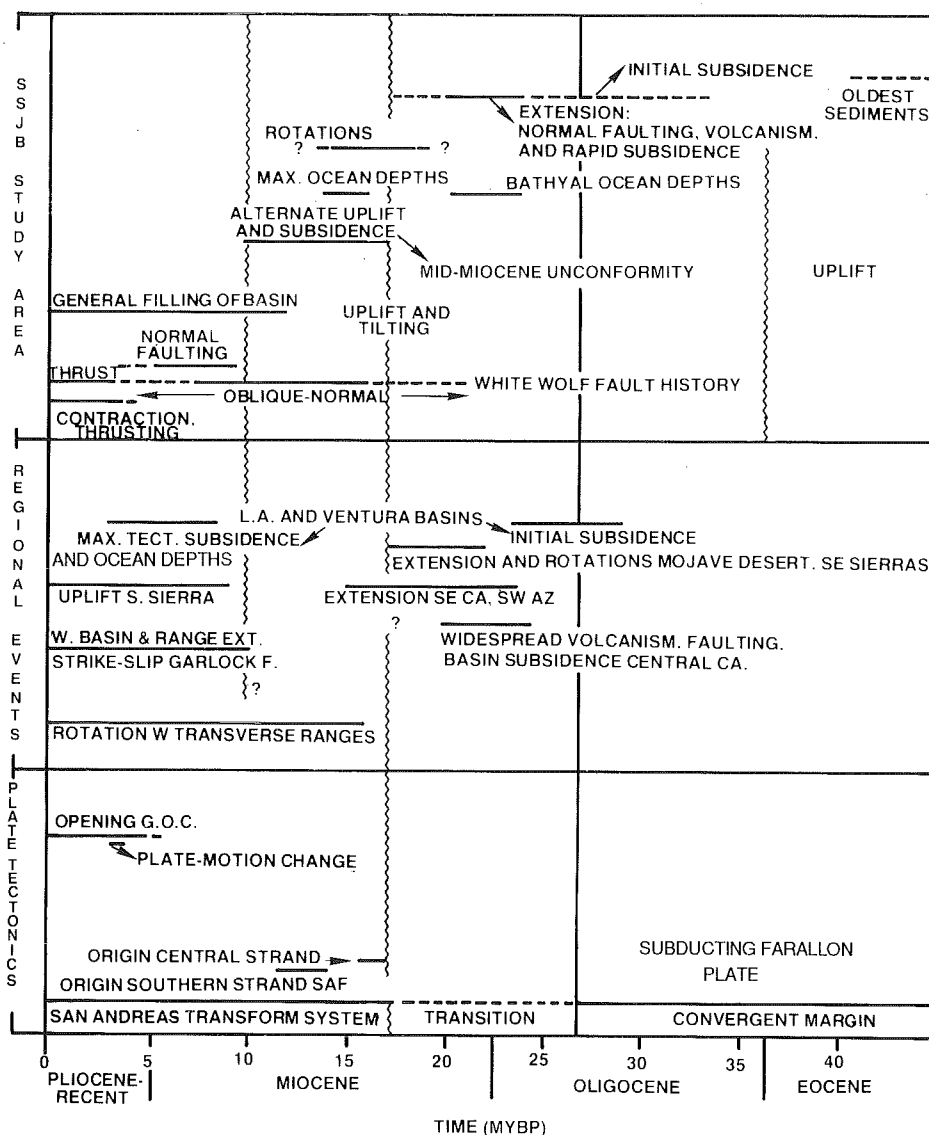


Fig. 11. Summary of major events in the Southern San Joaquin Basin (top), regional south-central California (middle), and along plate margins (bottom). Wavy lines indicate regional uplift and unconformities. Late Oligocene-early Miocene extension recognized in the SSJB is regional in extent and occurred during a long transition period between convergent and transform plate boundaries. Abbreviations are SE CA, southeastern California; SW AZ, southwestern Arizona; G.O.C., Gulf of California; and SAF, San Andreas fault. Chart is compiled from data of Goodman [1989], Atwater [1989], Mayer [1987], Dickinson et al. [1987], Dokka [1989], Stanley [1987, 1988], Graham et al., [1989], Harbert and Cox [1989], Hornafius [1985] and Chase and Wallace [1986].

La Honda, and Diligencia basins). It appears that all of these basins were defined, and subsided, in the broad mid-Tertiary extensional setting while located far from the SSJB. For example, the geology of the Diligencia Basin (SE California) is remarkably similar to the Tejon embayment. Oligocene and lower Miocene red beds with 22 m.y. old volcanic rocks unconformably overlie shallow marine deposits of middle Eocene age and gneissic basement rocks [Nilsen, 1984]. Normal faults formed an E-W trending graben in an intermontane setting that was occasionally lacustrine [Bohannon, 1975; Crowell, 1975].

As described above, mid-Tertiary regional extension ranged several hundred kilometers east and west of the SSJB (Figures

10 and 11). Extension from 23 Ma to 17 Ma has been documented to the east across the western and central Mojave Desert, with detachment faulting and 30° to 50° of clockwise rotations [Dokka, 1989 and personal communication, 1989; Walker et al., 1990]. The sites of mid-Tertiary extension can be mapped west and south of the SSJB to include a more than 400 km length of present-day west central California [Stanley, 1987]. In fact, regional extension, basin subsidence, and volcanism between 24 Ma and 17 Ma occurred across the entire width of south central California if Great Basin extension in SE California and SW Arizona is included (Figure 1) [Bohannon, 1975; Davis et al., 1980; Sherrod et al., 1987; Tennyson, 1989].

The mid-Tertiary extension-related subsidence in the SSJB is distinct from a middle Miocene episode of tectonic subsidence. This observation has important implications concerning the Cenozoic tectonic history of central California. Middle Miocene tilting and uplift (16-17 Ma) signaled the end to the mid-Tertiary extensional episodes in the SSJB, Mojave Desert and west central California and coincided with the end of the early Miocene episode of rotations in the eastern Tehachapi Mountains and in the central and western Mojave Desert [Golombek and Brown, 1988; Ross et al., 1989]. Evidence for mid-Miocene uplift and erosion can be recognized in the central SJB, on the west side of SJB, and in the La Honda, Salinas and offshore basins [Graham and Williams, 1985; Graham et al., 1989], as well as in the Mojave Desert [Dokka, 1989]. Angular schist clasts in the Unnamed conglomerate suggest that the now-dismembered Rand Schist body was exposed in the SSJB, and regionally, at this time. Alternatively, the mid-Miocene uplift in the SSJB is a more local phenomenon related to the subduction of the Mendocino fracture zone [Loomis and Glazner, 1986].

The regionally-recognized mid-Miocene uplift event was sandwiched between two subsidence events (Figure 11). The SSJB underwent combined subsidence and uplift totalling several kilometers. Subsidence was likely facilitated in the SSJB by fault reactivation, thermal decay, and sediment loading. We propose that the later mid-Miocene phase of regional subsidence, which had a large tectonic component, coincided with transtension (extension with a component of strike slip) adjacent to the active San Andreas fault. During this time, the crustal rotations probably continued in the SSJB/Tehachapi area, while several hundred kilometers south of the SSJB, clockwise rotations were initiated in the western Transverse Ranges.

Given the history of central California, the mid-Miocene uplift event likely represents contraction associated with movement along the organized SAF, discussed below (Figure 11). Indeed, the middle to late Miocene period of fluctuating uplift and subsidence in the SSJB (between 17 Ma and 10 Ma) can be related to alternating transtension and transpression adjacent to the young SAF (Figs. 3 and 11). At this time, the western portion of the SSJB began to be dismembered along the SAF. Since late Miocene time, the SSJB has filled with sediment; these sediments were mainly nonmarine by Pliocene time. In latest Miocene time, the final period of normal faulting in the SSJB was coeval with E-W extension that is also documented east of the Sierra Nevada beginning at 9 Ma, shortly after the inception of left-slip along the Garlock fault [Loomis and Burbank, 1988]. At about the same time, the southern Sierra Nevada was uplifted and tilted westward.

The late Miocene-Pliocene accumulation of thick, non-marine sediments in the MSB was coeval with deep-marine sedimentation in the Los Angeles and Ventura Basins which subsided to attain their maximum ocean water depths as late as 3-5 Ma (Figures 3 and 11) [Mayer, 1987; Dickinson et al., 1987]. The SSJB's restriction from the open ocean at this time was partly due to its location near the Garlock-San Andreas intersection along the "big bend" of the SAF (Figure 1), with rapid uplift and fault-normal contraction beginning in early Pliocene time along the basin margins. The present intermontane basin is defined by the rejuvenated southern Sierran, Tehachapi, and San Emigdio ranges and by the Salinian Block highlands to the west which moved north along the SAF to close off the SSJB to the west.

The Pliocene-Recent transition from general extension to contraction is the tectonic event most responsible for the present "overprinted" structural style of the SSJB. Regionally, contractile deformation includes folding and thrusting at high angles to the SAF, such as uplift of the Coast Ranges and along the west side of the Great Valley [Zoback, et al., 1987].

This deformation represents the normal component of strain that resolves the transpressional motion between the Pacific and North American plates, which is oblique to the SAF trace [see Namson and Davis, 1988]. Viewed on a larger scale, the transition from extension to contraction can be related to changes in Pacific plate motion between 3.9 Ma and 3.4 Ma that increased the component of convergence along most of the Pacific-North American plate boundary, or to the opening of the Gulf of California beginning approximately 5.5 Ma (Figure 11) [Harbert and Cox, 1989; Atwater, 1989].

The Tectonics of Transition

Two major regional transitions have been described here: (1) the transition between mid-Tertiary extension and post-lower Miocene strike-slip deformation and (2) the transition to contraction in Pliocene time. This discussion focuses on the Miocene transition which has important implications in light of the marine geophysical record for this time.

The contiguous late Oligocene/early Miocene extensional belt that existed across much of central California now lies scattered in the Colorado River area of SE California, in SW Arizona, across the Mojave Desert, north of the present trace of the western Garlock fault, and west of the central SAF (Figure 11). In our reconstruction, the north trending SSJB/Tehachapi Block separated the large mid-Tertiary extensional belts in the Mojave Desert from those in western California (Figure 10). The middle Miocene phase of deepening in the SSJB is distinct from the mid-Tertiary extensional subsidence and is probably related to transtension associated with the San Andreas transform. The SAF was well established at this time immediately west of the SSJB on the basis of geologic relationships across the fault [Graham et al., 1989]. Furthermore, plate reconstructions suggest that the MTJ had migrated northward, offshore, to the latitude of central California by this time. Over the remaining 15 m.y., the ages of volcanic rocks clearly are progressively younger to the north towards the present location of the MTJ (Figure 1) [Fox et al., 1985; Stanley, 1987]. In fact, the triple-junction model for localized extension, described above, works well in this later time frame.

However, the earlier geologic events of southern and central California suggest that organized strike slip along the San Andreas transform postdated, by many millions of years, the mid-Oligocene breakup of the Farallon plate, i.e., the first contact between the Pacific and North American plates offshore (Figure 11). The transition between the convergent and transform plate boundaries off SW California was likely a long and slow process. Along a diffuse plate margin, zones of spreading lay adjacent to areas where spreading had recently ceased [Atwater, 1989] during a time of generally eastward directed slow subduction and N-S trending shear. After Oligocene uplift, and extensive non-marine sedimentation, strike-slip began during late Oligocene/early Miocene time but occurred only locally onshore [Nilsen, 1984; Yeats et al., 1989]. At this time, plate motions were accommodated in the upper crust by a disorganized set of faults, as extensional basins formed onshore. The California plate margin, during this long plate boundary transformation, should be viewed neither as a convergent boundary between the Farallon and North American plates nor as a transform boundary between the Pacific and North American plates.

We propose that this complex tectonic setting be described as "transitional". The approximate time interval of this plate margin transition was 26 Ma to 17 Ma. Extension occurred over much of south central California during this reorganization, following the heating of the weakened continental crust by the impinging Pacific-Farallon Ridge (Figure 11). The organization of the modern San Andreas

transform onshore coincided with regional mid-Miocene uplift about 17 Ma, suggesting that the SAF is much younger than previously considered. Significant strike slip began in central California at this time, bringing an end to the "transitional" phase of tectonics. Future work in the region could focus on plate-scale kinematic and heat flow models for the mid-Tertiary extensional events in California and could examine their relationship with early Basin-Range extension farther east.

CONCLUSIONS

1. The changing of plate tectonic boundaries occurs over many millions of years and represents a distinct "transitional" phase of regional deformation. We have related Cenozoic regional deformation in central California to long periods of tectonic transition (1) between convergent and transform margin boundaries offshore in the mid-Tertiary (extension) and (2) normal to the SAF since the Pliocene (contraction).

2. Five main Oligocene-Recent basin phases are identified for the SSJB: (1) late Oligocene/early Miocene extensional subsidence, with high- and low-angle normal faulting, volcanism, coarse syntectonic fanglomerates, and the creation of a deep Neogene ocean basin before the San Andreas transform was organized, (2) Middle Miocene regional uplift,

(3) later Middle Miocene subsidence to lower bathyal depths, (4) alternating mid-to-late Miocene subsidence and uplift along the SAF, and (5) subsidence during Pliocene to Recent contraction along the basin margins.

3. Regarding mid-Tertiary paleogeography, the restored SSJB/Tehachapi Extensional terrane linked the Mojave Extensional terrane, then located to the east, and a Western California Extensional terrane which lay to the south and west.

Acknowledgments. This paper presents part of the dissertation of the first author. Research was supported by NSF CALCRUST grant 86-09347 and by Arco and Chevron fellowships. This study would not have been possible without access to the Tejon Ranch for field work and access to proprietary seismic and borehole data provided by Arco, Tenneco, Rancho Energy, Texaco, Occidental, Unocal, Sun, and Shell. We especially thank John Crowell, Steve Graham, Tanya Atwater, and John Suppe for sharing their knowledge of this region with us. Tor Nilsen and Thom Davis provided insightful reviews of the manuscript. We thank Exxon Production Research Company for assistance in preparing the manuscript, and Tom Loutit for reviewing an earlier version of the text. Figures and plates drafted by Gayle Jackson and Linda Myerson. ICS Contribution 0059-27-TC.

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(Received November 23, 1990;
revised August 30, 1991;
accepted November 8, 1991.)

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The editors of *Tectonics* welcome original scientific contributions in analytical, synthetic, and integrative tectonics. Papers are restricted to the structure and evolution of the terrestrial lithosphere with dominant emphasis on the continents. There will be no page charges for papers published in *Tectonics*.

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Manuscript submission. Four copies of the typescript should be submitted to one of the editors. One set of figures must be suitable for reproduction. (For details on style, see inside back cover.)

Tectonics

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