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NEOGENE TECTONIC EVOLUTION OF THE CALIFORNIA CONTINENTAL BORDERLAND AND WESTERN TRANSVERSE RANGES

By

James K. Crouch

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Scripps Institution of Oceanography

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Introduction

A series of continuously evolving models of the Mesozoic-Cenozoic tectonic history of western North America has been presented during the last decade by Hamilton (1969, 1978), Atwater (1970), Ernst (1970, 1974), Dickinson (1970, 1971), Blake and Jones (1974), Jones and others (1976), as well as many others. These models develop plate-tectonic concepts which genetically link the late Mesozoic and Paleogene tectonic history of western North America to the subduction of thousands of km of oceanic lithosphere beneath the Pacific margin. Although many aspects of these models remain controversial, most investigators agree that a longitudinally continuous, "Andean-type," continental-margin arc existed along western North America during long intervals of Mesozoic and Cenozoic time.

The major Late Jurassic to mid-Cenozoic tectonic elements of western North America (see Dickinson and Ingersoll, in press, fig. 3) included, from west to east: (a) the subduction complex formed landward of an active trench; (b) the forearc or outer-arc basin, within an arc-trench gap; and (c) the magmatic arc. Corresponding subparallel lithologic belts, which are recognized throughout much of northern California, as well as parts of southern California, Oregon, and Baja California are, from west to east: (a) the Franciscan assemblage; (b) the Great Valley sequence; and (c) the granitic and metamorphic rocks of the Klamath Mountains, Sierra Nevada and Peninsular Ranges. These three linear belts are relatively undisturbed in northern California (east of the San Andreas fault and south of the Klamath Mountains) and in southern Baja California. In the region extending from the Transverse Ranges south to about Sebastian Viscaino Bay, however, the Franciscan and Great Valley belts of this tripartite linear pattern have apparently been highly disrupted and only fragments of these belts are now recognized.

The Franciscan (subduction complex) and Great Valley (forearc basin deposits) are viewed here as linear lithologic belts which prior to 30 mybp were longitudinally continuous between Los Angeles and the southern tip of Baja California. A rise-trench encounter off southern California about 30 mybp and the subsequent development of migrating triple junctions and associated transform faults (McKenzie and Morgan, 1969; Atwater, 1970; Atwater and Molnar, 1973) are inferred to have caused major disruptions of these once continuous belts off southern California and Baja California. This paper outlines briefly the distribution of the Franciscan and Great Valley belts within the Transverse Ranges and the offshore California Continental Borderland, and presents a hypothesis to explain major aspects of the Neogene tectonic evolution of this region.

Characteristics of Franciscan and Great Valley Belts

The Franciscan and Great Valley lithologic belts include a wide variety of rock types which have undergone contrasting degrees of deformation and metamorphism. The following description outlines briefly some of the lithologic and structural aspects of Franciscan and Great Valley rocks which are useful for making correlations. The reader is referred to Bailey and others (1964), Berkland and others (1972), Jones and others (1976), and Hamilton (1978), for more detailed descriptions of the lithology and structure of these rocks.

Key lithologic components of the Franciscan assemblage are complexes of metasedimentary and blueschist-facies rocks. These occur in coherent terranes, or in disrupted belts of pervasively sheared and mixed rocks called mélange (Blake and Jones, 1974). Additional rocks associated with the Franciscan mélanges include serpentinites, amphibolites, pyroxenites, chert, and mafic volcanic rocks. The diversity of rock types and the chaotic character of the Franciscan assemblage are attributed to accretionary processes above an active subduction zone.

The coeval Great Valley sequence structurally overlies the Franciscan assemblage and consists chiefly of marine sandstone, shale and conglomerate deposited in a forearc basin within the arc-trench gap (Dickinson, 1971). The western or distal facies of this thick sequence (10,000 + meters) depositionally overlie Upper Jurassic oceanic crust (Bailey and others, 1970) and the eastern or proximal facies lap onto Sierran batholithic and prebatholithic basement complexes of dominantly Mesozoic age. The Great Valley strata are locally folded and faulted, but are markedly less deformed than the Franciscan assemblage. In addition, the metamorphic grade of the

Great Valley rocks never exceeds prehnite-pumpellyite facies, whereas some Franciscan rocks are regionally metamorphosed to high-pressure blueschists facies.

As originally defined (Bailey and others, 1964, p. 123), the Great Valley sequence includes only Upper Jurassic to Upper Cretaceous strata; but Paleogene forearc basin strata continue the Great Valley sequence upward in northern California (Ingersoll, 1978) and the other regions outlined in this paper. Thus, the Great Valley belt as used herein includes forearc strata of Late Jurassic through Paleogene ages. The Franciscan belt in southern California also includes rocks of Late Jurassic through Paleogene age as does the Franciscan assemblage in the northern California Coast Ranges (Evitt and Pierce, 1975).

Distribution of Franciscan and Great Valley Belts

Jones and others (1976) and Hamilton (1978) have recently outlined the present distribution of Franciscan and Great Valley belts in southern California, Baja California, and parts of the California Continental Borderland. The distribution of these belts, as illustrated in Figure 1 and discussed in the following text, is based on their interpretations with slight modifications and additional interpretations of my own. For specific localities cited in text but not shown on Fig. 1, the reader is referred to Moore (1969, fig. 19 and Chart 1).

Western Transverse Ranges

Forearc basin strata, assigned to the Great Valley belt, form the bulk of the western Transverse Ranges (Fig. 1). Included are Upper Cretaceous and Paleogene deep marine to continental deposits in the Santa Ynez Ranges, San Miguel, Santa Rosa and Santa Cruz Islands, Santa Monica Mountains, Simi Hills, and the Ventura Basin (see, for example, Dibblee, 1966; Vedder and others, 1974, sheet 4; Colburn, 1973). Most of this forearc basin assemblage consists of arkosic sandstones and interbedded shales that were derived from a continental crystalline source terrane to the east.

Facies relationships and northward trending paleocurrent directions determined from Eocene and Oligocene strata on San Miguel and Santa Rosa Islands and in the Santa Monica Mountains and Simi Hills (Yeats and others, 1974), and from Upper Cretaceous (Upper? Chico Formation) strata in the Santa Monica Mountains (Carey and Colburn, 1978), suggest that these localities were situated along the proximal side of the forearc basin. In addition, basement rocks with east-west structural trends, exposed on Santa Cruz Island (Santa Cruz Island Schists) and in the Santa Monica Mountains (Santa Monica Slate) have been correlated with Jurassic rocks in the Sierran western foothills belt which have north-south structural trends and border the proximal side of the Great Valley belt. Faunal correlations between the Santa Monica Slate and the Mariposa Formation (western foothills belt) were made by Imlay (1963). On these bases, correlations of the Santa Monica Slate with the Bedford Canyon Formation in the Santa Ana Mountains appear erroneous (Jones and others, 1976).

Based on these lithologic and faunal correlations and structural trends, Jones and others (1976) concluded that the Santa Cruz Island Schist and Santa Monica Slate were rotated clockwise during Late Cretaceous or Cenozoic time. Clockwise rotations have also been inferred by Kamerling and Luyendyk (1977, in press) whose paleomagnetic evidence strongly suggests that the Miocene volcanic rocks on Anacapa, Santa Cruz and San Miguel Islands and in the Santa Monica Mountains have been rotated clockwise at least 75 degrees. Combining these paleomagnetic data with the paleocurrent trends, provenance, structural trends and correlations noted previously, and with the recognition that the western Transverse Ranges were part of a forearc or "outer-arc" basin until at least Late Eocene time, Hamilton (1978) suggested that the entire western Transverse Ranges rotated clockwise, away from the Peninsular Ranges, beginning in late Oligocene or early Miocene time.

Inner Borderland

South of the Malibu Coast fault, the Great Valley belt is represented onshore in southern California (Fig. 1) by a nearly continuous north-south trending belt of Upper Cretaceous, Paleocene and Eocene strata that lap onto Mesozoic batholithic and prebatholithic rocks of the Peninsular Ranges (Yerkes and others, 1965; Kennedy and Moore, 1971). Further south, the belt is exposed at numerous localities along the northern Baja California coastline (Gastil and others, 1975) and on the Viscaino Peninsula where Upper Jurassic rocks rest on Jurassic ophiolite (Jones and others, 1976). This Upper Cretaceous and lower Paleogene assemblage consists of conglomerates, arkosic sandstones and shales that were largely derived from the eroded magmatic arc to the east. It includes facies that range from fluvial channel to upper slope deposits, and it is analogous to the eastern, proximal facies of the Great Valley sequence in northern California. The westward extent of this Great Valley belt (distal facies) is not well known, except where it is exposed in the Viscaino Peninsula.

Franciscan rocks form the next adjacent belt to the west. This belt, which includes blueschist and other Franciscan-like rocks, is delineated onshore from exposures in the Palos Verdes Hills (Woodford, 1924; Woodring and others, 1946) and from well samples in the western Los Angeles basin (Schoellhamer and Woodford, 1951; Yeats, 1973). Offshore, blueschist and related rocks are exposed on Santa Catalina Island (Platt, 1975) and have been sampled from seafloor outcrops at several localities (Vedder and others, 1974) within the inner borderland Franciscan belt outlined in Figure 1. Middle Miocene and younger rocks overlie much of this Franciscan belt, but Eocene deposits are not known.

If this belt and the adjacent belt of Upper Cretaceous-Eocene rocks exposed along the mainland coast are in fact equivalent to the Franciscan and Great Valley rocks of northern California, then, by analogy, a tectonic boundary (the Coast Range thrust of Bailey and others, 1970) should separate the two belts. In this context, the Newport-Inglewood fault zone may mark the boundary between Franciscan and Great Valley type rocks in the western Los Angeles basin. The western limit of Upper Cretaceous and Paleogene deposits, which are inferred to lie (∿8 km) east of the fault zone in the northwestern portion of the Los Angeles Basin (Yerkes and others, 1965, figs. 6 & 7), is probably either a tectonic or erosional contact, not a depositional one. The presumed ophiolitic sequence upon which these strata were deposited, however, may still be in contact with Franciscan rocks in the subsurface along the Newport-Inglewood fault zone (see Platt and Stuart, 1974).

Outer Borderland

The Great Valley and Franciscan belts are repeated in the outer borderland (Fig. 1) and are juxtaposed against the inner borderland complexes by major northwest-trending, right-lateral faults. This relationship, illustrated diagrammatically on Figure 1 as a single fault, is probably a system of faults, similar to the modern San Andreas fault system. The fault system inferred here is similar, except for the suggested amount of offsets, to the East Santa Cruz Basin fault system proposed by Howell and others (1974).

The outer borderland Great Valley belt consists of a thick succession of Cretaceous, Paleocene, and Eocene forearc basin marine strata. Seismic reflection profiles and numerous bottom samples indicate that these strata underlie Santa Cruz and San Nicolas Basins and most of the Santa Rose-Cortes Ridge (Vedder and others, 1974). More than 1000 m of Eocene strata are exposed on San Nicolas Island (Vedder and Norris, 1963), and a stratigraphic test well on Cortes Bank penetrated more than 2000 m of deep-water Upper Cretaceous, Paleocene, and Eocene marine sandstones and interbedded shales (Paul and others, 1976). Like the Great Valley belts in the western Transverse Ranges and inner borderland, this belt is characterized by mild deformation and slight metamorphism, and was derived from a continental crystalline source terrane.

This Great Valley belt is bounded on the west by a belt of Franciscan-like rocks that make up the outer margin of the borderland. Similar to the inner borderland Franciscan belt, Miocene rocks mantle much of this belt and Eocene deposits are not found (Crouch, J. K., unpub. data). Numerous bottom samples from the Patton Ridge, Patton Escarpment, and isolated knolls and banks, however, have recovered sheared, laumontite-bearing, lithic wackes, along with argillite, serpentinite, amphibolite, pyroxenite and mafic volcanic rocks (Vedder and others, 1974). Blueschist rocks in this belt were recovered from a bank 9 km southwest of Santa Rosa Island, and possibly are in place along the Patton Escarpment.

Southern Borderland

The southern borderland region, west of northern Baja California is bounded at the north by the southwest trending Santa Tomás fault (∿ 31°30'N.) and at the south by Sebastion Viscaino Bay (Moore, 1969).

Major differences exist between the northern and southern borderland regions. The southern borderland is deeper (by .5 - 1.5 km in the basins), narrower, has higher heat flow values, and appears to be floored largely by basalt (Krause, 1965; Moore, 1969). The greater depths and the relatively thin veneer of sediments overlying basement in the southern borderland (see reflection profiles in Moore, 1969) are especially anomalous, for the synclinal axis of the Upper Cretaceous and Paleogene forearc basin strata (> 10,000 m thick) in the Viscaino Peninsula (Minch and others, 1976) trends directly into this region. Krause (1965) suggested that thinned crust could explain the greater depths and "ubiquitous" basaltic volcanic rocks of the southern borderland. Suppe (1970) also inferred rifting in the southern borderland. Gravity and magnetic data which suggest a shoaling of the mantle from the northern borderland to the southern borderland, and a depth to mantle of 13-15 kms under the southern borderland (Plawman, 1978) is consistent with a north-south extension hypothesis. A southward increase in heat flow (Henyey, 1976) is also consistent with north-south crustal extension.

Proposed Model For Tectonic Evolution

A tectonic model to account for the present distribution of Franciscan and Great Valley belts shown in Figure 1 should incorporate clockwise rotation of the western Transverse Range--juxtaposition of Franciscan and Great Valley belts in the outer borderland--and north-south extension and rifting in the southern borderland. A series of paleotectonic-paleogeographic sketch maps (Fig. 2) illustrate the proposed evolution of the western Transverse Ranges and the California Continental Borderland since 30 mybp. The initial configuration of the continental margin is adapted from Johnson and Normark's (1974) model for the Neogene tectonic evolution of the Salinian block. The features of their model that are retained here include: (1) the Salinian block and adjacent belts of Great Valley and Franciscan rocks, which together make up the southern Coast Ranges, formed a westward protruding bulge in the continental margin prior to the initial contact between the Pacific and North American Plates; (2) the ancestral East Pacific Rise first intersected the subduction zone off western North America about 30 mybp; (3) this initial rise-trench encounter occurred at a position that lay south of the westward protruding southern Coast Ranges; (4) subduction of the Pacific plate was initiated at the southern end of the Coast Ranges as the Mendocino triple junction migrated northward past the protruding bulge.

Figure 2a shows the configuration of Pacific, Farallon and North American plate boundaries at about 30 mybp. The ancestral East Pacific Rise has just intersected the trench off southern California at a position now occupied by the northern California Continental Borderland. The Franciscan and Great Valley belts are shown as undisrupted and longitudinally continuous belts, which extend southward from about Los Angeles to the tip of Baja California.

By about 22 mybp (Fig. 2b) the Mendocino triple junction was off central California and the Rivera triple junction was off northern Baja California. The Farallon plate between the two triple junctions had since disappeared, and Pacific-North American relative plate motion was being taken up along a ridge-trench transform fault which closely followed the earlier trench. Subduction of the Pacific plate at the trench bounding the southern end of the Coast Ranges may have produced silicic volcanism within the Coast Ranges to the north. For example, the silicic volcanic rocks which make up the intrusive Morro Rock-Islay Hill porphyry complex (M, Fig. 2b) and the extrusive Cambria Felsite (C, Fig. 2B) are between 25 and 21 m.y. old (Ernst and

Hall, 1974) and lie respectively about 130 and 160 km north of the inferred subduction zone. Likewise, the Obispo tuffs which have yielded radiometric ages ranging between 15.3 ± 0.9 m.y. and 16.5 ± 0.8 m.y. (Turner, 1970) and occur in the same general vicinity, may be a younger expression of this same subduction zone.

The configuration in Fig. 2b lasted until about 18 mybp when the Rivera triple junction became unstable enough that the ridge jumped landward beneath continental crust (Fig. 2c). An alternative and perhaps a better explanation is that the triple junction progressively moved inland during its southward migration until it once again stabilized. In considering geometric requirements for triple junction stability, McKenzie and Morgan (1969) pointed out that the RFT Rivera triple junction would have remained stable only as long as the trench and transform fault replacing it are colinear. Instability of the triple junction is inferred to have resulted from the trench having had a more northerly strike than the transform fault replacing it. A similar argument is used by Dickinson and Snyder (in press) to explain initial Neogene basin formation in the California Continental Borderland. The landward jump or migration of the ridge initiated north-south extension and eventually rifting of the continental margin north of Sebastian Viscaino Bay. This rifting event began moving a large sliver, consisting mainly of Franciscan and Great Valley type rocks but also including a narrow strip of pre-tithonian basement northward along a newly formed ridge-trench transform fault (Fig. 2c). Andesitic and dacitic volcanic rocks exposed on Santa Cruz, Anacapa and San Clemente Islands and in the Santa Monica Mountains are between 12 and 18 m.y. old and may have been erupted along this northwest-trending transform fault. The initial stages of Neogene basin formation in the continental borderland may have resulted from complex deformation within and adjacent to the northward moving sliver.

Soon after rifting began, the northern end of the sliver began to collide with the east-west trending trench bounding the southern end of the Coast Ranges. Resistance to continued northward movement at the trench and right-lateral shear between the Pacific and North American Plates caused the northern end of this sliver (western Transverse Ranges) to begin rotating clockwise. Clockwise rotation of this segment of the sliver may have been enhanced by westward displacement of the Peninsular Ranges and inner borderland complexes due to mid-Miocene, roughly east-west, extension in the southern Basin and Range Province. The present geologic relationships in the borderland suggest that this westward displacement continued (perhaps accentuated by local extension within the Los Angeles basin) until the western Transverse Ranges had rotated approximately 120° clockwise and the inner borderland Franciscan belt had slid past the Santa Monica Mountains and impinged upon the outer borderland complexes.

Before and during the rotation of the western Transverse Ranges, most of the adjacent Franciscan belt, which initially lay seaward, was subducted and/or overridden by rocks of the Great Valley belt. Continued northward compression caused the Great Valley belt with its basement rocks to be thrust northward as a large flake over most of the remaining Franciscan rocks and against the southern Coast Ranges--annihilating the subduction zone (see also Hamilton, 1978, p. 52). Northward translation, clockwise rotation, and thrusting of the rifted sliver are inferred to have been largely completed by 8 mybp (Fig. 2d).

By about 8 mybp, the Rivera triple junction had reached the tip of Baja California and was once again unstable enough to jump or migrate landward. As a result a large sliver, which now makes up southern Baja California, was stripped from mainland Mexico and moved northward along a transpeninsular fault (Fig. 2d). Geological and geophysical evidence suggest that a major transpeninsular fault extends from about Santo Domingo (SD, Fig. 2d) on the Pacific side of Baja Peninsula, southward toward Loreto (L, Fig. 2d) on the Gulf side (J. Minch, personal commun., 1978). Projecting this fault southward from Loreto places it near the Tres Marias Islands (TM, Fig. 2d). Closure of the Gulf of California based on spreading centers and basement terrane (Moore, 1973, Fig. 4) leaves a 180 km gap in the continental margin (between the 2000-meter contours) in a region just south of the Tres Marias Islands. Closure of this gap along the projected transpeninsular fault would place the crystalline rocks at Cabo San Lucas (at the tip of Baja) against similar crystalline rocks of overlapping age (G. Gastil, personal commun., 1978) which crop out at Cabo Corrientes on the Mexican mainland. If Moore's (1973, Fig. 4) reconstruction is correct, this gap would have had to have formed prior to about 5 mybp, before the opening of the modern Gulf. One explanation which could account for the gap and the transpeninsular fault is that an earlier spreading ridge first slivered off a piece of Baja California from the mainland and then about 5 mybp the ridge jumped westward and began opening the modern Gulf. Larson (1970) discussed the possibility of an earlier spreading ridge and suggested that the oceanic crust in the vicinity of the Tres Marias Islands is 4 to 6 m.y. old. He also concluded, however, that this piece of isolated crust could be even older leaving open the possibility of an earlier (>6 mybp) formation of the gap. Using a 3 cm/yr half-rate of spreading the 180 km gap could be formed in 3 m.y. which would place the earlier rifting event at 8 mybp.

If a sliver of Baja was pushed northward along a transpeninsular fault by an earlier spreading ridge at the mouth of the Gulf of California, then north-south compression must have occurred in one or more of the following areas: Transverse Ranges; California Continental Borderland; southern Baja California Peninsula. The reason for this is that the earlier trench which bounded the southern Coast Ranges no longer existed and the southern Coast Ranges and the Transverse Ranges would have become an impediment to any northward movement of crustal blocks from the south. The most likely region for much of this north-south compression (interplate deformation) to be taken up would have been within the southern portion of the California Continental Borderland where young, ductile oceanic and highly attenuated continental crust had been formed. Thus, northward movement of the southern Baja Peninsula of 150-180 km may have telescoped the southern borderland and closed a large portion of the gap left behind by the earlier rifting event which removed the western Transverse Ranges and the outer borderland from this region.

Discussion

The repetition of Franciscan and Great Valley belts in the outer borderland corresponds well with available lithologic and structural data and explains the atypical width of the continental margin off southern California. Some of the available data in the western Transverse Ranges, however, do not fit the outline of the model. For example, Eocene paleocurrent indicators on Santa Cruz Island trend southwest (Yeats and others, 1974). If these deposits are restored to their original position, as indicated by the model and by Kamerling and Luyendyk (1978, in press), sediment transport directions would be pointing toward, instead of away from, their eastern source terrane. Also, based on lithologic correlations, Howell and others (1975) place the upper Eocene strata on Santa Cruz Island west of San Diego, about 200 km southeast of their present position. My model places the same strata off northern Baja California, about 500-550 km southeast of their present position. Northward translation by this amount, however, is supported by paleomagnetic data (Kamerling and Luyendyk, in press). Clearly, the discrepancy between the lithologic correlations and paleomagnetic data needs to be resolved.

An additional problem involves the boundaries of the western Transverse Ranges as they pertain to the model. In particular, the model requires that the western Transverse Ranges be bounded at the north by a major thrust fault. Evidence for such a fault exists along a recently inferred branch of the Santa Ynez fault (Sylvester and Darrow, in press) in the western Santa Ynez mountains but no evidence has been recognized for a thrust fault of this magnitude in the central and eastern Santa Ynez Ranges (J. C. Crowell, personal commun., 1978). An alternative northern boundary fault, now buried by Pliocene and younger sediment, may follow the Oak Ridge Fault trend and the axial portion of the onshore-offshore Ventura Basin. If so, the Santa Ynez Ranges would be excluded from the rotating sliver.

Implications of this model include the following:

1) Beginning about 18 mybp rocks assigned to the Franciscan (subduction complex) and Great Valley (forearc basin deposits) belts were rifted away from their former position off northern Baja California.

2) Rifting was caused by the unstable configuration of a ridge-fault-trench triple junction migrating southward along the continental margin.

3) During the rifting event the Franciscan and Great Valley belts were translated northward along a ridge-trench transform fault resulting in: (a) a repetition of these belts in the borderland off southern California, and (b) clockwise rotation and subsequent thrusting of these belts (western Transverse Ranges) against the southern Coast Ranges.

4) Neogene basin formation and volcanism in the borderland are related to this disruption.

5) The southern half of Baja California was translated northward ∿150 km by an earlier spreading event at the mouth of the Gulf of California, resulting in telescoping of the southern borderland.

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Figure 1. Selected tectonic elements of southwestern North America (modified from Hamilton, 1978, fig. 13).

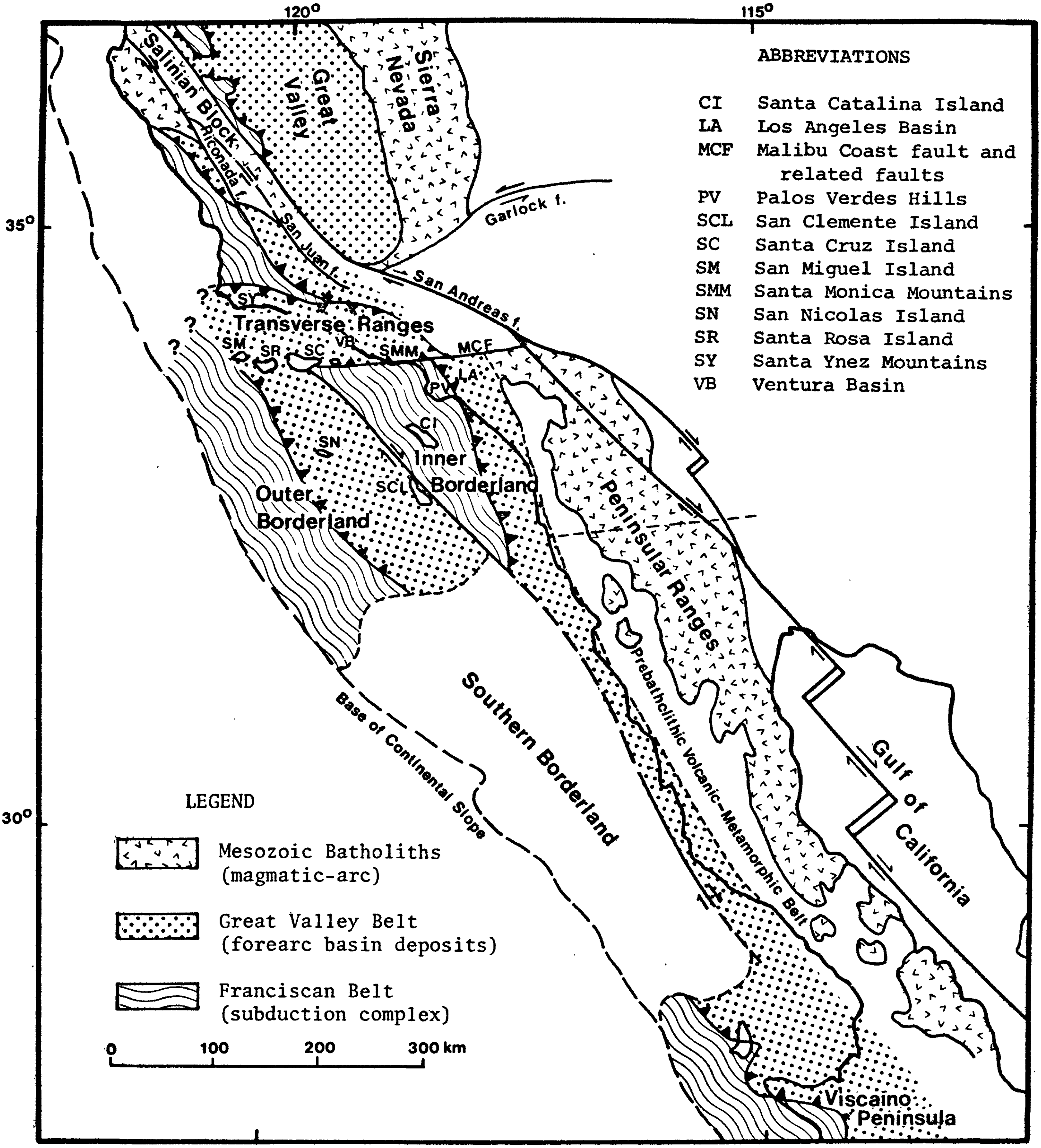
120°
115°
35°
30°
ABBREVIATIONS
CI Santa Catalina Island
LA Los Angeles Basin
MCF Malibu Coast fault and related faults
PV Palos Verdes Hills
SCL San Clemente Island
SC Santa Cruz Island
SM San Miguel Island
SMM Santa Monica Mountains
SN San Nicolas Island
SR Santa Rosa Island
SY Santa Ynez Mountains
VB Ventura Basin
Salinian Block
Great Valley
Sierra Nevada
Riconada f.
San Juan f.
Garlock f.
San Andreas f.
?
SY
Transverse Ranges
SM
SR
SC
VB
SMM
MCF
LA
PV
CI
SN
Inner Borderland
SCL
Outer Borderland
Peninsular Ranges
Prebatholithic Volcanic-Metamorphic Belt
Southern Borderland
Base of Continental Slope
Gulf of California
Viscaino Peninsula
LEGEND
Mesozoic Batholiths (magmatic-arc)
Great Valley Belt (forearc basin deposits)
Franciscan Belt (subduction complex)
0
100
200
300 km

Figure 1

Figures 2a, b, c and d. Schematic model for tectonic evolution of the California Continental Borderland and Western Transverse Ranges. The modern Gulf of California is closed. Prior positions of rise crests are modified from Atwater and Molnar (1973). Ages (in millions of years before present) are approximate. Base map is Mercator projection about Pacific-American rotation pole at 53°N, 53°W. Hachured pattern indicates southern Coast Ranges (including the Salinian Block) palinspastically adjusted 300 km to account for post-Miocene offset on the San Andreas fault (Graham and Dickinson, 1978). Arrows indicate plate motion relative to fixed North American plate. Dashed lines along Baja California shoreline in 2a, 2b, and 2c indicate extended shoreline to account for about 150 km of offset along transpeninsular fault between about 8 and 5 mybp. (a) 30 mybp: Pacific and North American plates first make contact. (b) 22 mybp: triple junctions have separated and arc volcanism (abbreviations C and M) occurs in the Coast Ranges. (c) 18 mybp: unstable southern triple junction configuration results in ridge jump and initial rifting of the continental margin off Baja California. (d) 10-8 mybp: rifted Great Valley and Franciscan belts juxtaposed in the outer borderland and Great Valley belt rotated into and over former subduction zone and adjacent Franciscan belt; (d) Early spreading event at the mouth of the Gulf of California moves southern Baja California northward about 150 km along a transpeninsular fault. Interplate deformation telescopes southern borderland region.

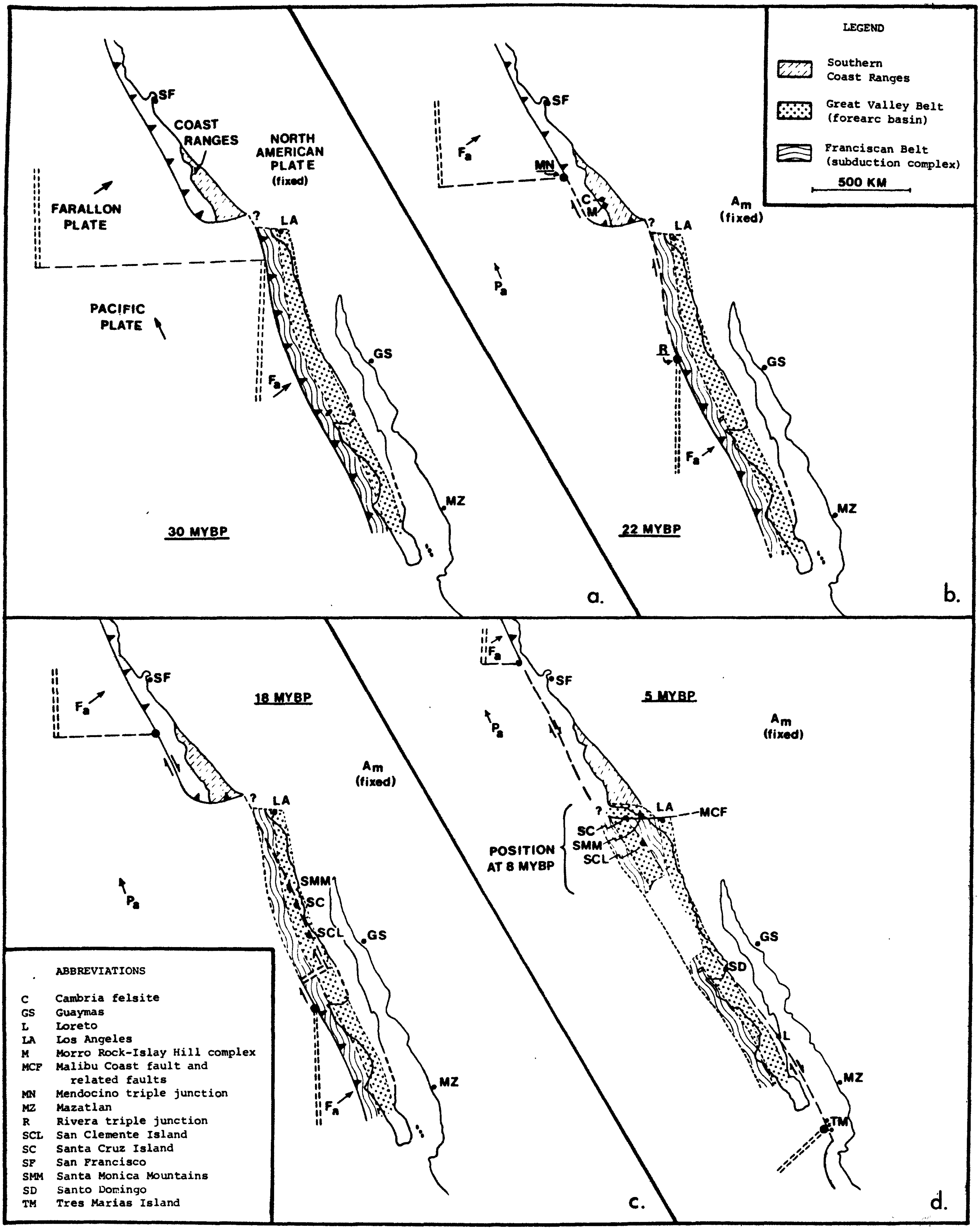LEGEND
Southern Coast Ranges
Great Valley Belt (forearc basin)
Franciscan Belt (subduction complex)
500 KM
SF
COAST RANGES
NORTH AMERICAN PLATE (fixed)
FARALLON PLATE
PACIFIC PLATE
?
LA
GS
F_a
MZ
30 MYBP
a.
MN
C
M
A_m (fixed)
P_a
R
22 MYBP
b.
18 MYBP
SMM
SC
SCL
c.
5 MYBP
MCF
POSITION AT 8 MYBP
SD
L
TM
d.
ABBREVIATIONS
C Cambria felsite
GS Guaymas
L Loreto
LA Los Angeles
M Morro Rock-Islay Hill complex
MCF Malibu Coast fault and related faults
MN Mendocino triple junction
MZ Mazatlan
R Rivera triple junction
SCL San Clemente Island
SC Santa Cruz Island
SF San Francisco
SMM Santa Monica Mountains
SD Santo Domingo
TM Tres Marias Island

Figure 2