PLATE TECTONIC HISTORY OF SOUTHERN CALIFORNIA WITH EMPHASIS ON THE WESTERN TRANSVERSE RANGES AND NORTHERN CHANNEL ISLANDS

Tanya M. Atwater
Department of Geological Sciences
University of California
Santa Barbara, CA 93106-9630
atwater@magic.geol.ucsb.edu

ABSTRACT

The Channel Islands occupy the southern edge of the Transverse Ranges block and thus the islands share and illuminate the history of this block. In the Mesozoic and early Cenozoic, the Transverse Ranges block was oriented north-south, so that the Channel Islands probably lay near San Diego. The block occupied the forearc region of a subduction zone, collecting continental shelf sediments equivalent to those in the Great Valley belt farther north. In the mid-Cenozoic, a spreading center approached the trench in this region, contributing to the uplifts recorded by the Sespe Formation terrestrial rocks. Between 27 and 18 Ma, the Pacific plate made contact with North America and continental pieces began to break off and join the Pacific plate, gradually establishing the modern San Andreas plate boundary.

In the early stage of plate boundary evolution (Miocene, 18-12 [-5?] Ma), the northern plate boundary lay within and inboard of the Salinian block, but then bent south-westward through the Southern California Borderland in a transtensional geometry. This transtensional phase is responsible for the extension and reconfiguration of the continental rim, including the onset of rotation and left lateral shearing of the Transverse Ranges block and deposition of San Onofre-type breccias, eruption of Conejo-age volcanics, and deposition of marine basin sediments including the Monterey and Sisquoc Formations.

In a late stage (Plio-Pleistocene, 5-0 Ma), Baja California joined the Pacific plate and began to obliquely ram into southern California. This transpressional phase is responsible for ongoing folding, uplift, tilting, and faulting of the modern Channel Islands.

Atwater, T., 1998, Plate Tectonic History of Southern California with emphasis on the Western Transverse Ranges and Santa Rosa Island, *in* Weigand, P. W., ed., Contributions to the geology of the Northern Channel Islands, Southern California: American Association of Petroleum Geologists, Pacific Section, MP 45, p. 1-8.

INTRODUCTION

The Northern Channel Islands occupy the southern edge of the Western Transverse Ranges block, a defining element in formulations of the plate boundary evolution of southern California. Geological and geophysical observations from the island have played a crucial role in the development of our ideas about how the entire region evolved to its present tectonic configuration. In this paper, I briefly describe the regional tectonic history, showing how local environments and events recorded on the islands support the larger story and where they may be in conflict.

SUBDUCTION REGIME

The western rim of North America experienced an immense amount of subduction during the Mesozoic and Cenozoic eras. Oceanic lithosphere of an area equivalent to the entire Pacific basin subducted under this continental edge (e.g., Atwater, 1970, 1989; Hamilton 1978). In central California, the first-order geologic manifestations of this convergence are a predictable series of belts: the granitic batholith belt, the foothills metamorphic belt, the Great Valley belt of forearc sediments, and the Franciscan subduction accretionary wedge complex. In southern California, elements of these belts can be recognized, but they have been reorganized by Neogene displacements. Figure 1A shows the identification of these belts in this area according to the compilation and interpretation of Crouch and Suppe (1993) and Figure 1B shows the relevant portion of this same map, reconstructed to a likely mid-Cenozoic configuration approximately as shown in Kamerling and Luyendyk (1985). A key aspect of the Crouch and Suppe interpretation is their inference that two areas (the Santa Maria basin and the Inner Borderland, cross-hatched in Figure 1A) were newly created during late Cenozoic rifting by core complex-like crustal extension. Use of this concept results in a tidier reconstruction of the

Figure 1. Regional distribution of principal lithotectonic belts. A. Present configuration from central California to central Baja California, including (cross-hatched) areas believed to have been created during late Cenozoic rifting, after Crouch and Suppe (1993). B. Likely mid-Cenozoic configuration of southern California and northern Baja California. Late Cenozoic rift areas (cross-hatched areas in A) have been removed and the other elements have been cut and pasted following the reconstruction of Kamerling and Luyendyk (1985). The Transverse Ranges have been rotated placing the (dismembered) northern Channel Islands offshore of San Diego. Reference city locations: SB, Santa Barbara; LA, Los Angeles; A, Anaheim; SD, San Diego. Transpressional bends in the San Andreas fault: BB, "Big Bend"; SBMB, San Bernardino Mountains Bend.

Mesozoic belts and a better plate tectonic fit for the southern California region than those allowed by more area-conservative reconstruction models (e.g., Hornafius et al., 1986; Dickinson, 1997).

A very different group of reconstructions has been proposed to explain observations of anomalously shallow paleomagnetic inclinations in coastal California and Baja California rocks. Those reconstructions would place these coastal terranes much farther south in the early Cenozoic (e.g., Champion et al., 1986; Howell and Vedder, 1981). I consider this to be a much less likely solution following the arguments in Butler et al (1991) and Smith and Busby (1993).

The Northern Channel Islands, according to the Crouch and Suppe interpretation, lie near the center of the restored Great Valley Belt (Figure 1B). Thus the Mesozoic metamorphic and igneous rocks on the islands are assumed to be exhumed Great Valley basement, while the Cretaceous-Paleogene sedimentary section is viewed as Great Valley-type sedimentation with provenance to the east (now south). Conglomerate beds with distinctive rhyolite clasts found in the Jolla Vieja Formation on Santa Cruz Island and in drill holes through the South Point Formation on Santa Rosa Island are believed to be the continuation of the Poway conglomerate, well documented near San Diego (Weaver, 1969; Abbott and Smith, 1978, 1989; Boles, 1997; Dibblee and Ehrenspeck, 1998) and are used as a tie to reconstruct Northern Channel Islands to a location adjacent to that coast. Likewise, the arkosic sands and micaceous shales of these same formations and equivalent rocks on San Miguel Island were derived from a granitic source area to the south (east after reconstruction), probably the Peninsular Ranges batholith (Dibblee and Ehrenspeck, 1998).

Subduction continued, uninterrupted, through the Paleogene, although its inland manifestations (Laramide orogeny) were unusual. By Oligocene time, the East Pacific Rise was nearing the continent offshore of this region (Atwater, 1970, 1989; Atwater and Stock, 1998). The resulting subduction of young, buoyant lithosphere is a possible explanation for the period of deformation and possible tectonic uplift recorded in terrestrial flood plain deposition of the Sespe Formation around southern California and on Santa Rosa Island (Dibblee and Ehrenspeck, 1998) and by a hiatus, angular unconformity and the deposition of the very shallow marine Vaqueros Formation conglomerates on Santa Cruz Island. An alternative (or additional) explanation for this terrestrial episode involves sharp global sea level drops that occurred in response to ice formation on Antarctica (Kennett, 1976, 1977). Again, paleocurrent directions indicate a source to the (reconstructed) east, suggesting a connection to the Sespe rocks of the Santa Ana mountains (Dibblee and Ehrenspeck, 1998).

PLATE BOUNDARY TRANSITION

The time-transgressive intersection of the East Pacific Rise with the North American subduction zone can be deduced by combining the identifications of offshore marine magnetic anomalies with round-the-world plate circuit reconstructions (Stock and Molnar, 1988; Atwater and Severinghaus, 1989; Atwater and Stock, 1998). In fact, this approach gives an upper-limit age for the intersection; actual age estimates require the additional assumption that no significant amount of the Pacific plate has been subducted since contact was established between the Pacific and American plates, a justifiable assumption. The following history uses that assumption.

At about 27 Ma (magnetic reversal chron 9 or 8) the first segment of the East Pacific Rise intersected the trench and the changeover from Farallon-North America subduction to the Pacific-North America transtensional margin began. Note that the new plate boundary was never a pure transform boundary, but, rather, always included an extensional component. This results from the fact that the Pacific-North American relative plate motion vector was never coast-parallel but rather was always somewhat more westerly (Stock and Molnar, 1988; Bohannon and Parsons, 1995). The latest plate reconstruction solutions show that the motion was significantly offshore in the Miocene (about N60^{o}W), then it changed to N37^{o}W at about 8 Ma, so that the plate motion since that time has been closer to coast-parallel but still offshore (Atwater and Stock, 1988).

As the contact region between the Pacific and North American plates lengthened, pieces of the continent became attached to the Pacific and the plate boundary was established within the continent. Because of the oblique Pacific-North American plate motion vector, this boundary consistently included dilational components or segments. For example, along the present plate boundary much of the required dilation is supplied by the spreading centers in the Gulf of California, and during the Miocene this role was played, in part, by extension within the continental Borderland (e.g., Legg, 1991), as illustrated in Figure 2. (The major expansion of the Basin and Range province was also part of this plate-driven continental dilation, Atwater and Stock, 1988.)

A number of latest Oligocene-earliest Miocene volcanic and basin-forming events are documented in the geologic record of the reconstructed southern California - northern Baja California region. These are interpreted to be manifestations of this earliest phase of transtensional plate boundary development (Crowell, 1974, 1987; Dickinson and Snyder, 1979; Atwater, 1989; Dickinson, 1997).

Figure 2. Schematic diagrams demonstrating the regional geometry of the Pacific-North American plate boundary, with regions of transtension and transpression dictated by the relationship between the relative plate motion vector and the trend of the plate boundary. The transfer of Baja California to the Pacific plate about 5 Ma (transition between B and C) changed the overall tectonic regime in southern California from transtension to transpression.

At about 19-18 Ma, with the stalling of the offshore Monterey microplate, a long segment of the Pacific-North America plate boundary was well established, including the region adjacent to the present Borderland (Nicholson et al., 1994).

MIOCENE TRANSTENSIONAL REGIME

From 18 to 5 Ma (nearly all of the Miocene), the Borderland was the site of the southern, oblique transtensional portion of the Pacific-North American plate boundary. From 19 to about 12 Ma the northern terminus of this boundary (the Mendocino triple junction) migrated northwestward up the coast attached to the Pacific plate, while the southern terminus (Rivera triple junction) was approximately stationary off northern Baja California (the northwestward drift of the Pacific plate being counteracted by the subduction of new segments of the East Pacific Rise). During this period a continental plate boundary zone was established, with the strike-slip component being accomodated by faults within and bordering the northern coastal and Salinian blocks, while a transtensional segment of the plate boundary traversed the California Borderland, connecting it to the southern junction at the rim of the continent (Figure 2A).

About 12 Ma, the southern triple junction was transferred far to the south when spreading and subduction stalled offshore of southern Baja California, but this shift probably did not immediately alter the tectonic situation in southern California. As long as the primary plate boundary remained on the Pacific side of Baja (i.e., until about 5 Ma), the Borderland segment of the boundary would continue to play its transtensional role (Figure 2B).

The geology of Miocene southern California is quite well-known and includes some distinct, unusual features that cry out for tectonic explanation. The most striking of these is the rotation of the Western Transverse Ranges block. Paleomagnetic data from the Ventura region and from both sides of the Santa Barbara channel show that rocks older than about 16 Ma have been rotated 80-110° clockwise while younger rocks show progressively lesser amounts of rotation (Luyendyk et al, 1980, Hornafius and Luyendyk, 1985; Luyendyk, 1991) while most

Figure 3. Paleomagnetic evidence for the Neogene rotation of the western Transverse Ranges. A. Declination directions for rocks older than 16 Ma, from Hornafius (1985). B. Declination directions vs age, from Luyendyk (1991) after Hornafius et al. (1986).

nearby rocks outside the Western Transverse Ranges show much less overall rotation (Figure 3). The widely accepted explanation of these results is that the Transverse Ranges block rotated as a more or less coherent piece 90-110º since the early Miocene. Many unusual geologic relationships are also much more easily explained with the incorporation of such a rotation.

Several kinematic models have been proposed to explain the rotation data (e.g., Kamerling and Luyendyk, 1985; Hornafius et al., 1986; Dickinson, 1996). The version elaborated by Crouch and Suppe (1993) and augmented by Nicholson et al (1994) is illustrated in Figures 1 and 4 and described here. Before rotation, the Western Transverse Ranges block lay adjacent to San Diego and Anaheim. During the early Miocene, it was one of three north-south blocks that broke off of the rim of the continent. The two outer blocks, the Santa Lucia Bank and Outer Borderland blocks, became attached to the Pacific plate and have been moving obliquely up the coast and slightly seaward ever since. The third, the Western Transverse Ranges block, was more deeply embedded in the continent so that its northern end essentially snagged in the continent while its southern end broke away and swung seaward and up-coast, inserting itself between the other two blocks. East of the rotating block, a gap opened, creating the space now occupied by the Los Angeles basin and inner California Borderland. This space was filled from below by igneous rocks and metamorphosed, underplated Franciscan rocks that rose in a ductile manner, similar to core complex emplacement events described in the Basin and Range Province and elsewhere (e.g. Wernicke et al., 1992).

A number of distinctive geologic features of Miocene southern California have analogs at other core complex-type extensions. These include the abrupt uplift and unroofing of mid-crustal metamorphic rocks (e.g., Catalina schist) and the formation of breccias therefrom (e.g., San Onofre

Figure 4. Schematic history of late Cenozoic rotations and rifts in southern California and northern Baja California, after Nicholson et al. (1994).

breccia), the eruption of extensive early Miocene volcanic rocks (e.g., Conejo volcanics), and the formation of distinct detachment and extensional structures (in the Santa Monica Mountains, Laguna Beach region, and in the seismically imaged subsurface). Furthermore, the formation of numerous isolated basins within this complexly extending region created the distinctive environment required for the deposition of the Monterey Formation.

On the Northern Channel Islands, most of these same geologic elements are present. The progressive uplift and unroofing of first basement and then underplated Franciscan-type schists are recorded in the Santa Cruz Island Vaqueros Formation, Rincon Formation, and San Onofre Breccia (Boles, 1997). The volcanics that commonly accompany the early stages of core complex style extensions may be represented by the Miocene volcanics that make up most of Anacapa Island and are extensively present on Santa Cruz as the Santa Cruz Island Volcanics and Blanca Formation volcanic debris. On Santa Rosa Island, the middle Miocene Beechers Bay Formation consists of volcanoclastic debris mixed with blueschist and other basement debris. It is tempting to take all these formations as a record of the emplacement of the Inner Borderland core complex, and many of the relationships are compatible with such an interpretation. The ages of the volcanics (near the beginning of the proposed extension) and their mixed compositions mirror observations of core-complex related volcanism elsewhere (e.g., Gans et al., 1989; Gans and Bohrson, 1998) and the timing and transport directions of volcanic and blueschist debris recorded in the Beechers Bay Formation on Santa Rosa Island fit the expected pattern. On the other hand, the age of the basement unroofing reported on Santa Cruz, earliest Miocene, is several million years older than the age supported by plate models and data from other areas (Crouch and Suppe, 1993) and sparse directional indicators on Santa Cruz favor a western source (in reconstructed coordinates) (Boles, 1997) rather than the expected eastern source.

PLIO-PLEISTOCENE TRANSPRESSIONAL REGIME

The tectonic regime of southern California completely changed about 5 Ma when the Pacific plate captured Baja California and began transporting it northwestward, ramming its northern

end into southern California. Another way to describe this event is that the southern section of the Pacific-North America plate boundary shifted from the Pacific coast into the Gulf of California and the plate boundary had to break a new path across southern California, reconfiguring itself to connect to this new inland plate boundary (Fig. 2C). The Borderland transtensional system was largely deactivated at this time and the present southern California segments of the San Andreas system, including two transpressional bends (the Big Bend and the San Bernardino Mountains bend, BB and SBMB on Figure 1A) were formed. Left lateral motion on the Garlock fault exacerbated this effect.

In this new configuration, the Western Transverse Ranges block was snagged again at its (now) eastern end, this time against the "Big Bend" (BB on Figure 1A). As a result, it is being extruded westward around the bend and shortened north-south. To accommodate these new displacements, major left-lateral faults have formed along the southern edge of the block and various Miocene normal faults have been inverted into reverse faults. The Santa Cruz Island fault and Santa Rosa Island fault are examples of the former while numerous young folds and uplifted, tilted beach terraces on all the islands are interpreted to be the result of ongoing shortening and uplift over a blind thrust system (Sorlien and Pinter, 1997; Sorlien et al., 1998).

ACKNOWLEDGMENTS

Thanks to Tom Wright, Eric Frost, and Craig Nicholson for Inner Borderland understanding and to John Crowell, Jim Boles, Peter Weigand, and Helmut Ehrenspeck for helpful reviews. An earlier version of this work appeared in the Santa Cruz Island, Geology Field Trip Guide, San Diego Association of Geologists, J.R. Boles and W. Landry, editors, October 1997.

REFERENCES

Abbott, P.L., and Smith, T.E., 1978, Trace element comparisons of clasts in Eocene conglomerates, southwestern California and northwestern Mexico: Journal of Geology, v. 86, p. 753-762.

Abbott, P.L., and Smith, T.E., 1989, Sonora, Mexico, source for the Eocene Poway conglomerate of Southern California: Geology, v. 17, p. 329-332.

Atwater, T.M., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513-3536.

Atwater, T.M., 1989, Plate tectonic history of the northeast Pacific and Western North America, Chapter 4, *in* Winterer, E.L., ed., The Geology of North America, V. N: The northeastern Pacific Ocean and Hawaii, p. 21-72.

Atwater, T.M., and Severinghaus, J.P., 1989, Tectonic maps of the northeast Pacific, Chapter 3, *in* Winterer, E.L., ed., The Geology of North America, V. N: The northeastern Pacific Ocean and Hawaii, p. 15-20.

Atwater, T.M., and Stock, J., 1998, Pacific-North America plate tectonics of the Neogene southwestern United States - an update: in press for International Geological Review.

Bohannon, R.G., and Parsons, T., 1995, Tectonic implications of post-30 Ma Pacific and North American relative plate motions: Geological Society of America Bulletin, v. 107, p. 937-959.

Boles, J.R., 1987, Geologic introduction and lithologic units, Chapter II, *in* Boles, J.R., and Landry, W., eds., Santa Cruz Island, Geology Field Trip Guide: San Diego Association of Geologists, p. 3-25.

Butler, R.F., Dickinson, W.R., and Gehrels, G.E., 1991, Paleomagnetism of coastal and Baja California: Alternatives to large-scale northward transport: Tectonics, v. 10, p. 561-573.

Champion, D.E., Howell, D.G., and Marshall, M., 1986, Paleomagnetism of Cretaceous and Eocene strata, San Miguel Island, California Borderland and the northward translation of Baja California: Journal of Geophysical Research, v. 91, p. 11557-11570.

Crouch, J.K., and Suppe, J., 1993, Late Cenozoic tectonic evolution of the Los Angeles basin and California Borderland: A model for core complex-like crustal extension: Geological Society of America Bulletin, v. 105, p. 1415-1434.

Crowell, J.C., 1974, Origin of the Late Cenozoic basins of southern California: Society of Economic Paleontologists and Mineralogists, Special Publication 22, p. 190-204.

Crowell, J.C., 1987, Late Cenozoic basins of onshore southern California: Complexity is the hallmark of their tectonic history, *in* Ingersoll, R.V., and Ernst, W.G., eds., Rubey Volume 6, Cenozoic Basin Development of Coastal California,: Prentice-Hall, p. 207-241.

Dibblee, T. W., and Ehrenspeck, H. E., 1998, General geology of Santa Rosa Island, California: American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 45 (this volume).

Dickinson, W.R., 1996, Kinematics of transrotational tectonism in the California Transverse Ranges and its contribution to cumulative slip along the San Andreas transform fault system: Geological Society of America Special Paper 305, 46 p.

Dickinson, W.R., 1997, Tectonic implications of Cenozoic volcanism in coastal California: Geological Society of America Bulletin, v. 109, p. 936-954.

Dickinson, W.R., and Snyder, W.S., 1979, Geometry of triple junctions related to San Andreas transform: Journal of Geophysical Research, v. 84, p. 561-572.

Gans, P.B., Mahood, G.A., and Schermer, E.R., 1989, Synextensional magmatism in the Basin and Range Province; a case study from the eastern Great Basin, Geological Society of America Special Paper 233, 53p.

Gans, P.B., and Bohrson, W.A., 1998, Suppression of volcanism during rapid extension in the Basin and Range Province, United States, Science, v. 279, p. 66-68.

Hamilton, W., 1978, Mesozoic tectonics of the western United States: *in* Howell, D., and McDougall, K., eds., Mesozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 33-70.

Hornafius, J.S., 1985, Neogene tectonic rotation of the Santa Ynez Range, Western Transverse Ranges, California, suggested by paleomagnetic investigation of the Monterey Formation: Journal of Geophysical Research, v. 90, p. 12503-12522.

Hornafius, J.S., Luyendyk, B.P., Terres, R.R., and Kamerling, M.J., 1986, Timing and extent of Neogene tectonic rotation in the western Transverse Ranges, California: Geological Society of America Bulletin, v. 97, p. 1476-1487.

Howell, D.G., and Vedder, J.G., 1981, Structural implications of stratigraphic discontinuities across the southern California Borderland, *in* Ernst, W.G., ed., The Geotectonic Development of California,, Rubey Volume 1: Prentice-Hall, pub., p. 535-558.

Kamerling, M.J., and Luyendyk, B.P., 1985, Paleomagnetism and Neogene tectonics of the northern Channel Islands, California: Journal of Geophysical Research, v. 90, p. 12485-12502.

Kennett, J.P., 1976, Oxygen isotopic evidence for the development of the psychrosphere 38 Myr ago: Nature, v. 260, p 513-515

Kennett, J.P., 1977, Cenozoic evolution of Antarctic glaciation, the circum-Antarctic ocean, and their impact on global paleoceanography: Journal of Geophysical Research, v. 82, p 3843-3860.

Legg, M.R., 1991, Developments in understanding the tectonic evolution of the California Continental Borderland, *in* Osborne, R.H., ed., From shoreline to abyss: Society of Economic Paleontologists and Mineralogists, Special Publication 46, p. 291-312.

Luyendyk, B.P., 1991, A model for Neogene crustal rotations, transtension, and transpression in southern California: Geological Society of America Bulletin, v. 103, p. 1528-1536.

Luyendyk, B.P., Kamerling, M.J., and Terres, R.R., 1980, Geometric model for Neogene crustal rotations in southern California: Geological Society of America Bulletin, v. 91, p. 211-217.

Nicholson, C., Sorlien, C.C., Atwater, T., Crowell, J.C., and Luyendyk, B.P., 1994, Microplate capture, rotation of the western Transverse Ranges, and initiation of the San Andreas transform as a low-angle fault system: Geology, v. 22, p. 491-495.

Severinghaus, J., and Atwater, T.M., 1990, Cenozoic geometry and thermal state of the subducting slabs beneath North America, *in* Wernicke, B.P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas: Geological Society of America Memoir 176, p. 1-22.

Smith, D.P. and Busby, C.J., 1993, Shallow magnetic inclinations in the Cretaceous Valle Group, Baja California: Remagnetization, compaction, or terrane translation?: Tectonics, v.12, p 1258-1266.

Sorlien, C.C., Mc Wayne, E.H., Kamerling, M.J., and Galloway, J.M., 1998, Late Cenozoic faulting and progressive folding of northern Santa Rosa Island and southwestern Santa Barbara Channel, California: *in* Kunitomi, D.S., Hopps, T.E., and Galloway, J.M., eds., Structure and petroleum geology, Santa Barbara Channel, California: American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 46, in press.

Sorlien, C.C., and Pinter, N., 1997, Faulting and folding of Santa Cruz Island, Chapter IX, *in* Boles, J.R., and Landry, W., eds., Santa Cruz Island, Geology Field Trip Guide: San Diego Association of Geologists, p. 72-90.

Stock, J., and Molnar, P., 1988, Uncertainties and implications of the Late Cretaceous and Tertiary position of North America relative to the Farallon, Kula, and Pacific plates: Tectonics, v. 7, p. 1339-1384.

Weaver, D.W., 1969, Paleogeographic implications and geologic history, *in* Weaver, D.W., ed., Geology of the Northern Channel Islands: American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, Pacific Section, Special Publication, p. 115-131.

Wernicke, B., 1992. Cenozoic extensional tectonics of the U. S. Cordillera,, Chapter 12 *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Geology of North America, v. G-3, The Cordilleran Orogen: Coterminus U.S., The Geological Society of America, p. 553-581.

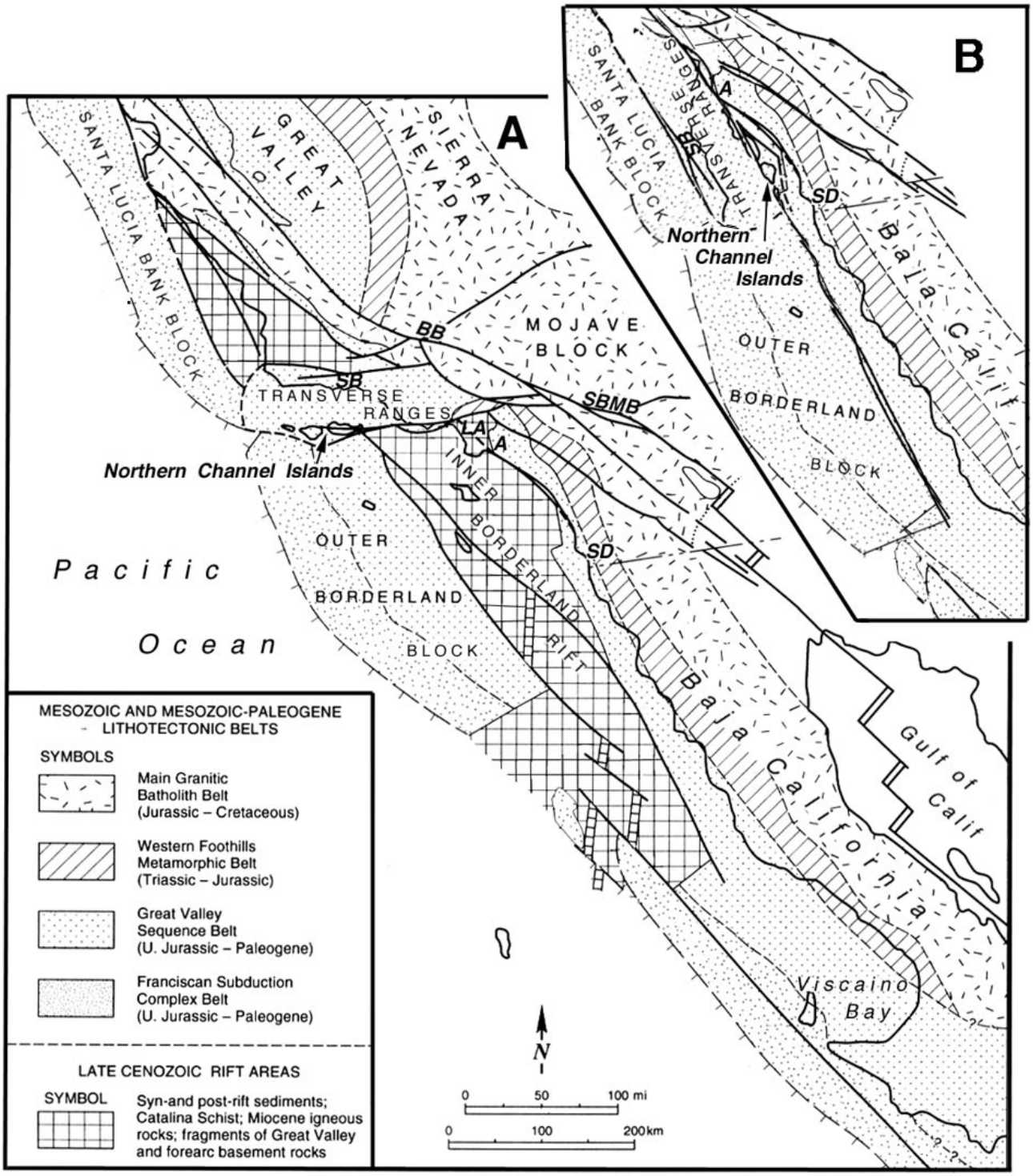
A
B
SANTA LUCIA BANK BLOCK
GREAT VALLEY
SIERRA NEVADA
MOJAVE BLOCK
TRANSVERSE RANGES
BB
SB
SBMB
LA
A
SD
Northern Channel Islands
OUTER BORDERLAND BLOCK
INNER BORDERLAND RIFT
Pacific Ocean
Baja California
Gulf of Calif
Viscaino Bay
Baja Calif
MESOZOIC AND MESOZOIC-PALEOGENE LITHOTECTONIC BELTS
SYMBOLS
Main Granitic Batholith Belt (Jurassic – Cretaceous)
Western Foothills Metamorphic Belt (Triassic – Jurassic)
Great Valley Sequence Belt (U. Jurassic – Paleogene)
Franciscan Subduction Complex Belt (U. Jurassic – Paleogene)
LATE CENOZOIC RIFT AREAS
SYMBOL
Syn-and post-rift sediments; Catalina Schist; Miocene igneous rocks; fragments of Great Valley and forearc basement rocks
N
0 50 100 mi
0 100 200km

Figure 1

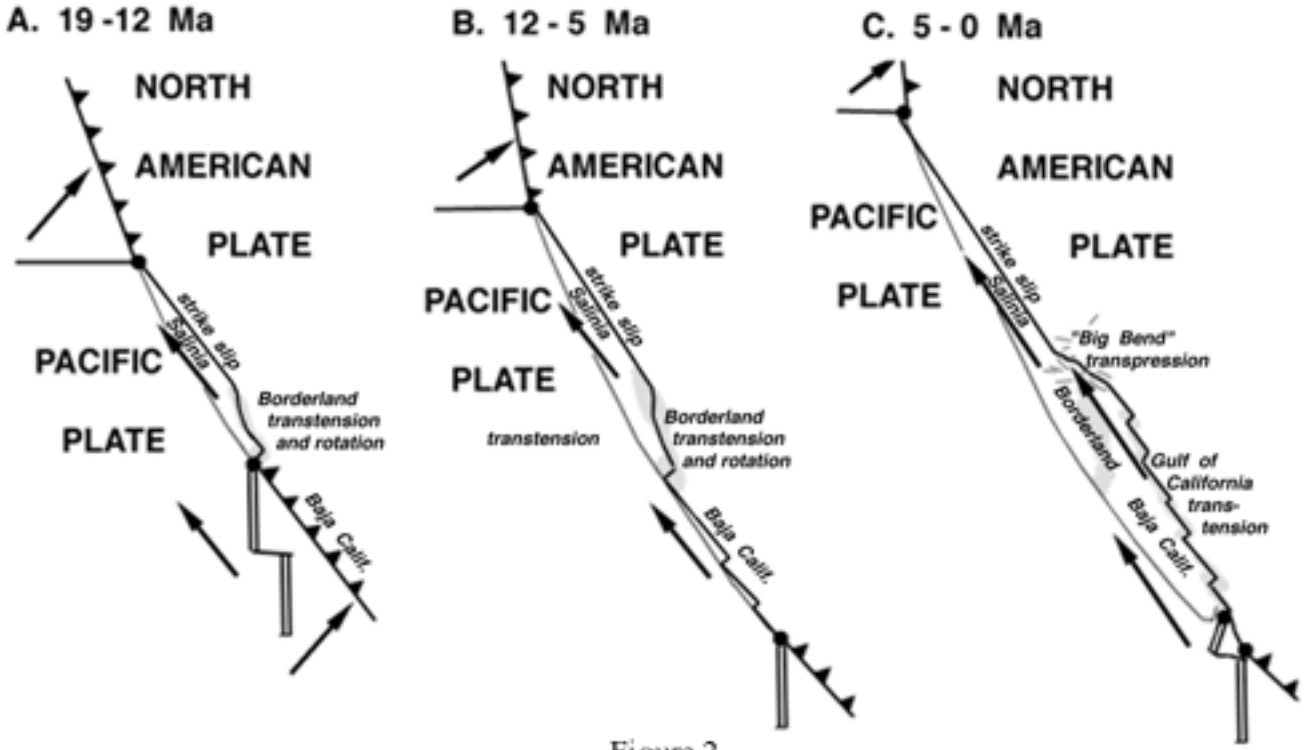
A. 19 -12 Ma
NORTH
AMERICAN
PLATE
PACIFIC
PLATE
strike slip
Salinia
Borderland
transtension
and rotation
Baja Calif.
B. 12 - 5 Ma
NORTH
AMERICAN
PLATE
PACIFIC
PLATE
strike slip
Salinia
transtension
Borderland
transtension
and rotation
Baja Calif.
C. 5 - 0 Ma
NORTH
AMERICAN
PLATE
PACIFIC
PLATE
strike slip
Salinia
"Big Bend"
transpression
Borderland
Gulf of
California
trans-
tension
Baja Calif.

Figure 2.

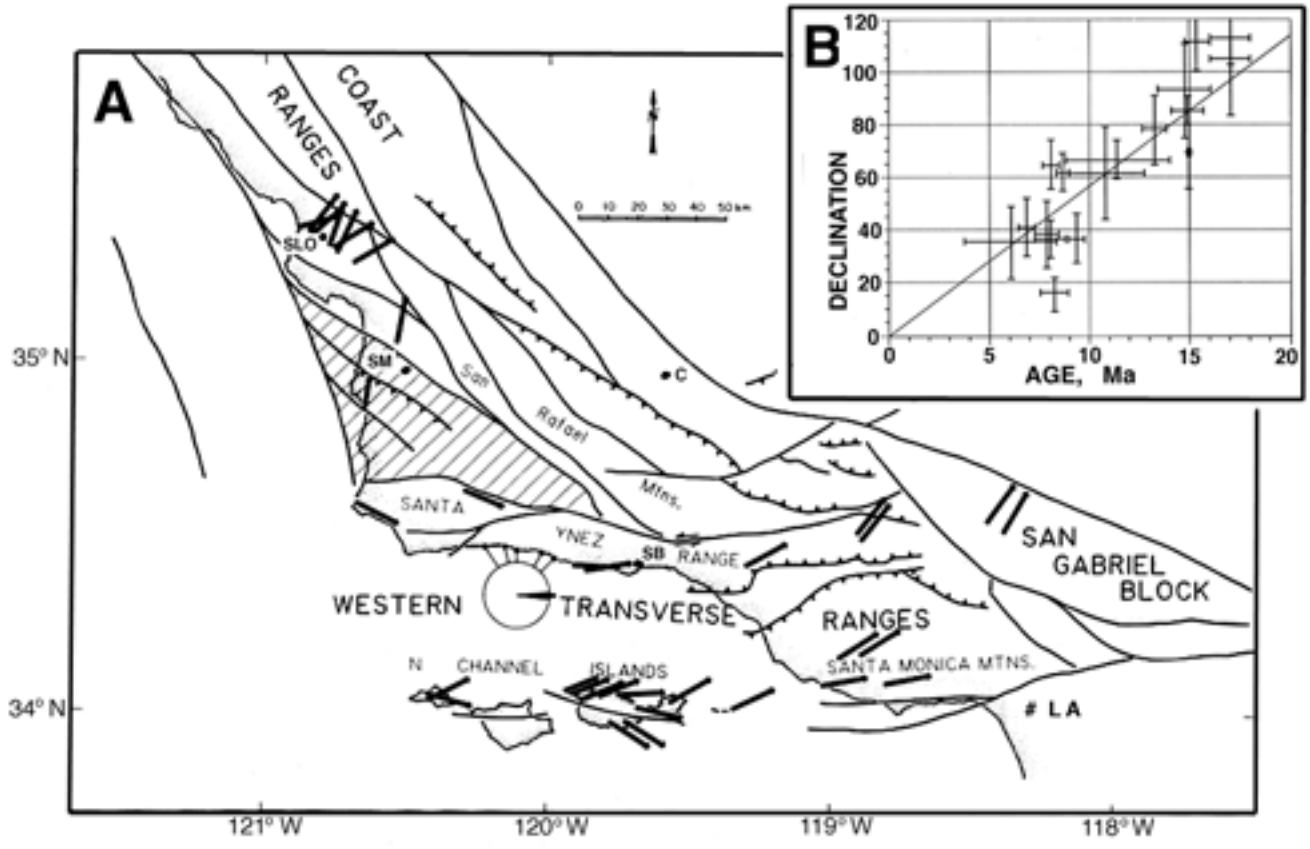
A
B
COAST
RANGES
SLO
SM
San
Rafael
Mtns.
SANTA
YNEZ
SB
RANGE
WESTERN
TRANSVERSE
RANGES
N
CHANNEL
ISLANDS
SAN
GABRIEL
BLOCK
SANTA MONICA MTNS.
LA
C
0 10 20 30 40 50 km
DECLINATION
AGE, Ma
0
20
40
60
80
100
120
5
10
15
20
35° N
34° N
121° W
120° W
119° W
118° W

Figure 3.

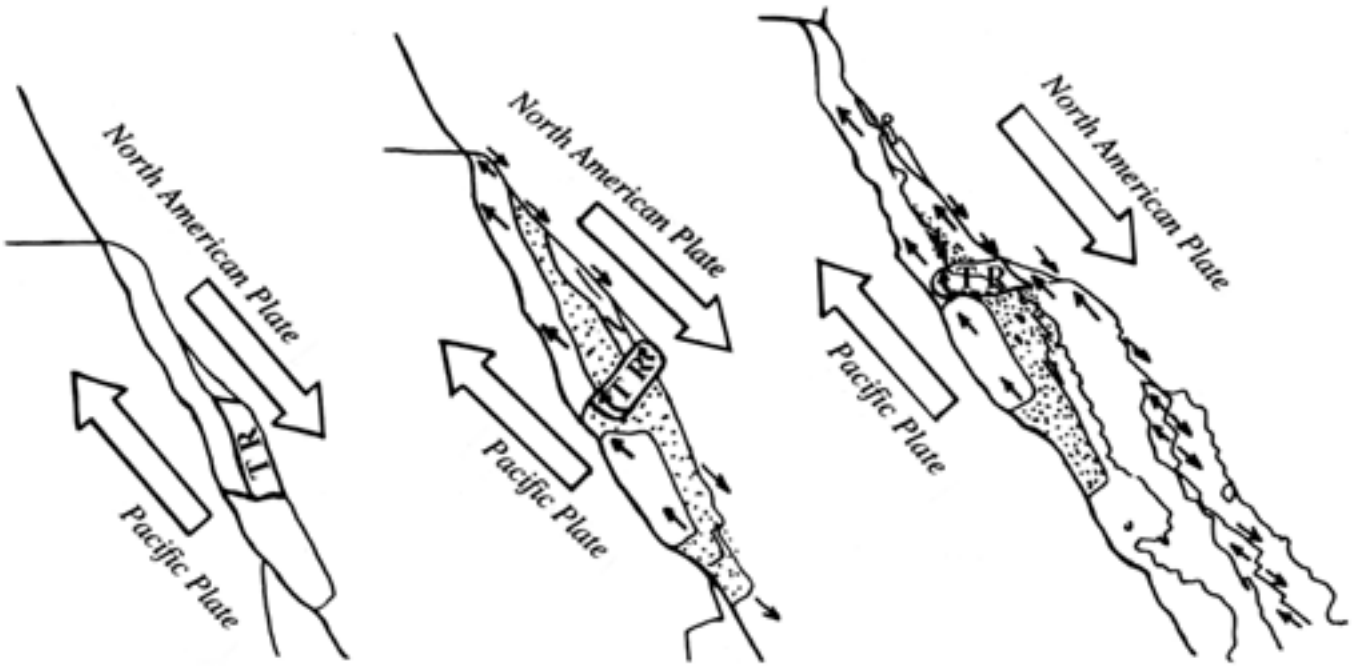
North American Plate
Pacific Plate
T R J
North American Plate
Pacific Plate
T R
North American Plate
Pacific Plate
T R
20 million years ago
10 million years ago
present

Figure 4.