The Geology of North America
Vol. N, The Eastern Pacific Ocean and Hawaii
The Geological Society of America, 1989

Chapter 4

Plate tectonic history of the northeast Pacific and western North America

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PRESENT PLATE CONFIGURATION AND CHAPTER OVERVIEW

In the present configuration of tectonic plates, the northeast Pacific region is dominated by the huge Pacific Plate. Along its eastern edge, the Pacific Plate presently interacts with two medium-sized oceanic plates, the Juan de Fuca and Cocos Plates, and a few related small platelets: the Yakutat, Explorer, South Gorda, and Rivera Plates (Fig. 1). All of these occupy relatively small regions along the edge of the Pacific Plate, interacting as well with the North American Plate along its western rim.

The most complex modern plate boundaries in the northeast Pacific region occur where the eastern edge of the Pacific Plate abuts directly against North America. These are primarily strike-slip boundaries with subordinate amounts of extension: the Queen Charlotte–Fairweather fault system, including the oblique motion of the Yakutat block, and the San Andreas fault system, including the oblique extension in the Gulf of California. The diffuse nature of the earthquake zones around these features, depicted in Figure 1, shows that plate boundaries within the continental lithosphere are not as narrow and simple as those within the oceanic plates. The broad zones of activity in the Great Basin show the existence of at least two diffuse inland zones of deformation, as well.

The present plate tectonic situation of the north Pacific is quite unusual in the world ocean system in that this vast expanse of ocean is so dominated by the one plate and contains so few spreading centers. The evidence embedded within the Pacific plate shows that this present odd configuration is a rather recent development. In the early Cenozoic and earlier times the north Pacific basin was rich in plates and spreading systems. Large oceanic plates lay to the north, east, and south of the Pacific Plate. In this chapter we review what is known about these ancient plates and their slow evolution to the present configuration. First we shall examine the magnetic anomaly isochron pattern in the northeast Pacific and its implications for the history of sea-floor spreading among the plates within the ocean basin. Next we examine global-scale data used for plate tectonic reconstructions and review the reconstructions that have been made in order to examine the interactions between the oceanic plates and their continental neighbors. Finally, we shall examine a few of the phenomena in the continental geologic record of the western United States that resulted from these plate interactions and that help us refine our understanding of them.

SEA-FLOOR SPREADING HISTORY OF THE NORTH PACIFIC

Magnetic anomaly data base and polarity reversal timescale

The primary data bases used in most plate tectonic reconstructions are maps of magnetic anomaly isochrons and topography of the ocean floor. In Plates 3A, 3B, and 3C we present new compilations of fracture zones and selected magnetic anomaly profiles and contours in the north Pacific, along with isochron interpretations. Printed in reverse on the backs of the plates, for use with a light table, are the bathymetric contours from Mammerickx (this volume). In Atwater and Severinghaus (this volume) we describe some details of the construction of these plates. Segments of the maps in the plates will be used in Figures 4 through 12 to examine the spreading histories of local regions. The areas covered by these figures are shown in red on Figure 2.

The primary difference between previous interpretations and the new ones presented here is our liberal use of propagating rift traces (pseudofaults and shear zones) wherever they are suggested by the data. These features, described in Hey and others (this volume), are the mechanism by which mid-ocean ridges reorient themselves following changes in direction of spreading and also seem to be associated with hot spots, although the relative importance of these two factors is not resolved.

Magnetic anomalies are dated by comparing them to the sequence of polarity reversals documented for the Earth's magnetic field. Magnetic anomalies will often be referred to in the text by their identification numbers with numbers in brackets to show ages in millions of years according to the revised polarity reversal scales of Kent and Gradstein (1985) and Berggren and others (1985). Portions of these time scales are presented on the plates and figures, as needed.

Atwater, T., 1989, Plate tectonic history of the northeast Pacific and western North America, *in* Winterer, E. L., Hussong, D. M., and Decker, R. W., eds., The Eastern Pacific Ocean and Hawaii: Boulder, Colorado, Geological Society of America, The Geology of North America, v. N.

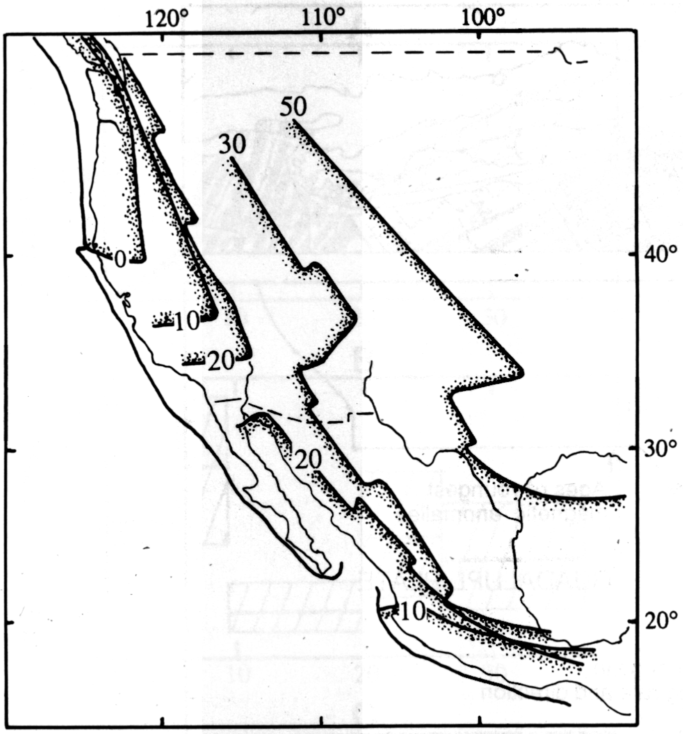

Figure 25. Approximate configuration of subducting slabs beneath North America for selected times in the Cenozoic, after Severinghaus and Atwater (1989). Numbers show ages in Ma. Slab length depends upon the age of the lithosphere when it enters the trench and the subduction velocity. Fast subduction of mature lithosphere produced long slabs in the early Cenozoic. Later, younger lithosphere was subducted more slowly, producing shorter slabs. The growth of the Pacific–North America plate boundary was accompanied by a growing gap in the slab.

sloping, cool base of the thin continental plate (Fig. 26). Heat escapes upward through the continent, and the asthenospheric rocks below cool, harden, and form new lower continental lithosphere. (This is somewhat analogous to the way in which oceanic lithosphere thickens.) The heat flows through the upper plate to the surface, creating a heat-flow anomaly.

One complication in heat-flow interpretation is that earth materials are poor heat conductors, so that a pulse of heat takes a long time to reach the surface. Thus, the maximum surface heat flow will not be found near the Mendocino edge but rather should be observed somewhere south, where the heat pulse has had time to make its way up through the crust. The observed heat-flow maximum near San Francisco fits this prediction very well if the original upper plate thickness was about 20 km (Lachenbruch and Sass, 1980; Zandt and Furlong, 1982). Other geophysical information also supports the slab-edge model in Figure 26. Gravity data collected near Cape Mendocino fit a model that includes the edge of the descending Gorda slab and thin lithosphere to the south (Jachens and Griscom, 1980), and seismic data show that the lithosphere is thin at Mendocino and thickens southward (Zandt, 1981).

The heat-flow time lag can also be invoked to explain the exceptionally low surface heat flow measured in the Sierra Nevada. The Cenozoic subducting slab would have kept this region cool, and the heat pulse following the rather recent removal of the slab would not yet have penetrated through the great crustal thickness.

Initiation and development of the Pacific–North America plate boundary—the San Andreas regime

Transition of regimes at the Rivera triple junction—ridge/trench to fault. The most obvious consequence of the growth of the Pacific–North America boundary has been the development of the San Andreas system. A primary problem in understanding this development concerns the manner in which the new plate boundary becomes established following the demise of the intervening plate. Figure 27 shows conceptual cross sections of the Pacific, Farallon, and North American Plates during the Cenozoic. The top section, Figure 27A, depicts the ocean-continent cross section for the early Cenozoic: an offshore oceanic spreading center and a subduction zone at the coast. The bottom section, Figure 27D, represents the present San Andreas system: the Pacific Plate includes the attached rim of the continent, while the rest of North America is moving away out of the page past it.

Figure 27C depicts the moment when the ridge crest meets the subduction zone, i.e., the first contact between the Pacific and North American Plates. At that moment, the Pacific–North America plate boundary is located at the base of the continental slope, offshore. At the present time, Figure 27D, the boundary is not there, but rather is inland, within the continent. To understand the early stages of development of the San Andreas system, we need to discover how this transition takes place.

One way to study this is to examine the similar but more recent transition that occurred around Baja California following the passage of the Rivera triple junction. We have noted that the Pacific–North America boundary was probably established about 12.5 Ma, nearly simultaneously all along central and southern

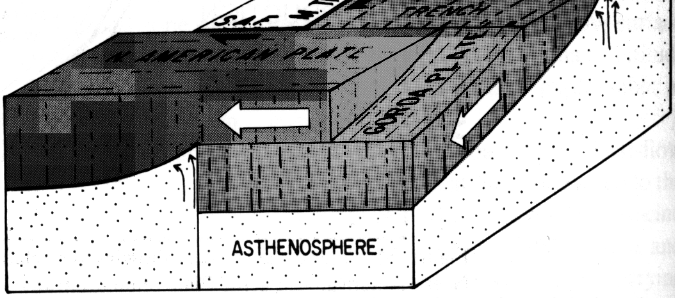

Figure 26. Conceptual block model of the Mendocino triple junction, showing transition from subduction regime to San Andreas regime, with the Mendocino slab gap edge at depth beneath the junction, after Lachenbruch and Sass (1980). M = Mendocino transform fault, SAF = San Andreas fault. Open arrows show motions with respect to a fixed Pacific Plate. Small arrows show likely motions in the asthenosphere.

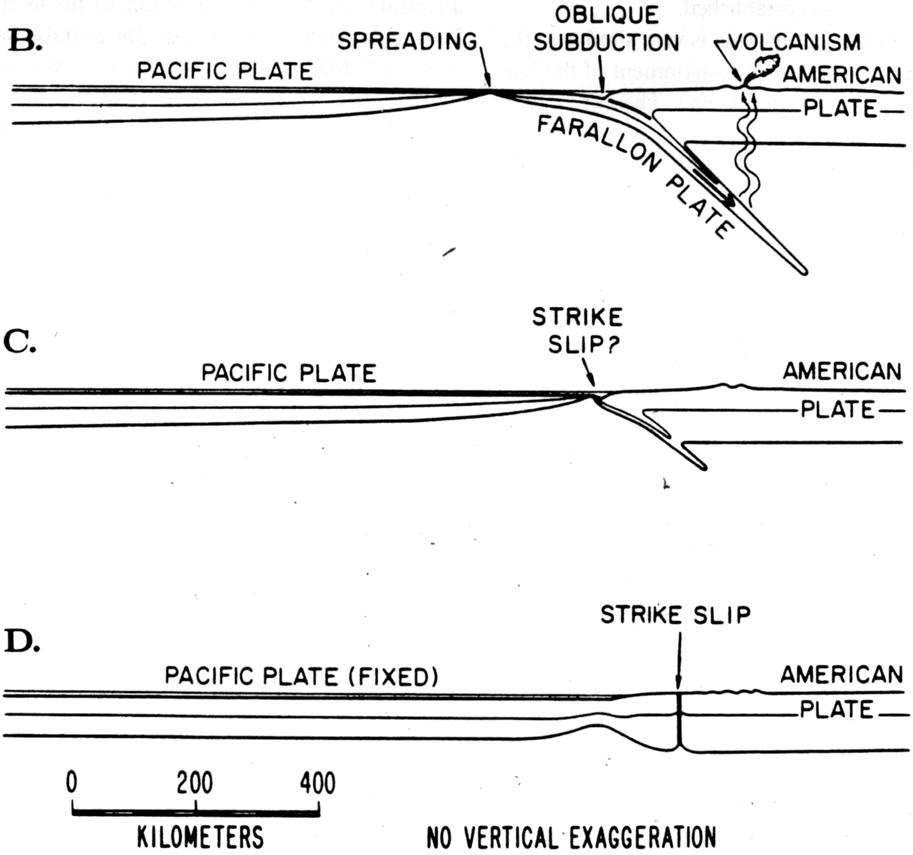

Figure 27. Conceptual cross sections of Pacific, Farallon, and North American lithospheric plates and the late Cenozoic transition in regimes, after Atwater (1970). Contours are schematic lithospheric isotherms. A: Ridge, trench, and down-going slab as they probably were in the early Cenozoic. B: As the spreading center approached the trench, the Farallon plate narrowed. It delivered younger, thinner, hotter lithosphere to the slab so that the latter had a shorter lifetime in the mantle before heating up. C: The ridge arrived at the trench and the Farallon plate ceased existence. The Pacific and North American plate came into contact. D: Present situation. The Pacific–North America boundary has shifted inland to the San Andreas fault, transferring the edge of North America to the Pacific plate. The timing and nature of this transfer should be expressed in the early history of the San Andreas regime.

ja (Figs. 10 and 24B). The present-day plate boundary consists a number of transform faults connecting small spreading basins the Gulf of California, but this rather simple boundary was ly established about 3.5 Ma. Prior to that time, the plate moon was spread over a broad band of faults in the Gulf (Lonsdale, is volume), but even this form of the inland boundary only gan about 5.5 Ma (Moore and Curray, 1982; Curray and oore, 1984; Lonsdale, this volume).

Where was the boundary between 12.5 and 5.5 Ma? Spencer and Normark (1979) document a major throughgoing fault zone along the Pacific edge of Baja California, the Tosco-Abreojos fault zone, shown in Figure 10. They suggest that this was the major Pacific–North America plate boundary before it shifted inland. The Gulf of California region was not without tectonism during this earlier time period. Normal faulting is seen all along the edges of the Gulf, beginning between about 12 and

10 Ma in many places (Gastil and others, 1979; Stock and Hodges, 1989) and forming a shallow marine "proto-Gulf" (Karig and Jensky, 1972; Moore and Curray, 1982).

To summarize, after the triple junction passed, the primary strike-slip plate boundary was established in the continental margin for about 7 m.y., with some extension occurring inland. About 5.5 Ma, Baja California was transferred to the Pacific plate, and the primary plate boundary shifted inland. For about 2 m.y., plate motion was taken up across a broad set of faults until the major throughgoing system was established.

This scenario for the Gulf of California is very similar to the one that may be postulated for the early development of the San Andreas system in southern California, as well. The earliest onland manifestations are the opening of basins and accompanying volcanism, starting about 23 Ma. Presumably the first strike-slip faults lay in the continental margin, since onshore strike-slip fault systems appear to have developed later, about 18 to 16 Ma, and migrated inland over time. Furthermore, the fault systems may have been more diffuse in their early stages, as implied by the rotations of the Transverse Range blocks. The present situation, with much of the motion being taken up on one or two major throughgoing faults, is a relatively recent development, starting about 12 Ma. In the next few sections I shall document and develop this history, but first we must examine the characteristics of the other junction, the Mendocino triple junction.

Lengthening of the San Andreas regime at the Mendocino triple junction—trench to fault. After the inception of the Pacific–North America plate boundary about 27 Ma, the boundary on North America was continually lengthened northwestward, following the drift up-coast of the Mendocino triple junction. As this junction passed, an observer standing on North America would have seen a change from subduction to strike-slip. Note that this tectonic transition should be quite different from those associated with the Rivera triple junction since in this case an old, cold subduction regime is being replaced by an old, cold strike-slip system. The appearance of the boundary onshore should be immediate. Indeed, the strike-slip regime might actually extend past the junction, as it appears to be doing at the Mendocino triple junction at present (see Fig. 29).

Some interesting insight concerning this transition can be gained by examining the plate tectonic geometry of the Mendocino triple junction: it is intrinsically unstable. McKenzie and Morgan (1969), in their classic treatise, showed that triple junctions can be stable or unstable, depending on their geometry and the nature of the boundaries involved. At a stable triple junction, the three plates concerned can continue to move as they have in the past, and the triple junction joining them will retain its configuration and boundary types. An unstable junction, on the other hand, is required by the evolving plate geometry to change type or to reorganize its configuration as plate motions continue. The Mendocino triple junction is slightly unstable, and many geologic effects in its vicinity can be thought of as results of this instability.

The Mendocino triple junction is a fault-fault-trench (F-F-T) junction. Figure 28A shows one of the few configurations of this junction type that is stable, namely a F-F-T junction in which the trench and one transform fault are colinear. This type of stable junction would occur if the San Andreas fault (i.e., the Pacific–North America plate motion direction) were exactly parallel to the coast. Figure 28B is a slightly more realistic version of the present-day junction. The San Andreas fault direction is about 10° west of the trend of the coastline and trench. As the plates continue their motions in this case, a small triangular space appears at the junction (red triangle on Fig. 28B). There is no spreading center at the junction to fill in the triangular space. Thus, this junction is intrinsically unstable and must constantly readjust. McKenzie and Morgan (1969) and Dickinson and Snyder (1979a) present more detailed and abstract analyses of this instability that the geometrically inclined reader may wish to explore.

Two geologic solutions to the geometric instability of the Mendocino triple junction seem likely. One possibility is that pull-apart basins are regularly being formed inland of the San Andreas near the junction. This would predict a time transgres-

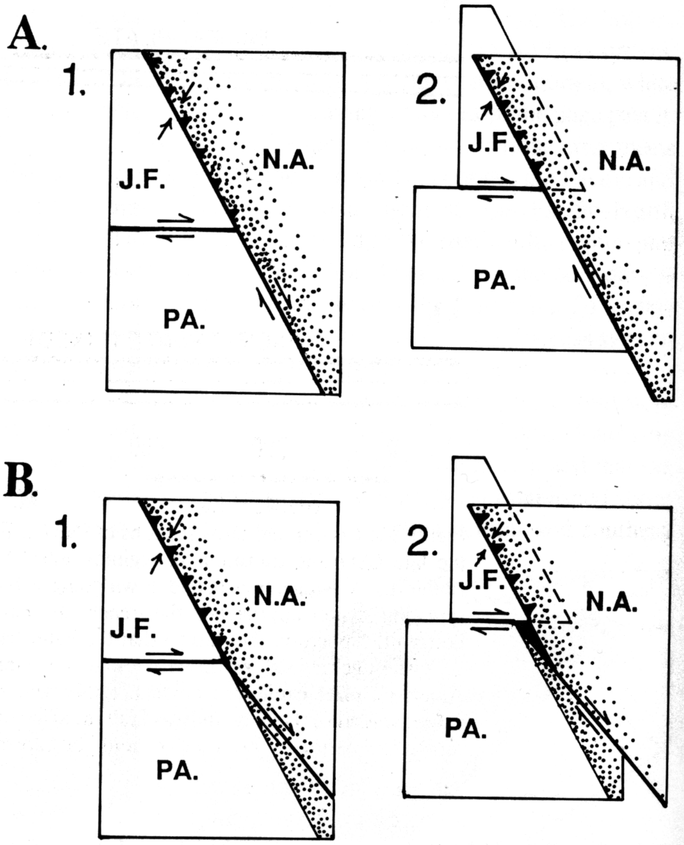

Figure 28. Idealized geometry of the Mendocino-triple junction, a fault-fault-trench (F-F-T) triple junction. PA. = Pacific Plate; J.F. = Juan de Fuca Plate; N.A. = North American Plate. A: Stable configuration for a F-F-T junction: The trench and one fault are colinear. As plate motions proceed, the junction maintains its geometry and boundary types. B: Approximation of the present Mendocino junction. The San Andreas fault and the Cascadia trench are not colinear. When the plates move, the triangular gap that appears at the junction (red triangle) must be accommodated by the surrounding regions. This junction is unstable.

sive, broadening belt of basins forming the eastern side of a stable, permanent San Andreas fault line. A second solution is that the San Andreas boundary shifts sideways, inland, from time to time, thus realigning its northern terminus with the trench. Note that this second solution is a variant of the first, simply transferring the extension to pull-apart basins farther south in the fault system.

The second solution, an inland shift, is very clearly shown in the young continental structures around Cape Mendocino today. The main strand of the San Andreas fault lies in the continental shelf here, but many obviously related structures are presently active inland of the junction (Fig. 29). Strike-slip faults with the San Andreas trend and slip sense lie more than 70 km inland of the junction, connecting to the coast and offshore systems via thrust faults as much as 150 km to the north (Kelsey and Cashman, 1983; Kelsey and Carver, 1988). The strike-slip faults connect to the main San Andreas strand to the south via pull-apart basins. Herd (1978) postulates the existence of a microplate, the "Humboldt Plate" (Fig. 29), that moves partly with North America, partly with the Pacific. Presumably this platelet is in the process of being transferred from the former to the latter (Kelsey and Carver, 1988).

Displacement history from fault offsets. One good way to quantify the geologic history of the Pacific–North America plate boundary would be to measure the amount and timing of late Cenozoic deformation and fault displacements along the boundary. Tectonic maps of California show a number of faults in the region, especially between the San Andreas fault and the continental margin (Fig. 30), all of which need to be quantitatively described. It appears that the present San Andreas fault itself is only the most recent strand to dominate the plate boundary and that the San Andreas system has gradually been stepping eastward into the continental interior and gradually transferring continental slivers from the North American to the Pacific plate. To quantify this evolution, both the magnitude and the timing of all fault offsets would need to be measured in some detail.

It is an unfortunate fact that measuring and dating offsets on strike-slip faults are difficult tasks, requiring a large amount of both hard work and good luck. One must search both sides of the fault for small, unique, datable geologic features that crossed the fault at high angles and were subsequently offset. Such serendipitous pairs of localities are called "piercing points" (Crowell, 1962). In spite of the difficulties, a large number of piercing points of various reliability and precision have been documented over the years. Some of these will be described below.

The most dramatic geologic match across the San Andreas fault is one that was described in the classic, groundbreaking work by Hill and Dibblee (1953). The northernmost outcropping of Sierran granite on the east side of the present strand of the San Andreas is near the San Emigdio Mountains; on the west side it is at Bodega Head. This offset implies a minimum of 510 km of right slip sometime since the Late Cretaceous. Since we do not know the extent of granite beneath the shallow waters north of Bodega Head, this number is a minimum. The actual displacement could be as much as 600 km (Silver and others, 1971). This offset and the others discussed in this section are tabulated in Table 2.

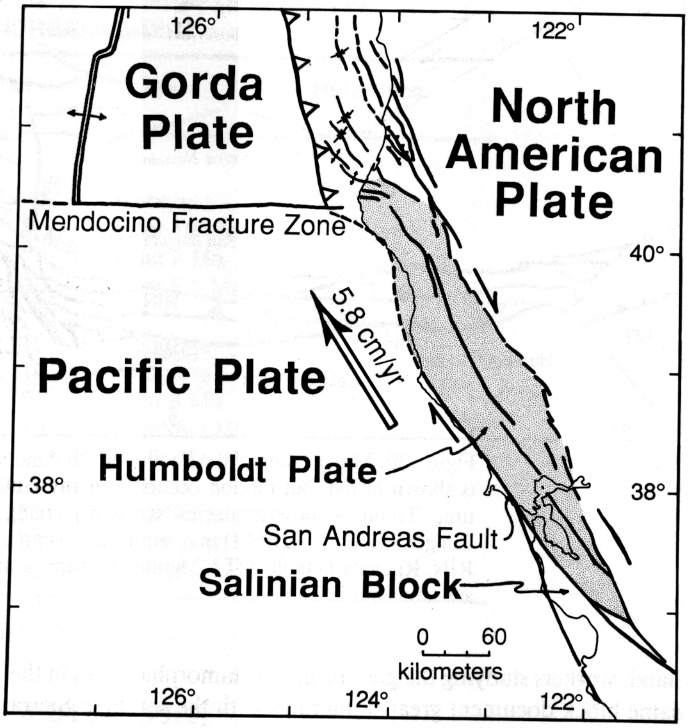

Figure 29. Active faults in the vicinity of the Mendocino triple junction, after Kelsey and Carver (1988). The main strand of the San Andreas fault lies offshore, but major young faulting also occurs inland of the junction. The "Humboldt Plate" (Herd, 1978) may be in the process of being transferred from the North American to the Pacific Plate.

In central California, a well-constrained piercing point (the Pinnacles and Neenach volcanic formations) establishes that the San Andreas has been offset about 315 km since 23.5 Ma (Huffman, 1972; Matthews, 1976). The discrepancy of 200 to 300 km between the Pinnacles and Bodega Head offsets along the present strand was worrisome to early workers, but it now seems likely that the difference can be found on the other adjacent faults to the west of the Pinnacles point. Loosely constrained estimates of 115 km and 55 km of right-lateral slip on the San Gregorio–Hosgri and Rinconada faults (Graham and Dickinson, 1978; Dibblee, 1976, respectively) and a modest, unknown amount of distributed shear within the blocks (Greenhaus and Cox, 1979) and on other faults bring us well within the Bodega Head range of total displacement (Hornafius and others, 1986).

An alternative explanation for the discrepancy in offsets just described is that the granites west of the San Andreas were never part of the Sierran belt but rather are exotic terranes. This interpretation is supported by some paleomagnetic measurements in the Salinian block indicating that it was 2,000 to 3,000 km farther south in the Cretaceous and was accreted to California in the early Cenozoic (Kanter and Debiche, 1985). On the other

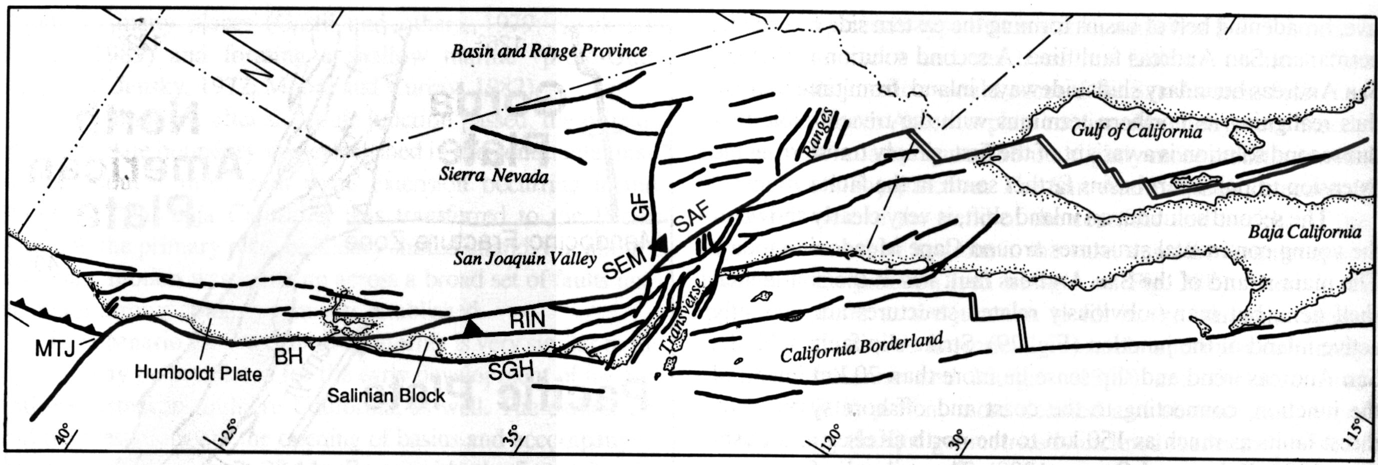

Figure 30. Major faults of the Pacific-North America Plate boundary. Main San Andreas strand (SAF) is shown in red, but motion occurs on many faults and appears to have been shifting inland through time. Triangles show Pinnacles-Neenach piercing point. Granites at Bodega Head (BH) and the San Emigdio mountains (SEM) may supply another tie. GF: Garlock fault, SGH: San Gregorio–Hosgri fault, RIN: Rinconada fault, MTJ: Mendocino triple junction. Measured and estimated offsets on these faults are tabulated in Table 2.

hand, workers studying the granitic and metamorphic rocks in the same block document great similarities with the southern Sierra Nevada (Mattinson and James, 1985). In either case, the younger offsets on the San Andreas system still hold. The primary interest in the granite offset is that it gives us a broader total displacement than can be measured on the central Californian strands, so that it is quite useful, if true.

The timing on central Californian faults is, for the most part, not well constrained. The initiation of wrench folding in the San Joaquin valley adjacent to the San Andreas fault indicates that some motion began about 16 Ma. However, Dickinson and Snyder (1979a) suggest that major motion on this strand did not begin before about 12 Ma, and another piercing point documents that about 200 km of offset, or about two-thirds of the total, has occurred since 7 Ma (Huffman, 1972; Dickinson and others, 1972). Although some weak evidence suggests that the offsets on the faults to the west are also young (Graham and Dickinson, 1978), the Transverse Range rotations (as well as my own prejudices) suggest that the offsets should be primarily older, taking up at least 150 km of the Pacific–North America shear between 16 and 10 Ma (Hornafius and others, 1986). Dickinson and Snyder (1979a) also assume that early motion was taken up by these and other faults offshore. This history of activity stepping inland through time is reminiscent of the features near the Mendocino triple junction. As we can with the Humboldt Plate, we may visualize a (somewhat deformed) Salinian Plate that has been gradually transferred from the North American to the Pacific Plate as the San Andreas system moved inland.

Southern California and northernmost Baja California are, by far, the most complicated parts of the San Andreas system. Late Cenozoic structures in this region include the rotated Transverse Ranges; numerous strike slip faults both subparallel to the San Andreas and in other directions; numerous basins, both pull apart and compressional; and mountain uplifts with variable histories. The continental shelf here, the broad California borderland, is profoundly fractured and rifted.

The predicted plate tectonic history of this region is likewise complex, as implied by Figures 21 and 24B. The first contact between the North American and Pacific Plates was near this region, off northern Baja California, and from that time until about 16 Ma, the Rivera triple junction, usually including a young, hot spreading center, lay offshore and shifted back and forth. During that period, and also the next when the boundary extended southward along the Pacific margin, this region acted as the connection zone between the southern offshore boundary and the onshore motion on the San Andreas system. This geometry, a right step in a right-lateral system, is intrinsically extensional—a "releasing geometry" (Crowell, 1974; Hornafius, 1985).

The plate boundary geometry in southern California changed about 5.5 Ma, with the transfer of Baja California to the Pacific plate. After the transfer, this region again acted as a connection zone, but now it was between the inland boundary in the Gulf of California and the more seaward faults of the San Andreas farther north. The new geometry, a left step in a right-lateral system, is intrinsically compressional—a "restraining geometry." As a further complication, Neogene expansion of the Basin and Range Province occurred primarily north of this latitude and was compensated by east-west left-lateral shear in this region. It is no wonder that this region is so complex!

Displacement history from block rotations. A second technique for estimating fault displacements, one that is still somewhat unproven but holds great promise, concerns the large-scale rotations of intact blocks and the geometric constraints imposed by such rotations. Both the timing and the magnitudes of rotations of geologic blocks are relatively easy to measure using paleomagnetism. A great many rocks within a given terrain carry

TABLE 2. SUMMARY OF LATE CENOZOIC OFFSETS PARALLEL TO THE SAN ANDREAS FAULT*

	Amount, km	Age	Reference
Strike Slip Fault Offsets			
Northern San Andreas (NSA)	550 ± 40	Neogene	1
Central San Andreas (CSA)	315 ± 5	Post 16 Ma	2, 3
	200 ± 10	Post 7 Ma	2, 4
Southern San Andreas (SSA) (+ San Jacinto + Elsinore)	300 ± 10	Post 5.5 Ma	2, 5, 6
San Gregorio–Hosgri (SGH)	115 ± 10	Neogene	7
Rinconada (RIN)	55 ± 10	Neogene	8
Hayward–Rodgers Creek (HRC)	43 ± 5	Post 8 Ma	9
Carneros–Calaveras (CAC)	28 ± 10	Post mid Mioc.	9
Distributed Shear			
Salinian block (SAL)	40 ± 25	Most 20 to 16 Ma	10
So. Sierra Orocline (SSO)	50 ± 50	23(?) to 16 Ma	11
Basin and Range (B&R)	100 ± 25	Late Neogene	12

*Data for Table 3 and Figure 32. Ages and slip distances adapted from the cited references. Modifications discussed in text.

References:

1. Hill and Dibblee (1953)
2. Huffman (1972)
3. Matthews (1976)
4. Dickinson and others (1972)
5. Ehlig and others (1975)
6. Hornafius and others (1986)
7. Graham and Dickinson (1978)
8. Dibblee (1976)
9. Fox and others (1985)
10. Greenhaus and Cox (1979)
11. Crowell (1987)
12. Stewart and others (1968); Stewart (1983)

magnetic signatures that were acquired during their formation, and the present declination of each shows the amount of rotation it has undergone with respect to magnetic north since it was magnetized. The paleomagnetic method has a great many pitfalls, but careful work and a little luck can yield well-timed, specific results.

Of particular use for the present discussion are the rotation results from the Transverse Ranges. Although most of the coastal mountains of California trend northwest-southeast, approximately parallel to the San Andreas system, the Transverse Ranges of southern California trend east-west across this grain. Paleomagnetic studies of rocks in the Transverse Ranges show that they have been rotated clockwise as large, coherent blocks by large amounts during the Neogene. In particular, Luyendyk and others (1980, 1985) report that many Neogene rocks contain rotated paleomagnetic directions, and the magnitudes of rotation as well as their changes through time are consistent across regional areas 40 to 110 km long. This remarkable consistency suggests that entire blocks within the ranges, shaded on Figure 31, rotated as coherent pieces. Particularly dramatic are the measurements in the western Santa Ynez Range, where samples from many rock types and many tectonic situations all indicate a clockwise rotation of about 95° since 16 Ma.

The time history of these rotations is now fairly well established. Hornafius (1985) studied the paleomagnetism of the dolomites in the Monterey formation and younger sedimentary rocks and documented, in detail, the timing of the rotations of the Santa Ynez range from 16 Ma to the present. These results are shown in Figure 31B for adjacent segments of the ranges. These time histories of rotation are interesting in themselves, but in addition they provide powerful constraints on the amount and timing of shear deformation that occurred across the fault systems both north and south of the ranges. To explain the relationship of these Transverse Range rotations to the San Andreas shear, Luyendyk and others (1980, 1985) and Hornafius and others (1986) combined the known block rotations with known and implied fault offsets to formulate a quantitative time history of distributed deformation for southern and central California, as follows.

Before about 16 Ma, Pacific–North America motion was primarily accommodated on faults in the continental shelf and at the continent-ocean join. About 16 Ma, major shear began within the continent. Between 16 and 10 Ma, a Transverse Range block rotation of about 55° requires about 220 km offset being distributed across a region about 200 km in width both to the north and the south. The overall configuration was a releasing geometry, so that many pull-apart basins formed in the mismatches around the rotating terrain. About 12 Ma, the San Andreas broke across the

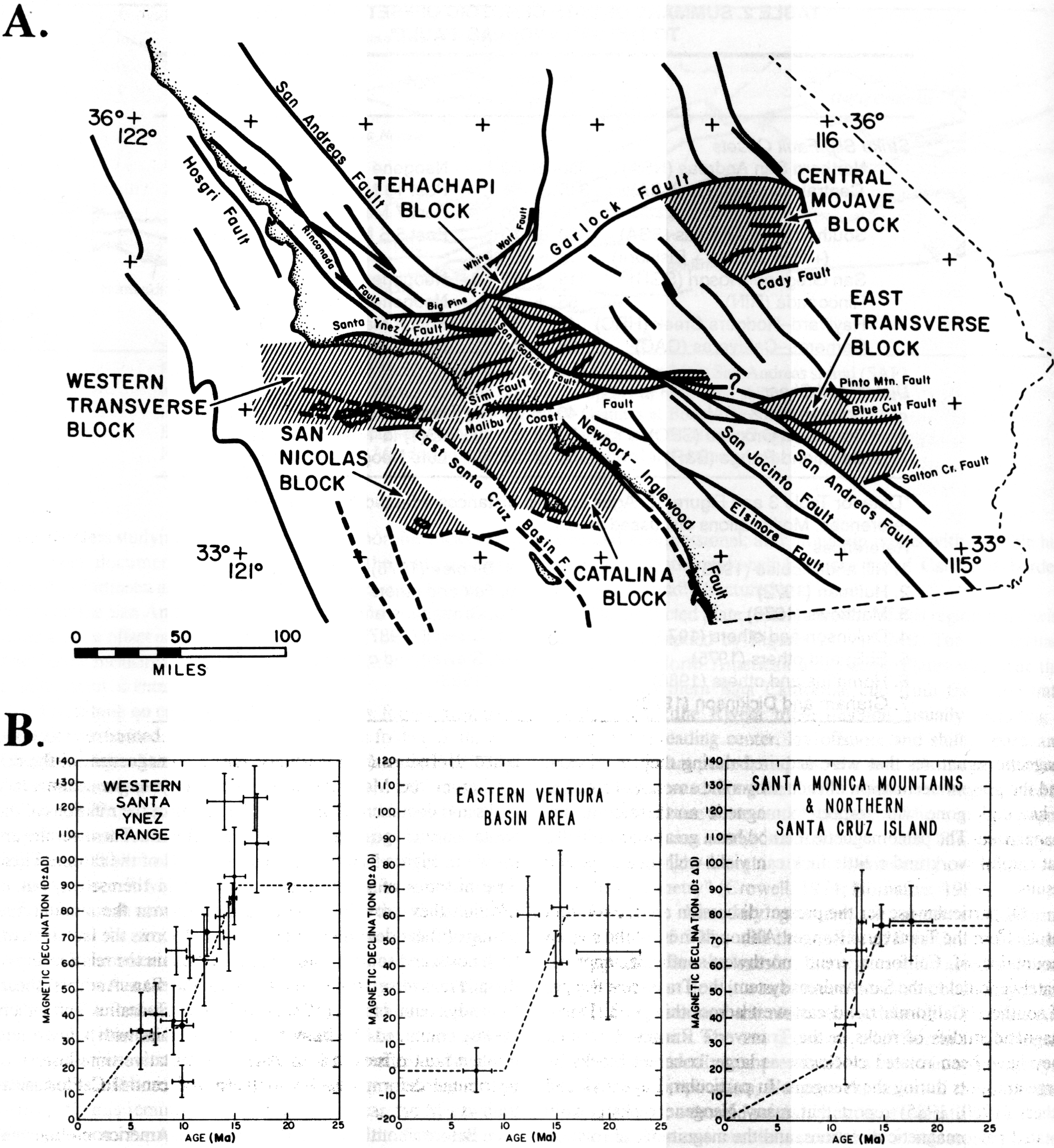

Figure 31. Rotations of the Western Transverse Ranges. A: Major Neogene structures of southern California, after Luyendyk and others (1980). Transverse blocks are shaded. Paleomagnetic vectors consistently show large clockwise rotations for the Transverse Range and San Gabriel blocks and relatively small rotations for other regions. B: Paleomagnetic declinations vs. age for rocks in three adjacent segments of the western Transverse Ranges, after Hornafius and others (1986). Patterns suggest that all rotated together, clockwise, 50 to 60° between 16 and 10 Ma. Slower clockwise rotation continued in the western blocks, mostly since about 6 Ma.

Transverse Range block (San Gabriel fault), and the rotation nearly ceased.

Since the transfer of Baja California to the Pacific Plate about 5.5 Ma, the majority of the Pacific–North America plate motion has been taken up in offsets on the San Andreas fault, inland; lesser amounts have been distributed across coastal faults, corresponding to the additional 35° rotation in the western Transverse Ranges. The broad-scale configuration has switched to a restraining geometry, and many southern California basins have switched from pull-apart to compressive shortening. Superimposed upon these effects is the result of the westward expansion of the Basin and Range province. This has resulted in up to 80 km of left-lateral offset on the Garlock fault and extensional splaying in the Mojave block, adding to the "Big Bend" in the San Andreas and superimposing a counterclockwise rotation upon the San Gabriel block.

In a complete compilation of late Cenozoic strike slip, oblique deformation in the western Basin and Range province cannot be ignored. Although it seems clear, for the reasons discussed in an earlier section, that the onset of extension here was related to earlier events in the region, it is also clear that the Pacific–North America shear system at the coast has superimposed its effects in the western part of the province. Numerous young northwest-southeast strike-slip features are found here, and the north-south block faults show oblique slip in mapped fault features, in geodetic measurements, and in earthquake first-motion solutions (Stewart and others, 1968; Stewart, 1983; Thompson and Burke, 1974; Gumper and Scholz, 1971). Zoback and Thompson (1978) show structures in Nevada that document an earlier stage of west-southwest–east-northeast extension and a later northwest-southeast motion. This change is presumed to arise from the influence of the Pacific–North America shear regime, which was superimposed upon the older structures sometime between 15 and 6 Ma. Eaton (1980) concluded that this northwest-southeast deformation is limited to the western, highly seismic portion of the province, while the eastern portion is still experiencing east-west extension.

Late Cenozoic pull-apart basins. Another geologic expression of the Pacific–North America interaction has been the formation of pull-apart basins. Since the San Andreas motion is now and may always have been oblique to the coast, the system has included an amount of extension as well as strike slip. The resulting instability of the Mendocino triple junction suggests that the opening of basins may mark its passage. The initiation of pull-apart basins and activity in them are relatively easily documented and dated, both because their sediments record the history and are likely to be preserved and because the pull apart is commonly associated with volcanism.

The first systematic attempt to track the triple junctions in the coastal Californian basins was made by Dickinson and Snyder (1979a). They compiled volcanic dates and initiation dates for a number of pull-apart basins and compared these to plate tectonic predictions. Fox and others (1985), Crowell (1987), Bachman and Crouch (1987), and McCulloch (1987) refined and detailed these data. The initiation times from these studies are compiled in Table 3. On Figure 32 they are shown in their present geographic locations (open symbols) and also in their reconstructed positions (filled symbols), displaced according to the offsets compiled in Table 2 to show their approximate original locations with respect to cratonic North America. These, in turn, are superimposed on the predicted tectonic regime pattern developed in Figure 24B. Nearly all lie within the predicted strike slip region. Southern California dates tend to lag the tectonic pattern by a few million years, while northern California volcanic dates tend to follow the passage of the junction quite closely, as expected from the discussion of lag times above.

An interesting relationship can be seen in the difference between the onset ages of the basins and those of the faults in southern California. The basins record deformation beginning about 22 Ma, very soon after the Pacific–North America boundary was first established. Strike-slip offsets on the faults appear to begin later, about 16 Ma, and they are distributed over many faults at first. It seems that the deformation was more diffuse and broad in its early stages and became concentrated with time.

The oroclinal bending of the southern Sierra Nevada batholith may be part of the earlier, diffuse deformation. Paleomagnetic measurements show that plutonic rocks in this block were rotated clockwise about 45° (Kanter and McWilliams, 1982; McWilliams and Li, 1985) sometime between their emplacement at 80 Ma and the addition of their unrotated overlying volcanics and sediments 16 to 20 m.y. ago. Crowell (1987) links the bending to the rapid deepening of the adjacent San Joaquin Basin that began about 23 Ma. Perhaps the oroclinal bending and early basin formation show an early, diffuse extensional shear regime, active prior to the inland shift and localization of throughgoing strike-slip faults. Beck (1986) suggests another alternative, that the bending was related to drag from early Cenozoic oblique subduction. Although this is a possibility, the timing is not ideal. As described above (Fig. 16B), the tangential component of subduction during much of the Cenozoic may have been small.

Plio-Pleistocene compression in the Coast Ranges. An additional structural event in coastal California deserves attention. It has often been noted by California geologists that a pure strike-slip motion along the San Andreas does not explain some important young tectonic features, even along the simplest segment of the San Andreas system in central California. The fault is a dramatic feature in the landscape here, but most noticeable are the Coast Ranges: rugged, young fold-and-thrust mountains indicating a component of east-west compression. B. M. Page, in an extensive personal communication (1982) reported by Engebretson and others (1985), listed a substantial number of compressive events that can be dated as 5 to 3 Ma and younger. We may conclude that the direction of relative motion along this boundary has not been quite parallel to the San Andreas fault trace but rather has included a component of compression in the past few million years.

A component of compression is also suggested by present-day global plate-motion solutions. Minster and Jordan (1984,

TABLE 3. PULL-APART BASINS AND MAJOR VOLCANIC FIELDS, INITIATION AGES, AND POST FORMATIONAL OFFSETS*

	Age, Ma	Ref.	Offsets†	Total Offset, km
Basins				
Los Angeles (LA)	22 ± 1	1	SSA+SSO+B&R	450 ± 85
Ventura (VN)	22 ± 1	1	SSA+SSO+B&R	450 ± 85
San Joaquin (SJ)	21 ± 1	1	SSO+B&R	150 ± 75
Central Salinian (CS)	23 ± 1	2	CSA+SSO+B&R(+RIN)	490 ± 100
Santa Maria (SM)	16 ± 2	2	CSA+RIN+SAL+B&R	485 ± 55
Offshore S. Maria (OS)	20 ± 2	3	CSA+RIN+SGH+SAL+SSO+B&R	675 ± 100
Bodega (BO)	20 ± 2	3	NSA+SSO+B&R	675 ± 90
Point Arena (PA)	23 ± 2	4	NSA+SSO+B&R	675 ± 90
Volcanic Fields‡				
Morro Rock (R)	26 ± 2		CSA+RIN+SAL+SSO+B&R	570 ± 115
Felton (F)	24 ± 2		CSA+SSO+B&R	465 ± 80
Tecuya (U)	24 ± 2		SSO+B&R	150 ± 75
Pinnacles (P)	23 ± 3		CSA+SSO+B&R	465 ± 80
Iverson (I)	23 ± 2		NSA+SSO+B&R	700 ± 115
Neenach (N)	21 ± 2		SSO+B&R	150 ± 75
Mindego (M)	20 ± 1		CSA+SSO+B&R	465 ± 80
Tranquillon (T)	17 ± 1		CSA+RIN+B&R	470 ± 40
Obispo (O)	16 ± 2		CSA+RIN+B&R	470 ± 40
Triple (L)	16 ± 2		CSA+B&R	415 ± 30
Page Mill (G)	15 ± 2		CAC+HRC+B&R	171 ± 40
Quien Sabe (Q)	11 ± 3		B&R	100 ± 25
Berkeley Hills (B)	9 ± 3		CAC+B&R	128 ± 35
Sonoma–Tolay (S)	8 ± 5		CAC(+HRC)+B&R	140 ± 40
Coyote (Y)	4 ± 1		CAC+HRC+(B&R)	120 ± 50
Clear Lake (C)	2.5 ± 1		(B&R)	50 ± 50

*Data for Figure 32.
†Table 2. Brackets indicate that less than the full effect was assumed.
‡Dates as compiled by Fox and others, 1985.
References:
1. Crowell (1987)
2. Dickinson and Snyder (1979a)
3. McCulloch (1988)
4. Bachman and Crouch (1987)

1987) examined the uncertainties in global least-squares solutions for Pacific–North America motion, including estimates of the effects of young deformation in the Basin and Range Province. They showed that although the uncertainties are large enough to encompass models from pure slip to those with substantial components of compression, the preferred solution is one that includes a small component of compression along the San Andreas.

Cox and Engebretson (1985) note that the timing of onset of this compression may correspond to a change in the Hawaiian hot-spot trace. The Hawaiian chain of seamounts generally fits a single small circle from the Emperor bend (43 Ma) to Kauai, with perhaps, a minor shift about 20 Ma (McCulloch, 1988). The Hawaiian Islands themselves, however, follow a more southerly trend. This difference may simply be a local variation, but Cox and Engebretson (1985) and Pollitz (1986) suggest that the change faithfully records a subtle change that occurred between 5 and 3.2 Ma in Pacific Plate motion over the hot spots. The effect of this change would be to add a small component of compression to motion along the San Andreas fault.

SUMMARY AND CONCLUSIONS

The Pacific Plate began as a rather small plate. During the Mesozoic it grew rapidly, as three plates—the Izanagi, Farallon, and Phoenix—spread away from it to the north, west, and south, respectively. During the Cretaceous magnetic quiet period, the northern border of the Pacific Plate was reorganized with the birth of the Kula Plate. The Kula Plate was relatively short-lived but had a fast northward velocity, so that it played an important role in transporting terranes to the north. The Farallon Plate con-

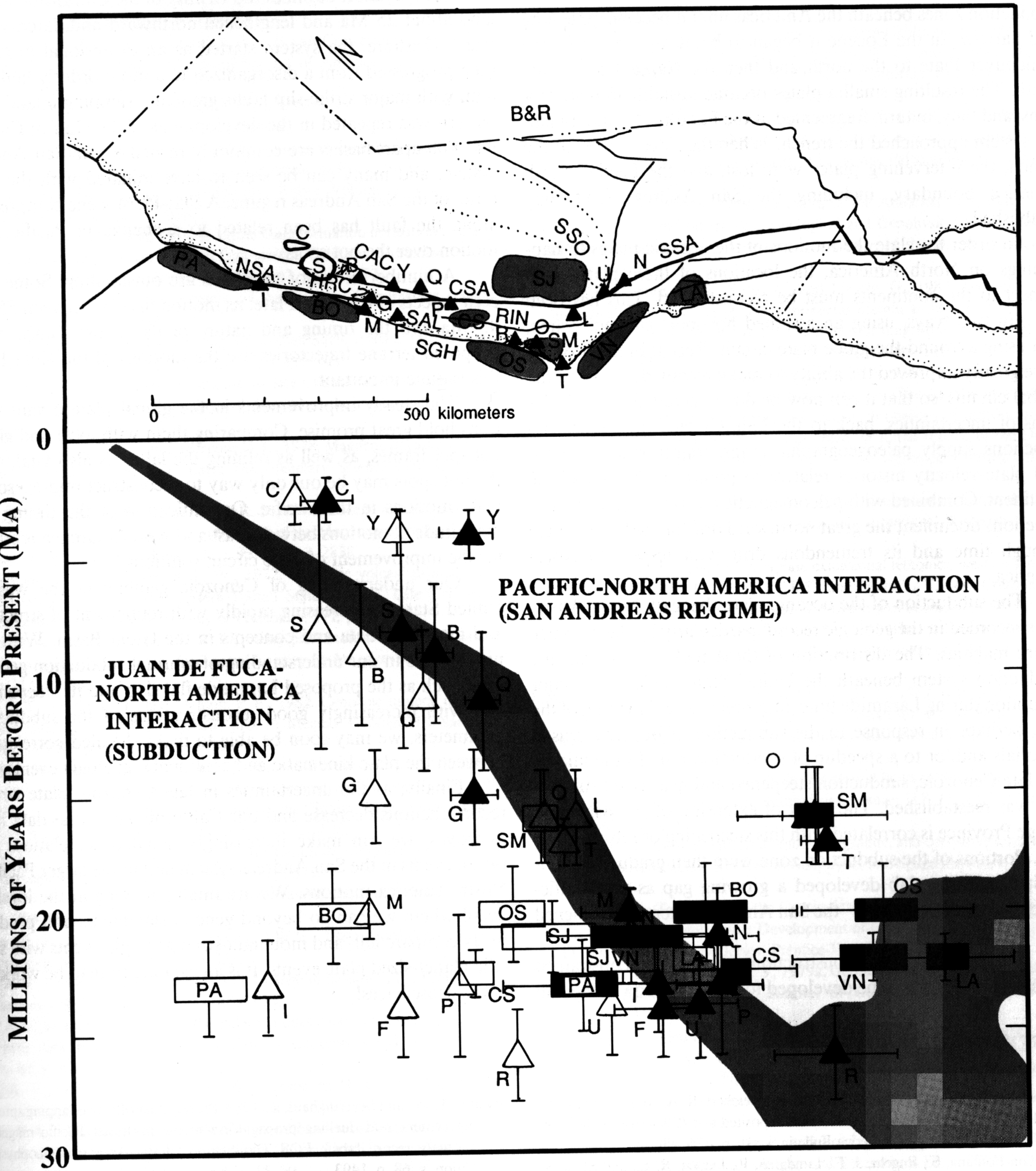

Figure 32. Time-distance plot of initiation ages of pull-apart basins (rectangles) and related volcanic fields (triangles) in coastal California. Open black symbols show locations and ages, with uncertainties, of features in their present geographic positions on North America. Solid red symbols show features after removal of approximate subsequent offsets, with uncertainties, as listed in Table 3. Light red shaded curve is the time-distance plot of plate interaction geometry from Figure 24B, for comparison. Initials and sources of data are listed in Tables 2 and 3.

tinued to move eastward away from the Pacific and into the subduction zones beneath the Americas until it became quite long and narrow. In the Eocene it began to break up, spawning the Vancouver Plate to the north and then the Nazca Plate to the south. The resulting smaller plates became unstable in their motions, and they, in turn, fragmented as the Farallon-Pacific spreading system approached the trench. When the ridge arrived at the trench, the intervening plates were lost, and the Pacific–North America boundary, including the San Andreas fault, was established.

In order to relate the motions of the oceanic plates to happenings on North America, the locations of these plates with respect to the continents must be reconstructed. This has been done in two ways, using an assumed hot-spot reference frame, and using a 'round-the-globe plate circuit. Recent breakthroughs have greatly improved the ability to make reconstructions via the global circuits, so that it can now be done, including the calculations of uncertainties, back to the Late Cretaceous. The reconstructions supply paleogeographic maps, trajectories of points, and plate-velocity histories relative to points on the rim of the continent. Combined with paleomagnetic information, the reconstructions document the great northward drift of the Pacific plate through time and its tremendous drift with respect to North America.

The subduction of the oceanic plates beneath North America is recorded in the geologic record, particularly by the presence of arc magmas. The distribution of these rocks shows that the subduction system beneath the United States suffered a major disruption during Laramide time, interpreted as a flattening of the slab, perhaps in response to the subduction of buoyant crustal materials and/or to a speedup of subduction rate. In the middle and late Cenozoic, subduction steepened and near-coast subduction was reestablished. The onset of extension of the Basin and Range Province is correlated with this steepening or retreat of the slab. Portions of the subduction zone were then gradually extinguished, and the slab developed a growing gap as the Pacific-American plate boundary—the San Andreas system—lengthened along the coast.

New global circuit reconstructions allow a well-constrained plate motion history to be developed for the evolution of the San Andreas system. It began in the vicinity of the California borderland about 25 Ma and lengthened northward and, later, southward. Onshore, the system started as an extensional province, then progressed from a disorganized to a more orderly fault system, with major strike-slip faults gradually stepping inland. This pattern was repeated in the development of the Gulf of California. Pull-apart basins are commonly related to the San Andreas system, and many can be seen to have initiated with the local onset of the San Andreas regime. A Plio-Pleistocene compression along the fault has been related to a change in Pacific Plate motion over the hot spots.

A number of major problems are outstanding. Some concern aspects of the Kula Plate: its motion history between 55 and 43 Ma and the timing and nature of its demise. Since many proposed terrane trajectories use the motions of the Kula Plate, this is quite important.

The steady improvements in the global plate circuit solutions hold great promise. Comparing them with local and global hot-spot frames, as well as refining the latter, is also vital, since the hot spots may be our only way to reconstruct mid-Mesozoic plate motions in the Pacific. Quantification of the timing and magnitude of motions between east and west Antarctica is crucial for the improvement of plate circuit solutions.

Our understanding of Cenozoic geology in the western United States is increasing rapidly with refinement of structural and magmatic data and concepts in the Great Basin. With improvements in our understanding of unusual subduction geometries, such as the proposed Laramide flat slab and its steepening, and with increasingly good reconstructions of the subduction parameters, we may soon be able to make detailed correlations between the plate kinematic and continental geologic events.

Finally, as the uncertainties in late Cenozoic plate circuit reconstructions decrease and our California structural data base improves, we can make increasingly detailed correlations between events in the San Andreas system and in the larger Pacific–North America motions. We are finally arriving at the level of detail where we can go beyond general statements and productively compare hill- and mountain-sized geologic events with specific planet-sized plate events. It is an exciting time to be working in the geosciences!

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MANUSCRIPT ACCEPTED BY THE SOCIETY SEPTEMBER 14, 1988

ACKNOWLEDGMENTS

I dedicate this chapter to my mentor of many years, Allan Cox, whose dependable friendship, encouragement, and sympathetic ear helped me over many a rough spot, and to my mentee, Jeff Severinghaus, whose intense excitement and pleasure at the unfolding of nature's secrets continually remind me why I do science.

I thank the following for helpful reviews and comments: Wendy Bartlett, Emery Goodman, Roger Larson, Warren Hamilton, Jonathan Peterson, George Thompson, and an anonymous reviewer. Jeff Severinghaus, Peter Molnar, and Joann Stock supplied particularly in-depth reviews.

This work would be much impoverished without access to many prepublication manuscripts. I thank Peter Lonsdale, Joann Stock, Doug Wilson, Jacqueline Mammerickx, Will Sager, Dave Caress, John Crowell, José Rosa, Peter Molnar, George Sharman, Kensaku Tamaki, Dave McCulloch, Warren Hamilton, and their coauthors for generously allowing me to use their work in prepublication form. I particularly thank Joann Stock for supplying early versions of the circuit reconstructions.

Jeff Severinghaus provided invaluable aid for every aspect of the manuscript, including substantial scientific input. Dave Crouch, Rose Ballard, Chris Smith, Nancy Riggs, Michael Ort, Steve Richard, Claire Zucker, and Bill Morris helped with the preparation of the final manuscript and figures. Finally, I thank Pete Palmer for his great patience and expertise and his generous accessibility during the production of this work.