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GEOMETRY OF TRIPLE JUNCTIONS RELATED TO SAN ANDREAS TRANSFORM

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Abstract. Understanding the evolution of the San Andreas transform is a key not only to broad aspects of regional geology but also to the development of specific structural provinces. Though stable in the regional sense, the paired triple junctions at the ends of the transform have had transient unstable configurations wherever the trends of the prior trench and the newly developing transform were locally not collinear. The resulting instabilities were mainly of kinds inferred to induce extensional tectonics within a nearby region. Passage of the Mendocino fault-fault-trench triple junction northward along the central California coast coincided well with pulses of initial subsidence in Neogene sedimentary basins near the continental margin and with eruptions at local volcanic centers in the Coast Ranges. Passage of the Rivera ridge-trench-fault triple junction southward was associated with the rifting events that formed the California Continental Borderland and the Gulf of California.

Introduction

The San Andreas fault system played a major role in the evolution of plate tectonics. The recognition of transform faults by Wilson [1965] was the key concept that allowed the separate notions of continental drift and sea floor spreading to be joined into one integrated view of intact plates. Of the various transform faults that Wilson [1965] originally noted, the San Andreas was the only one known, from independent geologic data on land [Hill and Dibblee, 1953], to have had the kind of large lateral offsets that his idea required. Moreover, in their later demonstration that plate motions could be treated rigorously, by methods from spherical geometry, as movements of spherical caps, Mckenzie and Parker [1967] used the strike of the straightest segment of the San Andreas to help control the inferred geographic position of the Euler pole of rotation between the Pacific and American plates. Morgan [1968] also relied heavily on the trends of faults within the San Andreas system for his elaborations on the geometry of plate motions. Finally, McKenzie and Morgan [1969] discussed the development of the San Andreas transform as their salient example of the evolution of triple junctions where three plates meet.

Quite naturally, therefore, the San Andreas fault system was one of the first major structural features within a continental block for which a detailed kinematic explanation was attempted within the framework of plate tectonics. In her landmark study, Atwater [1970] showed clearly how the logic of plate theory can be brought to bear on the geologic history of the San Andreas. With different assumptions about the relative movements through time of the various plates involved in its development, different predictions about the offset history of the San Andreas can be made. Alternatively, improved data on the cumulative offsets can be used to correct assumptions about plate motions through time. Feedback of this type makes it possible now to achieve improved understanding of the history of the San Andreas by incremental adjustments in thinking as the data base increases and analysis proceeds.

In our discussion here of aspects of San Andreas history, we distinguish sharply between the San Andreas transform as a plate boundary and the San Andreas fault as a discrete shear zone. Failure to do so leads to severe ambiguities. Although idealized as single lines with no width, plate boundaries in the real world are belts of deformation having finite width. In California, the whole elongate field of en echelon wrench folds in the Coast Ranges [Wilcox et al., 1973] can be viewed, in a sense, as lying within the plate boundary of interplate deformation where transpression [Harland, 1971] is in progress. We prefer, nonetheless, to regard such folding, where not accompanied by wrench faulting with strike slip, as deformation of adjacent plate edges. Clearly, however, all simultaneously active subparallel faults along which strike slip is intermittently under way must be regarded as subsidiary strands of the master San Andreas transform. The rate of transform motion is the sum of rates of motion across such a family of faults. Crowell [1962] proposed the term San Andreas system to embrace all subparallel related faults, even including widely spaced major fault zones. This concept is quite close to the correct idea of a San Andreas transform and is flexible enough to permit newly discovered faults, even those lying offshore, to be incorporated into the scheme as they come to light.

Also critical, however, is the necessity to stipulate that various members of the San Andreas system as a whole may serve at any particular time as the master slip surface for the San Andreas transform. A transform fault takes on full and rigorous meaning only in terms of instantaneous plate motions. On the one hand, then, the San Andreas system can be thought of as a geographic set of braided shear surfaces and includes all subparallel faults related to the development of the system regardless of their times of activity or whether they were jointly active at the same time. By contrast, the San Andreas transform can be thought of as involving different components of the San Andreas system

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for different time slices in the past.

Most previous discussions of the San Andreas in relation to plate tectonics have placed their prime emphasis on implications for broad regional geology, or even global tectonics. In this paper, we examine implications of San Andreas evolution for the development of more restricted structural provinces. In doing so, we do not challenge the broader insights outlined in references cited above. Instead, we address facets of development not fully treated in previous accounts. Our key topic is an inquiry into the geometric and structural properties of unstable triple junctions, which hold important implications for the origin of the Gulf of California, the continental borderland off southern California, and the petroliferous sedimentary basins of central California, as well as for the modern alluviated valleys and young volcanics of the Northern Coast Ranges north of San Francisco Bay.

Migratory Triple Junctions

The San Andreas transform between the Pacific and American plates was generated in the Oligocene [Atwater and Molnar, 1973], when a segment of the ancestral East Pacific rise first encountered the subduction zone that then lay along the western margin of the North American continent [McKenzie and Morgan, 1969, Figure 5; Atwater, 1970, Figures 2 and 5]. The encounter took place when an intervening portion of the old Farallon plate was consumed at the Farallon-American trench. The transform has since lengthened by the simultaneous northward migration of a fault-fault-trench (FFT) triple junction and southward migration of a ridge-trench-fault (RTF) triple junction. Figure 1 shows the present plate configuration in the region, together with selected key geologic provinces on land. The small Juan de Fuca, Rivera, and Cocos plates are remnants of the once vast and continuous Farallon plate.

We here take the name of the northern (FFT) triple junction, as did Silver [1971a], from the associated Mendocino fracture zone, which had its origin as a Pacific-Farallon transform; and the name of the southern (RTF) triple junction from the associated Rivera plate, which has apparently been detached from the larger Cocos plate and almost fully attached to the American plate during the past few million years [Atwater, 1970]. Figure 1 shows the present locations of the Mendocino and Rivera triple junctions at either end of the currently active San Andreas transform system.

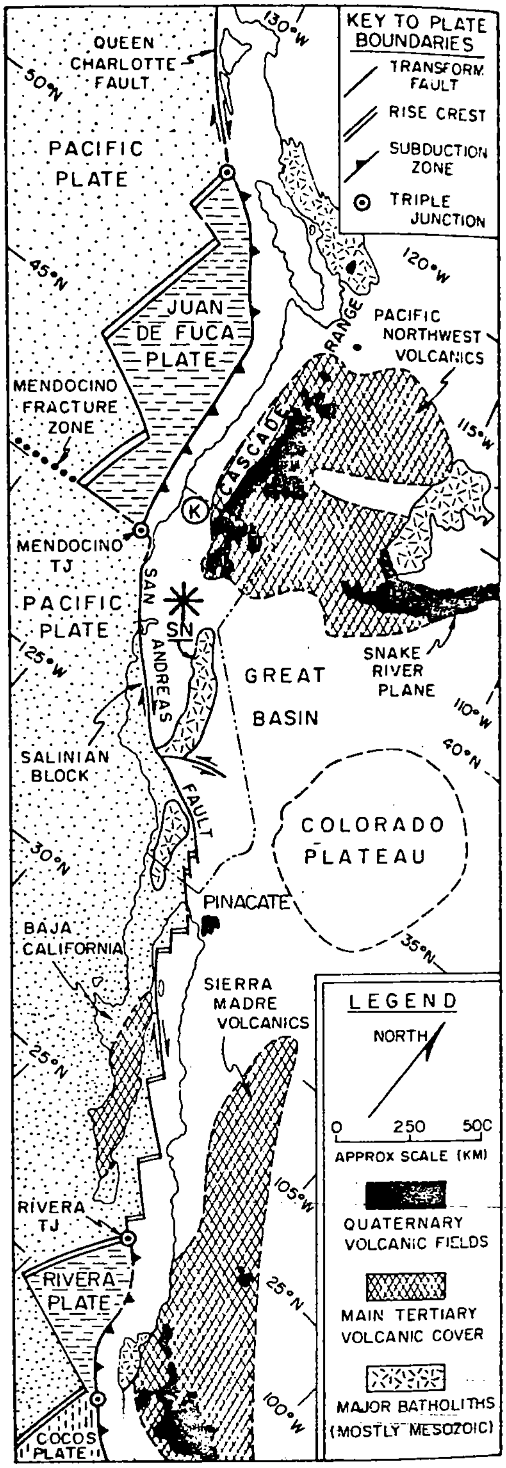


Fig. 1. Diagrammatic map showing present plate configurations related to current San Andreas transform and fault. Note dashed outline of California (asterisk within). Base Map is Mercator projection [Atwater, 1970, Figure 14] about a pole at 53°N, 53°W (the approximate Euler pole of rotation for Pacific-American motion after Morgan [1968b]). American plate is blank except for local ornament (see legend). Pacific plate is stippled, and remnants of Farallon plate (see text) are dashed.

The Neogene migration of the Mendocino and Rivera triple junctions along the continental margin has had the tectonic effect of terminating subduction and initiating transform shear, which has been operative only in the region between the two triple junctions [e.g., Atwater, 1970, Figure 17]. Provided the triple junctions could maintain stable configurations during their migration, no other major tectonic effects would be expected as a result of their respective passages along the coastal region. However, the conditions for stability of the two types of triple junction are stringent [McKenzie and Morgan, 1969, Figure 3]. In general, they can maintain stability while they migrate only if the trench and the transform that supplants it are collinear. In a broad sense, it is clear

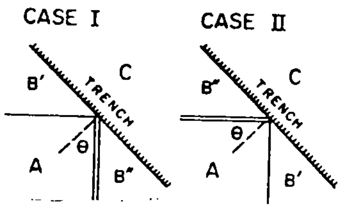


Fig. 2. Initial configurations of trenches (hachured lines), rise segments (double lines), and orthogonal rise-rise transforms (single lines) at the exact moments of rise-trench encounters leading to the generation of dextral transforms that will develop between plates A and C, whose relative motion is parallel to the trench. Plates B' and B" are the remnants of an intervening plate B as they exist adjacent to a rise-rise transform and a rise segment, respectively. Case I leads to San Andreas type (SA-type) transforms, and case II to non-San-Andreas type (NSA-type) transforms. See text for discussion.

that this powerful constraint has been met, for the gross trend of the continental margin where the trench was located coincides well with the direction of Pacific-American plate motion [McKenzie and Parker, 1967, Figure 3]. The direction is reflected by the local strikes of the San Andreas and Queen Charlotte faults (see Figure 1). This curious and important coincidence [McKenzie and Morgan, 1969] between present Pacific-American plate motion and the trend of a former Farallon-American trench remains unexplained but seems unlikely to be wholly fortuitous on such a grand scale.

In detail, the presence of irregularities along the continental margin causes local bends and deflections in the trend of the trench bordering North America. For example, the presently active subduction zone between the Juan de Fuca and American plates west of the Cascades volcanic chain is not collinear with the San Andreas fault (see Figure 1). Consequently, the Mendocino triple junction cannot maintain stability as it continues its northward migration. Thus local projections of and reentrants into the continental margin have the capacity, to the extent that they influence the local trend of the trench, to induce temporary instabilities in the configurations of migratory triple junctions. Presumably, unstable triple junctions produced locally in this manner could temporarily impose, at various places along the continental margin, styles of tectonic deformation that would not be predicted from general knowledge of the overall kinematic evolution of the San Andreas transform. Our purposes here are (1) to consider the probable nature of the transient tectonic regimes associated with the passage of migratory triple junctions and (2) to call attention to possible examples of resulting structural provinces along or adjacent to the San Andreas system.

Paired Triple Junctions

For the sake of completeness, we will now discuss all possible pairs of triple junctions formed at the ends of dextral transforms generated by encounters between rises and trenches. Analogous relations exist, in the nature of mirror images, for sinistral transforms generated in similar fashion. In all instances, the transform is generated when the width of an interior plate, bounded on opposing sides by a rise and a trench, is reduced to zero by plate consumption at the trench. When the rise meets the trench, those two plate boundaries cancel as the intervening part of the interior plate disappears. The transform is generated beteen the two exterior plates, which are thus brought into contact for the first time.

We assume here that spreading is always symmetric and occurs exactly perpendicular to rise crests and that relative plate motions are exactly parallel to the trends of the transforms. Deviations from these rules are expected to be minor and could readily be incorporated into more elaborate treatments without much change in derived geometric patterns. So long as these rules hold, however, rise segments and the transforms that offset them form a strictly orthogonal pattern (see Figure 2).

For simplicity, we here discuss the evolution of the transforms generated by rise-trench encounters in terms of plane geometry. For individual triple junctions, the geometric insights derived are valid, because the effect of the curvature of the earth is not significant within a surrounding area of limited size. However, where both triple junctions at either end of a long transform are to be considered simultaneously with rigor, spherical geometry is necessary, and special projections are required to display important relations in plan view (e.g., Figure 1).

For the generation of dextral transforms that terminate in paired triple junctions, two general cases of rise-trench encounter can be inferred (Figure 2). Case I pertains to the Neogene San Andreas, whereas Case II does not. For both cases, we arbitrarily designate as the angle of incidence θ the angle between the azimuthal trend of the rise segment and the normal to the azimuthal trend of the trench (see Figure 2); the analogous angle of incidence between the trends of orthogonal rise-rise transforms and the normal to the trench is always the angle (90° - θ). The special case where the rise crest is exactly parallel to the trench is trivial and does not

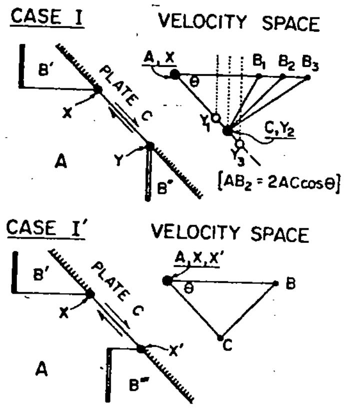


Fig. 3. Plate configurations in plan view (left) and plate motions in velocity space (right) during evolution of SA-type transforms (case I of Figure 2). See text for discussion.

generate any triple junctions. Where the rise crest is not parallel to the trench but is also not offset by any transforms, paired triple junctions cannot develop, and plate configurations at the time of the initial contact between the two exterior plates (A and C of Figure 2) cannot be uniquely determined.

Figures 3 and 4 depict, in plan view and in velocity space, the plate configurations and motions associated with the dextral transforms generated between plates A and C by the two cases of Figure 2. We follow the methods of McKenzie and Morgan [1969, Figure 3] for the construction of velocity triangles. The new transforms shown are all collinear with the preexisting trenches; hence all the triple junctions shown are stable. In case I (Figure 3), for the SA-type transform, the rise crest makes a clockwise acute angle with the trench. In case II (Figure 4), for the NSA-type transform, the rise crest makes a counterclockwise acute angle with the trench. For both cases, constant relative plate motions are assumed. In particular, all remnants of plate B (i.e., plates B', B", B‴ of Figures 3 and 4) are assumed to maintain the velocity of ancestral plate B. This assumption is doubtless unrealistic in many cases. Provided the relative motion of plates A and C remains unchanged, however, the effects of any postulated changes in the motions of the small plates derivative from plate B can readily be gauged by appropriate modifications of Figures 3 and 4.

In cases I and II (Figures 3 and 4 (top)), SA-type and NSA-type transforms (XY) each lengthen with time as points X and Y, which are FFT and RTF triple junctions, respectively, gradually move apart. In cases I' and II' (Figures 3 and 4 (bottom)), which are transient configurations that are not discussed further here, SA-type and NSA-type transforms (XX') do not change in length because the two FFT triple junctions, X and X' at either end, occupy the same position in velocity space. Note that for all cases (I, I', II and II'), the plan views in map space and the vector triangles in velocity space are geometrically related by the fact that the angle of incidence θ (see Figure 2) is the same as angle BAC, or its acute supplement, in velocity space (see Figures 3 and 4). Note also that remnants of plate B are consistently designated as B' where adjacent to X, B" where adjacent to Y, and B‴ where adjacent to X' (Figures 3 and 4).

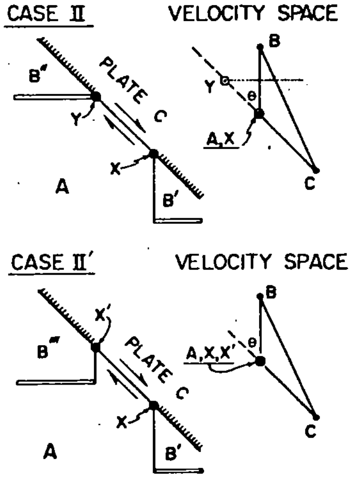
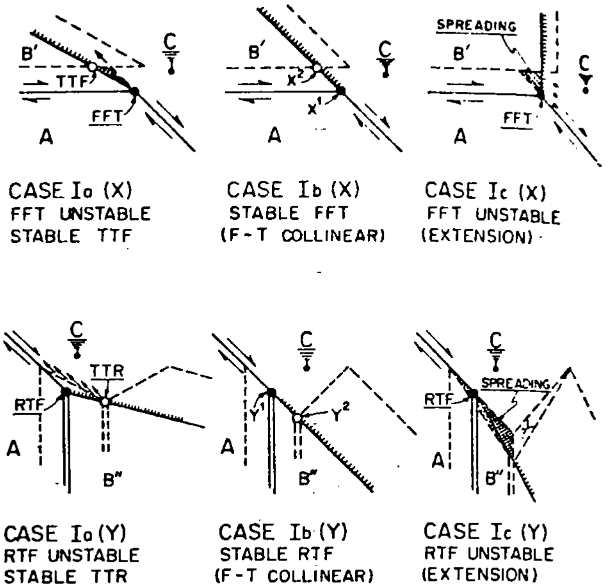


Fig. 4. Plate configurations in plan view (left) and plate motions in velocity space (right) during evolution of NSA-type transforms (case II of Figure 2). See text for discussion.



CASE Ia (X)
FFT UNSTABLE
STABLE TTF

CASE Ib (X)
STABLE FFT
(F-T COLLINEAR)

CASE Ic (X)
FFT UNSTABLE
(EXTENSION)

CASE Ia (Y)
RTF UNSTABLE
STABLE TTR

CASE Ib (Y)
STABLE RTF
(F-T COLLINEAR)

CASE Ic (Y)
RTF UNSTABLE
(EXTENSION)

Fig. 5. Diagrams showing inferred tectonic effects of migratory triple junctions X (top row) and Y (bottom row) associated with SA-type dextral transforms. Plate C is arbitrarily held fixed in position. Case Ib (center column) depicts stable varieties where transform and trench are collinear. Cases Ia (left-hand column) and Ic (right-hand column) depict unstable varieties where the trench being eliminated strikes more westerly and more northerly, respectively, than the transform supplanting it (i.e., in notation of Figure 2, the angle θ increases in case Ia and decreases in case Ic). See text for discussion.

In Case I (Figure 3) for SA-type transforms, the FFT triple junction X moves with plate A, hence plots at the same point in velocity space, and progressively eliminates successive segments of the trench between plates B' and C. The RTF triple junction Y plots at various positions in velocity space depending upon relative plate motions. For a constant AC vector, Y is located at Y_1, Y_2(C), and Y_3 when B is at B_1, B_2, and B_3, respectively, in velocity space. With respect to plate C, Y_2 holds still at the plate boundary, whereas Y_1 and Y_3 move in opposite directions along the plate boundary. The RTF triple junction Y thus migrates as Y_3 in the manner that progressively eliminates successive segments of the trench between plates B" and C only when the length of vector AB is greater than $2AC\cos\theta$ (see Figure 3). Relations are quite different in case II (Figure 4) for NSA-type transforms; the RTF triple junction Y always moves in a manner that progressively eliminates successive segments of the trench between plates B" and C, while the FFT triple junction X never moves so as to eliminate increments of the trench between plates B' and C but instead continually creates new increments of that trench by its motion.

Unstable Triple Junctions

Figure 5 portrays both stable and unstable configurations of the two types of migratory triple junctions whose movements serve to progressively eliminate successive segments of trenches at either end of SA-type transforms (Figure 3). In each diagram, the solid lines represent plate boundaries at some arbitrary time. The dashed lines show the changed positions of those same plate boundaries after some arbitrary span of time has elapsed. The changed positions shown were obtained by holding plate C fixed and then simply moving plates A and B' or B" sequentially in the correct relative directions. The dashed lines are thus virtual or ghost boundaries whose positions are a guide to how the configurations of the triple junctions may have evolved during the time span under consideration. For the actual San Andreas transform, the fixed plate C is the American plate, plate A is the Pacific plate, and plates B' (Juan de Fuca plate) and B" (Cocos plate) are derivatives of the Farallon plate (B).

Only in Case Ib, where both triple junctions remain stable, do the indicated shifts in plate boundaries yield unique solutions for the final positions and configurations of the two triple junctions. The FFT triple junction X moves from X^1 to X^2 while eliminating the trench segment X^1X^2. The RTF triple junction Y moves from Y^1 to Y^2 while eliminating the trench segment Y^1Y^2. Note that the dashed lines in case Ib(X), and in the other cases for X, conserve all plate areas but that the dashed lines in case Ib(Y), and in the other cases for Y, embrace new areas of plates A and B" generated at the intervening rise crest. The other diagrams can be interpreted as follows (refer to Figure 5):

1. In case Ia(X) at the top left, the FFT triple junction might attempt to migrate along the dashed arrow to induce contractional deformation of plate A or C or both plates within the crosshatched area, or a new trench-trench-fault (TTF) triple junction might migrate along the boundary of plate C as part of plate A was subducted beneath plate C.
2. In case Ic(X) at the top right, the crosshatched area indicates a region not occupied by any of the three plates; presumably some style of extensional deformation of plate A or C or both plates would be induced within and adjacent to that region. Alternatively, the transform between plates A and C might tend to shift to one of the positions indicated by the small arrows within plate C and thus to move inland into the continental block in the actual San Andreas example.
3. In case Ia(Y) at the lower left, the multiple small arrows again denote schematically a series of possible new positions to which the transform boundary between plates A and C might tend to shift; alternatively, a new trench-trench-ridge (TTR) triple junction might migrate along the boundary of plate C as part of plate A was subducted beneath plate C.
4. In case Ic(Y) at the lower right, extensional deformation within the crosshatched area might fragment the margin of plate C and create a new spreading center to avoid the impossible alternative of creating the stippled region where no plate would exist.

Analysis of the nature of the instabilities of the migratory triple junctions thus give rise to three generalities of structural significance: (1) where the trench at the continental margin strikes more westerly than the newly generated transform (thus increasing the angle θ of Figure 2), passage of a triple junction tends to induce continued subduction beneath the continental margin in a new direction and orientation, a pulse of contractional deformation along the continental margin, or both; (2) where the trench at the continentral margin strikes more northerly than the newly generated transform (thus decreasing the angle θ of Figure 2), passage of a triple junction tends to induce a pulse of extensional deformation along and near the continental margin; and (3) where the paired triple junctions propagate along a convex plate boundary and thus link cases Ic(X) and Ia(Y) at opposite ends of the same transform, slivers of the bulging plate may be attached successively to the indented plate. This third phenomenon indeed appears to have occurred in the actual San Andreas case.

The triple junction X (Figures 3, 4, and 5) is an analogue of the Mendocino triple junction (Figure 1), and the triple junction Y (Figures 3, 4 and 5) is an analogue of the Rivera triple junction (Figure 1). We can therefore test our general conclusions about the tectonic effects of transient instabilities against the known geologic history of the California region.

Mendocino Triple Junction

The present Mendocino triple junction is clearly unstable in two senses. First, the trend of the Mendocino fracture zone is no longer parallel to the vector of relative motion between the Pacific and Juan de Fuca plates. Silver [1971a] discussed the resulting deformation of the sea floor north of the Mendocino fracture zone and also noted an associated component of underthrusting at the Mendocino fracture zone. Second, and more important for continental geology, the current subduction zone off the Pacific northwest is not in line with the San Andreas transform. Thus the geometry of the Mendocino triple junction is similar to that of case Ic(X) in Figure 5.

Recall, however, that the diagram was constructed with the assumption that plate B' maintained the relative motion of plate B without change. In our case, the Juan de Fuca plate (B') has not maintained the same motion as the Farallon plate (B). Instead, the velocity triangle has changed as indicated in Figure 6. Consequently, the crosshatched area in case Ic(X) of Figure 5 would be slightly smaller if the change in relative motions were taken into account. The associated tendency for extensional deformation near the unstable triple junction would presumably be correspondingly less after the motion change. Moreover, the tendency for extensional deformation might be at least partly counteracted by contractional deformation of the sort expressed now by local underthrusting along the Mendocino fracture zone. From the mapped trends of dated magnetic anomalies on the sea-floor off the Pacific northwest [Silver, 1971a, Figure 4], the time span during which the change in motion occurred was roughly 5 to 7.5 m.y. B.P.

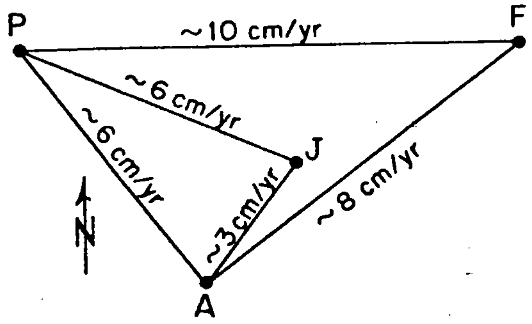


Fig. 6. Approximate velocity triangles relating motions of Pacific (P) and American (A) plates to old Farallon (F) plate (large triangle) and to present derivative Juan de Fuca (J) plate (small triangle). Modified after Atwater [1970] and Silver [1971b]. Implied motion change occurred 5 to 7.5 m.y. B.P. (see text).

Figure 7 is a tectonic sketch map showing structural relationships in central and northern California from which we can infer the general nature of the Mendocino triple junction as it migrated up the coastal region during the Neogene. We focus here on the region north of the Transverse Ranges because the Mendocino fracture zone was approximately in the latitude of that province when the San Andreas transform was first well established about 25 m.y. B.P. [Atwater and Molnar, 1973, Figure 1]. The circled points denote oblique intersections between the San Andreas fault and tectonic trends related to pre-San-Andreas subduction. The numbered circles refer respectively to intersections with the following features: (1) the eastern limit of the late Mesozoic subduction complex on the outcrop or in the subsurface, (2) the position of the main flexure in the Coast Range thrust along which the Franciscan Complex of the subduction zone underthrust the forearc basin in which the coeval great Valley Sequence accumulated, (3) the eastern limit of Paleogene components within the subduction complex; and (4) the currently active subduction zone along the continental margin. Clearly, none of the four trends related to the subduction zone are collinear with the present San Andreas transform. Instead, the geometry suggested by all four intersections is roughly that of Case Ic(X), as qualified for the change in plate motions discussed previously.

Interpretations are unfortunately complicated, however, by the fact that the modern San Andreas fault was not the master slip surface of the San Andreas transform for the full span of time during which the Mendocino triple junction was migrating up the coast. Studies of offset geologic features of different ages on land indicate that slip on the San Andreas fault proper was minor until perhaps 10 to 12.5 m.y. B.P. and that the San Andreas fault itself probably did not become the dominant slip surface within the transform system prior to about 5 to 7.5 m.y. B.P. [Dickinson et al., 1972, Figure 2; Graham and Dickinson, 1978, Figure 4].

The total Neogene offset on the San Andreas fault between the Transverse Ranges and San Francisco Bay (see Figure 7) is only 305 km [Graham and Dickinson, 1978]. By contrast, the net cumulative transform displacement between the Pacific and American plates has been roughly 800 ± 200 km since 25 m.y. B.P. [Atwater and Molnar, 1973, Figure 2]. The indicated discrepancy of about 500 km can be reconciled by postulating that the principal slip surface of the transform system occupied fault zones lying west of the modern San Andreas for more than half of the time that transform motions have been under way. For example, about 115 km of Neogene offset can be inferred for the San Gregorio-Hosgri fault trend [Graham and Dickinson, 1978]. No other fault of comparable magnitude can be discerned on land. Perhaps the main slip surface lay at the continent-ocean interface along the continental slope for a considerable period early in the history of the transform system [Atwater, 1970].

Note that both the continental slope and the San Gregorio-Hosgri fault trend lie generally parallel to the subduction trends that make oblique intersections with the modern San Andreas (see Figure 7). If the vector of relative motion between the Pacific and American plates once had that orientation, then a triple junction migrating parallel to those trends clearly would not experience the tectonic instabilities implied by case Ic(X) of Figure 5.

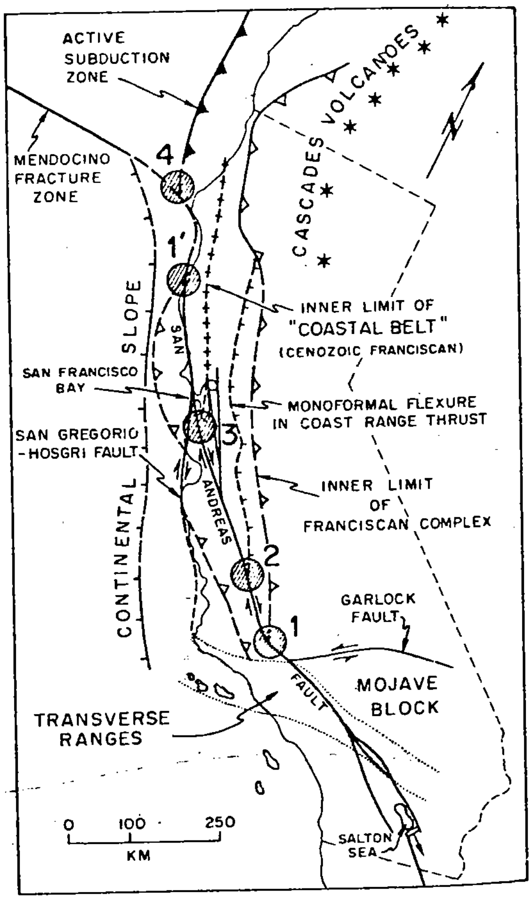


Fig. 7. Sketch map of California (dashed outline) showing places (shaded circles) north of Transverse Ranges where tectonic elements parallel to pre-San-Andreas subduction zone intersect and are offset by San Andreas fault. See text for discussion of numbered points.

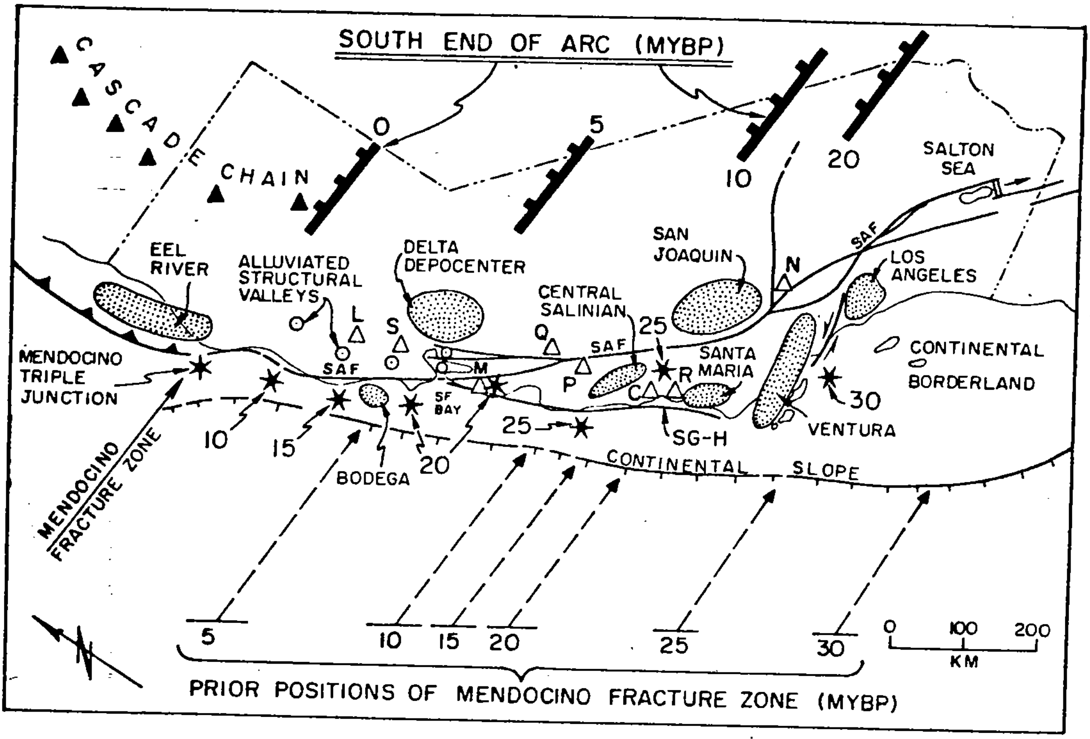


Fig. 8. Sketch map of California (dashed outline) showing approximate prior positions of Mendocino fracture zone with respect to interior North America [after Atwater and Molnar, 1973, Figure 1], coordinate positions of the southern end of the Cascades arc [after Snyder et al., 1976, Figure 7], and asterisks marking the general locations (numbers denote m.y. B.P.) along the continental margin toward which the Mendocino fracture zone impinged within the structural slices bounded by the continental slope, the San Gregorio–Hosgri (SG-H) fault trend, and the San Andreas fault (SAF). Thus the locations of asterisks that are displaced from coordinate positions of the Mendocino fracture zone with respect to the continental interior reflect Neogene slip of coastal slices with respect to the continental interior. Asterisks were positioned by assuming post-Miocene offsets of 305 km on San Andreas fault and 115 km on San Gregorio–Hosgri fault trend [Graham and Dickinson, 1978], but distributed offsets on the order of 50 km net between these two faults were not accommodated. Note that quality of data and complexity of geometry preclude rigorous drafting. Stipples indicate major sedimentary basins of Cenozoic age. Solid triangles are active Cascades volcanoes. Open triangles are major Cenozoic volcanic fields in the coastal region: L, Clear Lake; S, Sonoma; M, Mindego, Q, Quien Sabe; P, Pinnacles; C, Cambria; R, Morro Rock; N, Neenach. Circles with dots are alluviated structural valleys in the northern Coast Ranges.

However, extensional deformation along the continental margin in the vicinity of the migratory triple junction would still be expected if its lateral position with respect to the continental block were intermittently changing in response to shifts in the position of the master transform fault. Such a net shift in position is obviously required to detach from the American plate the continental sliver between the modern San Andreas and the continental slope and to attach it to the Pacific plate [Garfunkel, 1973]. Either pull-apart or fault-wedge basins [Crowell, 1974] could form, depending upon whether shifts in the locus of the dominant faulting took place by en echelon stepping or by bending. On Figure 7, the Salton Sea apparently occupies an active pull-apart basin having the requisite geometry, and the lowlands around San Fancisco Bay may occupy fault-wedge basins related to the splaying of active strands of the San Andreas fault system.

Central California Coast

Some form of extensional deformation, coordinate with the passage of the migrating Mendocino triple junction, is thus seemingly predicted for coastal California by our geometric analysis. Figure 8 was constructed to test for this relationship. We use the rapid subsidence of local sedimentary basins and local volcanic activity as potential indicators of such deformation. The arrows at sea point toward successive reconstructed locations of the Mendocino triple junction relative to the interior of the continent. The general validity of the reconstructions, which were obtained by backtracking global plate motions inferred from patterns of geomagnetic anomalies at sea, is confirmed by independently plotting the southern limit of arc volcanism at coordinate times in the past (see Figure 8). The asterisks show, for the same times, the inferred latitude of the Mendocino triple junction within structural slices along the continental margin west of the San Andreas fault. The asterisks have been placed in their correct offset positions to reflect 305 km of Neogene slip along the San Andreas fault and 115 km of Neogene slip along the San Gregorio-Hosgri fault; for example, the two asterisks marked for 20 m.y. B.P. were at that time adjacent to one another and in line with the dashed line offshore showing the position of the Mendocino fracture zone at 20 m.y. B.P. If passage of the Mendocino triple junction along the coastal region triggered episodes of extensional deformation, the dated arrows and asterisks should be a guide to the timing of pulses of subsidence and eruption in the sedimentary basins and volcanic fields shown on Figure 8.

Clearly, some data need not fit the pattern sought. For example, the Eel River basin is a Neogene forearc basin that still lies north of the Mendocino triple junction, and the Delta depocenter was a Paleogene remnant of a large Mesozoic forearc basin [Dickinson and Seely, 1979]. Moreover, some basins farther south experienced continuing or renewed Neogene subsidence under a wrench regime after transform activity was well under way in their vicinity [e.g., Harding, 1973, 1976]. Thus only the time and style of the initial Neogene subsidence is significant.

For the southernmost examples, the Los Angeles and Ventura basins, marked lower to middle Miocene (22.5-12.5 m.y. B.P.) subsidence [Ingle, 1979] was clearly too late to correspond to passage of the Mendocino triple junction. The intitiation of the paired triple junctions delimiting an incipient San Andreas transform between 30 and 25 m.y. B.P. was quite close to this region [Atwater and Molnar, 1973, Figure 1]. We conclude here that the development of these basins, like those of the nearby continental borderland, was more closely linked to evolution of the Rivera triple junction (see below) than to migration of the Mendocino triple junction.

Farther north in central California, however, the onset of rapid Miocene sedimentation and outbreaks of local volcanism were roughly coeval with inferred passage of the Mendocino triple junction, as the following summary indicates:

1. Eruption of the late Oligocene Cambria Felsite (C, Figure 8) and emplacement of the Morro Rock-Islay Hill porphyry complex (R, Figure 8) occurred about 25 m.y. B.P. [Ernst and Hall, 1974] as the triple junction was passing the appropriate segment of the coastal region (see 25 m.y. B.P. asterisk of Figure 8). Slightly farther south, the younger Obispo Tuff and Tranquillon Volcanics [Turner, 1970] were erupted, however, near the end of the early Miocene (15-17.5 m.y. B.P.) and are here presumed to be related to the middle Miocene opening of the Santa Maria basin (Figure 8) as a pull-apart structure within the San Andreas transform system [Hall, 1979].

2. In the San Joaquin basin [Bandy and Arnal, 1969], rapid late Oligocene and early Miocene subsidence (15-25 m.y. B.P.) achieved maximum water depths at the beginning of the middle Miocene or about 15 m.y. B.P., just after the triple junction had passed (see 15 m.y. B.P. arrow of Figure 8). Basin filling and wrench folding during the middle Miocene (10-15 m.y. B.P.) was followed by renewed late Miocene and Pliocene subsidence (2.5-7.5 m.y. B.P.) that accompanied wrench tectonics in a marginal belt lying beside the nearby San Andreas fault [Harding, 1976].

3. On the central Salinian block [Graham, 1976], abrupt subsidence of fault-bounded basins at the beginning of the Miocene (ca. 22.5 m.y. B.P.) reflected a wave of extensional deformation that coincides well with the passage of the triple junction. At the beginning of the middle Miocene (ca. 15 m.y. B.P.), these basins began to be modified by en echelon wrench folds, from which local throughgoing faults with strike slip developed later in the middle Miocene (ca. 12.5 m.y. B.P.). The onset of central Salinian wrench tectonics in the middle Miocene presumably records an early step in the transfer of the main San Andreas transform from the San Gregorio-Hosgri and other faults now offshore toward the modern San Andreas [Graham, 1976, 1979].

4. The correlative Pinnacles (P, Figure 8) and Neenach (N, Figure 8) volcanic formations [Matthews, 1976], now offset on opposite sides of the San Andreas fault, were erupted about 23.5 m.y. B.P. near the Oligocene-Miocene boundary. Both remaining exposures plot roughly midway between inferred positions of the Mendocino triple junction for 20 and 25 m.y. B.P. (see Figure 8).

5. Radiometric dates for the early Miocene Mindego Volcanics (M, Figure 8) of the Santa Cruz Mountains [Turner, 1970] suggest an age of 20 to 22.5 m.y. B.P., close to the figure of about 20 m.y. B.P. predicted by Figure 8.

6. Limited offshore data [Hoskins and Griffiths, 1971] suggest that the Neogene development of the Bodega basin as a Miocene basin with deep water began during the early or middle Miocene (15-20 m.y. B.P.), as Figure 8 would imply.

7. Unpublished radiometric dates [Powell, 1974] on the Quien Sabe Volcanics (Q, Figure 8) indicate a late Miocene age (7.5-10 m.y. B.P.) in harmony with the inferred passage of the triple junction shortly after 10 m.y. B.P. (see Figure 8). Similar dates of 7.5-11.5 m.y. B.P. [Evernden et al., 1964] on the Grizzly Peak Volcanics of the San Francisco Bay area (see Figure 8) are also compatible with passage of the triple junction nearby.

8. The Sonoma Volcanics (S, Figure 8) are dominantly Pliocene (2.5-5 m.y. B.P.) and hence were erupted mainly during and just after the passage of the triple junction [Mankinen, 1972]. The nearby Clear Lake Volcanics (L, Figure 8) have been erupted entirely since 2.5 m.y. B.P. [Donnelly et al., 1977] and hence are somewhat younger than expected. We are unable to decide whether the motion change of the Juan de Fuca plate (see Figure 6) may have somehow aided the prolongation of volcanism near Clear Lake beyond our predicted time.

We conclude that the timing of salient Neogene events in central California was in general coordinated with the passage of the Mendocino triple junction. We are well aware that other significant events may not be explicable in those terms but argue simply that the notion of an unstable migratory triple junction is one key tectonic concept for understanding the structural evolution of coastal California. Other features that have not been well studied, and are not listed

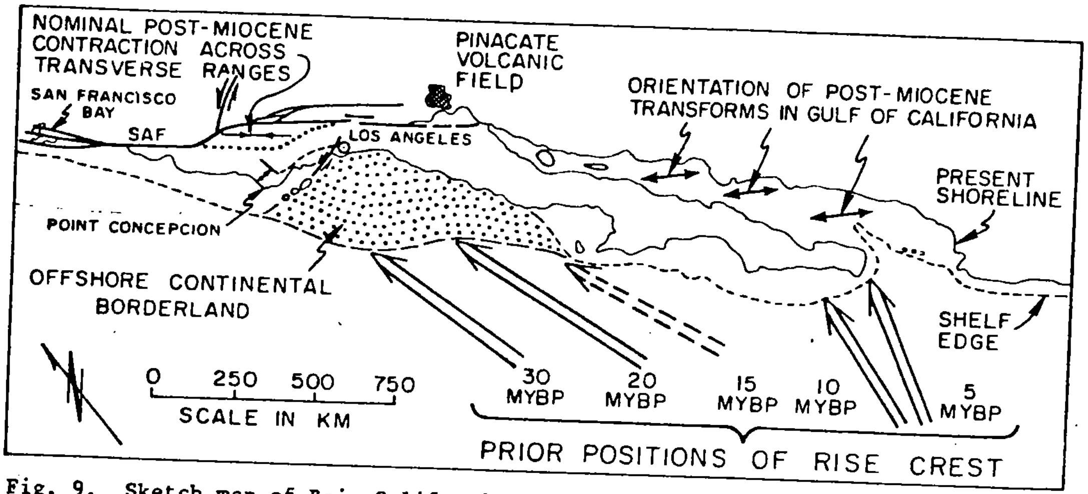


Fig. 9. Sketch map of Baja California and nearby areas showing Neogene tectonic relations prior to 5 m.y. B.P. before the modern Gulf of California opened. Pinacate volcanic field for orientation only. Prior positions of rise crest after Atwater and Molnar [1973, Figure 1], with position at 15 m.y. B.P. (dashed) interpolated from anomaly pattern [Atwater, 1970, Figure 1]. Base map is Mercator projection about Pacific-American rotation pole (see Figure 1). Dashed line and double arrow near Point Conception show restoration of shoreline to recover 60 km [Sage, 1973] of mid-Miocene [Campbell and Yerkes, 1976] sinistral offset on Malibu Coast fault (shown near Los Angeles). SAF is San Andreas fault in central California.

above, may also be related to the passing triple junction. For example, a number of fault-bounded intermontane valleys (circles with dots, Figure 8) harboring thick sequences of nonmarine late Cenozoic deposits are present in the Coast Ranges north of San Francisco Bay [Irwin, 1960]. Somewhat analogous valleys, partly submerged, within the bay area (SF Bay, Figure 8) are probably fault-wedge basins still in process of formation between active strands of the San Andreas system. Some basins farther north, however, are more distant from the active San Andreas and are currently undergoing dissection. Perhaps their origin can be linked to the passage of the triple junction in post-Miocene time.

Rivera Triple Junction

The present Rivera Triple junction is nominally stable geometrically (see Figure 1). However, the adjacent Rivera plate [Molnar, 1973] apparently has existed only since a time about 5 m.y. B.P. near the Miocene-Pliocene boundary [Larson, 1972]. It evidently represents a fragment of the ancestral Farallon plate that is in process of attachment to the American plate. The curved end of the Middle America Trench and the continuing volcanism nearby on land to some extent are residual indicators of Rivera-American subduction that is diminishing as time passes [Larson, 1972]. By this interpretation, the Rivera triple junction, defined as the southern end of the San Andreas transform, will soon shift to a position at the southern apex of the present Rivera plate (see Figure 1) where the larger Pacific, American, and Cocos plates will then meet. The transient existence of a small Rivera plate is thus circumstantial evidence that migration of the Rivera triple junction can involve instabilities (Figure 5) that could have influenced the structural evolution of the coastal region between the Transverse Ranges and the mouth of the Gulf of California. Figure 9 is a sketch map of Baja California and adjacent regions designed to test that possibility. The map was constructed by restoring the Gulf of California to the closed position that existed about 5 m.y. B.P. before spreading began in the mouth of the Gulf [Atwater, 1970].

The trends of the younger transforms active during the later opening of the Gulf of California (see Figure 9), when compared to the trend of the continental margin, suggest that the Rivera triple junction may have had the unstable configuration of case Ic(Y) in Figure 5 for much of its passage down the coast. We infer that the resulting extensional deformation of the continental margin was responsible for the initial formation of the deep fault-bounded basins within the California Continental Borderland off southern California and Baja California (see Figure 9). The absence of a comparable structural province farther south off Baja California may reflect a period of very rapid migration of the triple junction as a segment of the rise crest pivoted into the subduction zone [Menard, 1978].

The early history of the borderland basins is commonly inferred from drill data in the Los Angeles basin (see Figures 8 and 9), which is interpreted as a filled borderland basin now on land. Major subsidence began there near the beginning of the middle Miocene about 15 m.y. B.P. [Yerkes et al., 1965]. Coeval volcanism was widespread around the northern borders of the Los Angeles basin and in the Channel Islands along strike with the Malibu Coast fault (see Figure 9) along the northern fringe of the borderland [Turner, 1970]. The tectonic geometry portrayed in Figure 9 is fully compatible with extensional deformation of the requisite type implied by case Ic(Y) of Figure 5, and at the appropriate time for the Los Angeles region, toward which our reconstruction of the 15 m.y. B.P. rise crest points (see Figure 9). However, Figure 9 predicts that the onset of the pulse of extensional deformations should be somewhat older farther west and in the offshore borderland. Data suggestive of this effect have been reported by Ingle [1979], who infers that peak subsidence rates and maximum water depths in the Ventura basin were achieved in the early Miocene (15-20 m.y. B.P.), slightly sooner than the same conditions were reached in the middle Miocene (12.5 m.y. B.P.) for the Los Angeles basin. The Ventura basin (Figure 8) lies to the northwest of the Los Angeles basin between Los Angeles and Point Conception (see Figure 9). Complicated subsequent patterns of subsidence, deformation, and uplift in the Ventura basin during the latest Miocene and Pliocene were probably related in some way to complex transform movements within the established San Andreas system [e.g., Crowell, 1976]. This part of its history is related to the origin of the present Transverse Ranges.

Even given the inherent uncertainties in the reconstructions of the past rise crests shown on Figure 9, some relationship between the Miocene rise crest and the origin of the continental borderland is difficult to avoid. In the offshore borderland, all the basins began to form in Miocene time and the basins appear to be sequentially younger eastward in the borderland area [Blake et al., 1978, p. 358], as our model would predict. Moreover, volcanism was most widespread about 20-25 m.y. B.P. in the western borderland, but about 15-20 m.y. B.P. in the eastern borderland. We prefer the relationship specified by case Ic(Y) in Figure 5 but note that Campbell and Yerkes [1976] have independently proposed a slightly different rationale that also in effect ties the inception of the Los Angeles basin to the passage of the triple junction. Much of the structural relief and bathymetry in the present offshore borderland dates, however, only from the latest Miocene or even the Pliocene [Doyle and Gorsline, 1977]. It must be assumed, therefore, that any initial Miocene configuration of the borderland has been extensively modified by later rift or wrench tectonics that postdated the passage of the Rivera triple junction.

The opening of the Gulf of California was a discrete event that began near the Miocene-Pliocene boundary shortly after 5 m.y. B.P. Given the slight bulge in the outline of the continental block near the southern tip of Baja California (see Figure 9), case Ia(Y) of Figure 5 may apply to the Rivera triple junction of 4 to 5 m.y. B.P. If so, the diagram may explain why the San Andreas transform shifted at that time from a position along the continental slope west of Baja to its present position east of Baja [Atwater, 1970; Atwater and Molnar, 1973]. Because there is an oblique extensional component of motion within the Gulf of California, this shift is often viewed as a ridge jump, but it is better regarded as a transform jump. Prior to the shift of the San Andreas transform into the Gulf, intra-Miocene dextral slip of about 200 to 250 km is required along the western side of Baja California [Atwater and Molnar, 1973, Figure 2; Normark, 1977]. An elongate field of en echelon Neogene folds and faults along the continental slope and outer shelf off southern Baja California probably reflects wrench tectonics related to this paleotransform motion [Normark, 1977].

Finally, case Ia(Y), or possibly Ia(X), of Figure 5 may conceivably have application for some parts of Miocene history along the northern fringe of the continental borderland where east-west trends are prominent now along the edge of the main continental block For example, the mid-Miocene volcanic rocks of the Channel Islands and the Malibu coastal region west of Los Angeles (Figure 9) are an andesitic suite of the sort related elsewhere to subduction rather than to extensional tectonics [Crowe et al., 1976; Higgins, 1976]. Perhaps a short-lived subduction zone having the general geometric relations shown by one of our diagrams can be invoked to explain this occurrence.

Conclusions

1. The geometry of migratory triple junctions related to the San Andreas transform has implications for local tectonic regimes.

2. The paired Mendocino and Rivera triple junctions at the ends of the San Andreas transform have had transient unstable configurations during their Neogene migration along the continental margin.

3. Successive episodes of Neogene extensional tectonics along the central California coastal region coincided with passage of the Mendocino triple junction; they are reflected by pulses of initial subsidence in local sedimentary basins and by eruptions at local volcanic centers.

4. The inception of the California Continental Borderland was triggered by passage of the migratory Rivera triple junction.

5. The carving of a crustal slice from the North American continent by the San Andreas transform, and the attachment of that continental slice to the Pacific plate, reflects the migration of unstable triple junctions in opposite directions along a convex oceanward bulge in the continental margin.

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