INGERSOLL 1982

Triple-junction instability as cause for late Cenozoic extension and fragmentation of the western United States

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ABSTRACT

Regional extension in the western United States began soon after 30 m.y. B.P., the time of first interaction between the Pacific and North American plates. Previous explanations for extension include lithospheric-active processes and asthenospheric-active processes; the former are favored because of coincidence of timing with lithospheric interactions, relative timing of volcanism and deformation, and coincidence with pre-existing structures. Although extension has occurred, in part, in a back-arc setting, it cannot be attributed to age of subducted crust or azimuth of subduction, because both attributes favor back-arc contraction (characteristic behavior before 40 m.y. B.P.

The Mendocino triple junction has been unstable since its inception. The continental margin was relatively straight before 30 m.y. B.P., and it has become more convex westward as the triple junction has migrated northward. The continental margin and arc have been anchored to the subducting slab (Farallon–Juan de Fuca), whereas the triple junction must move parallel to the San Andreas transform. The combined result has been the northwestward and clockwise movement of coastal blocks relative to the continental interior and the eastward stepping of the San Andreas transform relative to the coast. These effects result from the unstable geometry of the Mendocino triple junction. Lack of a subducted slab (slab window) beneath the extended lithosphere enables asthenospheric rise but does not cause extension.

INTRODUCTION

Many hypotheses have been proposed to explain late Cenozoic crustal extension and fragmentation of the western United States. These hypotheses may be divided into two classes: those involving lithospheric processes as the driving forces and those involving asthenospheric processes as the driving forces. Most explanations of the former type involve distributed shear (Atwater, 1970; Christiansen and Lipman, 1972; Livaccari, 1979), whereas most explanations of the latter type involve mantle upwelling (Dickinson and Snyder, 1979b; Eaton and others, 1978; Scholz and others, 1971). None of these explanations is completely satisfactory, although lithospheric-active processes seem favored because of coincidence of timing of extension with lithospheric interactions, relative timing of magmatism and deformation, and coincidence of deformation with pre-existing structures (Ingersoll, 1981). [See Baker and Morgan (1981) and Sengor and Burke (1978) for reviews of criteria for distinguishing these two types of crustal extension.]

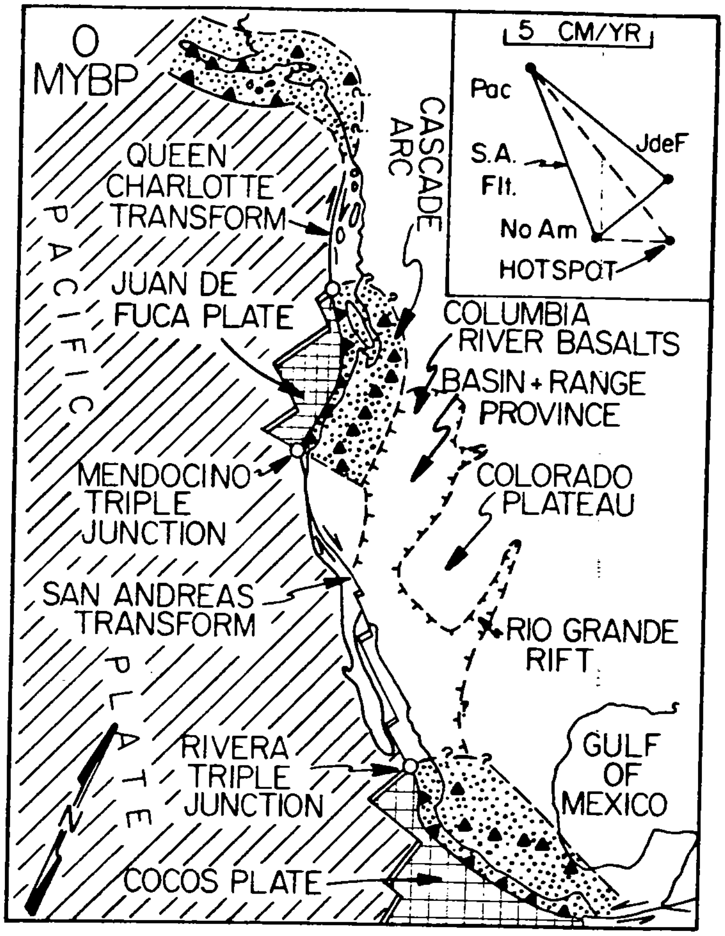

Figure 1. Location and tectonic map of western United States at present (after Dickinson, 1979), showing major tectonic features discussed in text. Vector triangle shows modern relative motions of Pacific, North American, and Juan de Fuca plates. Tick marks denote areas of major crustal extension. Triangles denote active magmetic-arc volcanoes.

Regional extension in the western United States began soon after 30 m.y. B.P. in many areas (best documented in the Rio Grande rift; for example, Chapin, 1979; Chapin and Seager, 1975; Lucas and Ingersoll, 1981; Riecker, 1979). This extension has corresponded to development of the San Andreas transform, which began soon after 30 m.y. B.P. (Atwater, 1970; Atwater and Molnar, 1973). Initiation of extension did not correspond to initial steepening of the subducted slab (at about 40 m.y. B.P.; Coney and Reynolds, 1977; Dickinson, 1979; Keith, 1978). Timing and style of deformation and magmatism have varied greatly from location to location, but an overall regime of crustal extension has dominated the late Cenozoic evolution of virtually the entire western United States (Hamilton and Myers, 1966). Although extension has occurred, in part, in a back-arc setting (Fig. 1), it cannot

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be attributed to age of subducted lithosphere (Molnar and Atwater, 1978) or azimuth of subduction (Moore, 1973), the two most likely causes of back-arc spreading in general. The subducting lithosphere has been young, and the polarity of subduction has been west-facing during the late Cenozoic; both of these attributes favor back-arc contraction (Dickinson, 1978), which was the characteristic behavior of the arc-trench system prior to about 40 m.y. ago (for example, Dickinson and Snyder, 1978). Thus, another mechanism apparently is necessary to explain late Cenozoic extension in this unique setting. I have proposed (Ingersoll, 1981) that regional extension and fragmentation is the natural consequence of the geometry of the Cape Mendocino triple junction, as outlined below.

The purpose of this paper is not to review all that is known about late Cenozoic tectonics of the western United States (see, for example, Davis, 1980; Dickinson, 1979; Eaton, 1980; Hamilton and Myers, 1966; Lucas and Ingersoll, 1981; Riecker, 1979; Smith and Eaton, 1978), nor is it to outline all of the consequences in terms of timing and local style of deformation. Rather, the purpose is to show how extension and fragmentation are the natural consequences of the complex plate interactions that have occurred as the Cape Mendocino triple junction has evolved. Details of stress orientations, fault geometries, geophysical responses, magmatism, and other manifestations are local responses to these plate interactions and are influenced greatly by previous history. Local responses of the lithosphere undoubtedly are complex, but I feel that the broad coincidence of regional timing of deformation and magmatism throughout the western United States warrants examination of the hypothesis outlined below.

GEOMETRY OF PLATE INTERACTIONS

Atwater (1970), Dickinson and Snyder (1979a), and McKenzie and Morgan (1969) have outlined the geometric characteristics of evolving triple junctions in general, as well as many of the details of the Mendocino triple junction. The reader is referred to these papers for discussion of the methods employed in the following analysis.

Figure 2 shows an idealized FFT triple junction with colinear trench and transform, geometry similar to the Mendocino triple junction. This is the geometry used by Atwater (1970) and McKenzie and Morgan (1969). It is a stable configuration as long as the northwest-trending fault is parallel to the subduction zone, a potential coincidence that remains unexplained (Dickinson and Snyder, 1979a; McKenzie and Morgan, 1969). A more realistic depiction of the modern Mendocino triple junction is shown in Figure 3. The Cascade subduction zone is *not* parallel to the San Andreas fault; thus, the triple junction is *not* stable. In fact, the Mendocino triple junction probably has been unstable since its inception, because it is unlikely that Pacific-American movement was exactly parallel to the subduction zone between the Farallon (Juan de Fuca) and American plates. The continental margin probably was relatively straight before interaction between the Pacific and American plates (see Hamilton and Myers, 1966), but the likelihood of this margin being parallel to Pacific-American relative motion before encounter of these two plates seems remote.

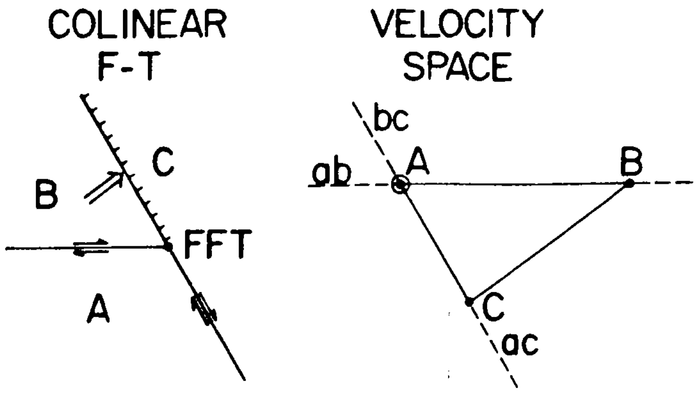


Figure 2. FFT triple junction with colinear fault and trench (left). Velocity triangle (right) indicates that configuration is stable (see McKenzie and Morgan, 1969). Velocities shown are those that probably existed before about 7.5 m.y. B.P. (see Fig. 6 of Dickinson and Snyder, 1979a). Vector triangle of Figure 1 reflects modern motions.

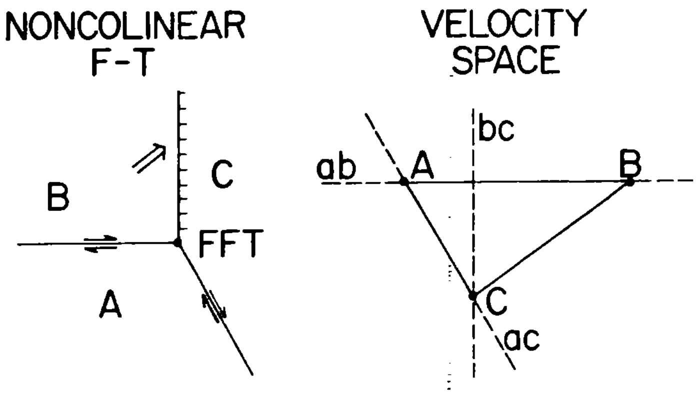


Figure 3. FFT triple junction with noncolinear fault and trench (left). Velocity triangle (right) indicates that configuration is unstable (see McKenzie and Morgan, 1969). This is more realistic portrayal of Mendocino triple junction during most of its history than is Figure 2.

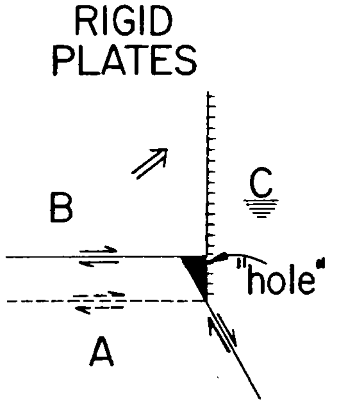
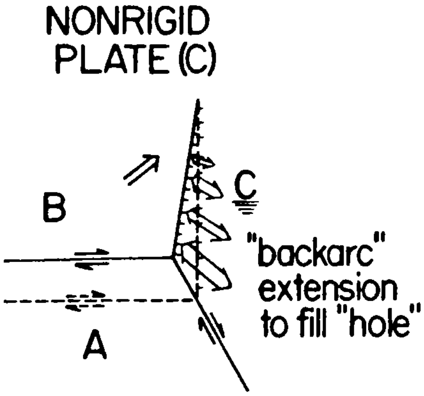


Figure 4. Evolution of triple junction shown in Figure 3 (dashed line) with plate C arbitrarily held fixed. If three plates are rigid, a "hole" forms (see text for discussion).

There are two types of processes by which the unstable triple junction (Fig. 3) can persist. If the three plates are truly rigid and nondeformable, then a "hole" must form (Fig. 4). This "hole" would have to be filled by "oceanic" crust formed from rising mantle material and/or by sedimentary and volcanic rock derived from the surrounding plates. Microplates complete with spreading centers could develop in such a setting. The other process by which the triple junction can persist involves internal deformation of one or more of the (nonrigid) plates (Fig. 5). Carlson (1981) and Silver (1971a, 1971b) have discussed evidence for internal deformation of the Juan de Fuca plate as well as for the partially nontransform nature of the Mendocino escarpment. Dickinson and Snyder (1979a) suggested that extensional tectonics in the form of basin formation and magmatism along the California coast has

Figure 5. Evolution of triple junction shown in Figure 3 (dashed lines) with plate C arbitrarily held fixed. If two oceanic plates (A and B) are rigid, but continental plate (C) can deform (nonrigid), then plate C is extended over wide zone, some of which is in back-arc setting and some of which is east of transform fault (San Andreas).



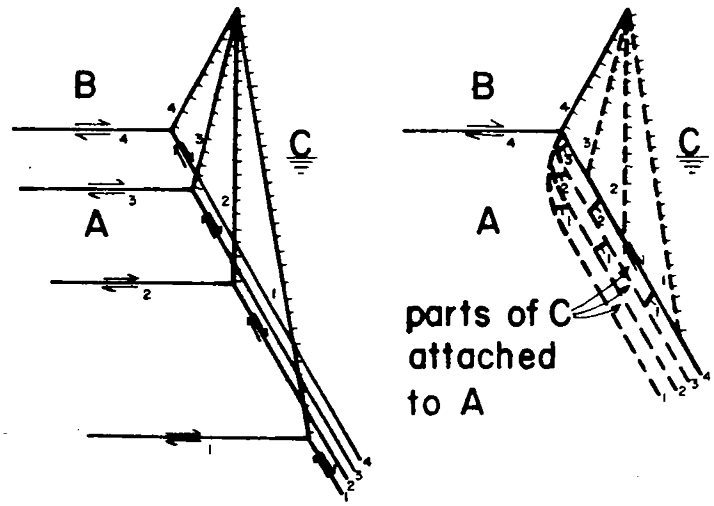


Figure 6. Sequential development of plate boundary between Pacific (A) and North American (C) plates as motion shown in Figure 5 continues. Left diagram shows location and orientation of triple junction and plate boundaries at four moments in time (1 through 4) in frame of reference of plate C. Right diagram shows cumulative deformation as transform (San Andreas) steps inland (eastward relative to C) and continental margin of C is rotated clockwise (with extension of C, as shown in Fig. 5). Note that southwest extensions of former continental margin are rotated clockwise, with southwesternmost pieces undergoing greatest rotations and greatest northwestward transport because they have been part of plate A for longer time. This geometric model explains four characteristics of late Cenozoic tectonics of western United States: (1) major blocks (for example, Sierra Nevada) have been rotated northwestward; (2) regional extension has occurred to east of these blocks; (3) small coastal blocks have been rotated clockwise and northwestward; and (4) San Andreas transform has stepped eastward, thus transferring coastal blocks to Pacific plate. In the process, extension and shear have occurred to southeast of coastal blocks (for example, opening of Gulf of California).

been the result of the northward migration of the unstable triple junction. In addition, they suggested that the inward (eastward relative to the United States) stepping of the active strands of the San Andreas transform has been the result of triple-junction instability.

Internal deformation of the heterogeneous continental crust of the western United States along pre-existing zones of weakness probably is the most likely process by which the triple junction can persist (Fig. 5). Prior to 30 m.y. B.P., much of the western United States experienced a long and complex history of magmatism and tectonism. The Great Basin area was affected by the Antler, Sonoma, and Sevier orogenies, among others (Burchfiel and Davis, 1972, 1975), and the area of the Rio Grande rift was affected by the ancestral Rocky Mountain and Laramide orogenies (Chapin and Seager, 1975; Kluth and Coney, 1981). During subsequent regional extension, these areas have been pulled apart. In contrast, regionally coherent crustal blocks such as the Colorado Plateau have undergone minor extension, just as they underwent minor internal compression during Laramide deformation (for example, Chapin and Cather, 1981; Hamilton, 1981).

Location of magmatic arcs during various stages of development of the triple junction (for example, modern Cascade arc) has been determined by the geometry of the subducted slab (for example, Dickinson and Snyder, 1979b). The arc has been geometrically locked onto the subducting slab. In contrast, the triple junction must move northwestward parallel to the San Andreas transform. The combined result in the case of nonparallel transform and trench (Fig. 3) is the northwestward and clockwise movement of coastal blocks relative to the interior (Figs. 5, 6). Another consequence is the inward stepping of the San Andreas transform, thus transferring parts of coastal California to the Pacific plate (Fig. 6).

DISCUSSION

The geometry and sense of deformation predicted by this simple model are identical to the type of deformation suggested by paleomagnetic data (see Fig. 4 of Magill and Cox, 1981). Bates and others (1981), Beck (1980), and Magill and Cox (1981) have discussed paleomagnetic evidence for major clockwise rotation and fragmentation of coastal parts of the western United States. Major coherent crustal blocks such as the Sierra Nevada batholith have rotated northwestward, resulting in extension along pre-existing zones of weakness. An additional result has been the increasing convexity of the continental margin, as envisaged by Hamilton (1975) and Hamilton and Myers (1966) (Fig. 6).

Possible modifications to this simple model include interactions involving the Rivera triple junction, which likely has been unstable for much of its existence (since 30 m.y. B.P.) (Dickinson and Snyder, 1979a). Instability of both triple junctions while in proximity soon after 30 m.y. B.P. probably was expressed in complicated ways along the southern California coast and inland in the southern Basin and Range province. An additional complication of this simple model is that three-plate relative motions at the Mendocino triple junction have changed through time (Atwater, 1970; Dickinson and Snyder, 1979a; Silver, 1971b). Therefore, local and regional orientations of stress and deformation have changed. If, however, the basic unstable geometry of the triple junctions has persisted, then the geometric necessity for regional and or local extension must have persisted, but with temporal and geographic variations in its expression. A more thorough knowledge of relative plate motions might delineate times of greater and less stability, which might have been expressed in changes in regional extension.

Several authors (for example, Lipman, 1981; Zoback and Thompson, 1978) have noted that regional orientation of extension changed from northeast-southwest to northwest-southeast during the Miocene. This clockwise rotation of extension direction [see Fig. 10 of Lipman (1981) and Fig. 6 of Zoback and Thompson (1978)] is consistent with the model presented here. Note that present extension direction in both the Great Basin and the Rio Grande rift is directed toward the Mendocino triple junction. Nonetheless, an alternative cause for clockwise rotation of extension direction may be reorientation of three-plate motions.

Kilty (1981) has discussed the difficulties involved in using distributed shear alone to explain extension in the western United States, as suggested by Atwater (1970), Christiansen and Lipman (1972), and Livaccari (1979). Specifically, Kilty has demonstrated that the concept of a continental buttress (Livaccari, 1979) as the reason for lack of extension east of the Queen Charlotte fault (Fig. 1) is not valid. The lack of an unstable triple junction at the north end of the Queen Charlotte fault is consistent with the lack of extension if the model presented here is valid.

In summary, the geometry of the Mendocino triple junction alone necessitates regional extension in at least one of the plates. Magmatism, geophysical responses of the lithosphere and asthenosphere, structural deformation, and other local expressions of tectonism probably are the results of these lithospheric interactions. The presence of a slab window beneath the modern area of greatest extension (Dickinson and Snyder, 1979b) probably has facilitated asthenospheric rise as a response to regional extension and may constrain the area of extension. However, the driving force of regional extension appears to be the triple-junction geometry. This hypothesis should be tested.

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ACKNOWLEDGMENTS

Reviewed by W. R. Dickinson, S. A. Graham, and W. R. Seager.

Manuscript received April 12, 1982
Revised manuscript received June 28, 1982
Manuscript accepted July 7, 1982