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# On the origin of the Cocos-Nazca spreading center


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## ABSTRACT

**To investigate the mechanism underlying the break-up of the Farallon plate into the Cocos plate and Nazca plate, we analyze the state of stress in the Farallon plate at about 30 m.y. B.P., just prior to the fragmentation. To this purpose we use finite element methods and a reconstruction of regional plate boundaries appropriate for 30 m.y. B.P. A key role in the model is played by the dependence of two important plate-tectonics forces (slab pull and ridge push) on the age of oceanic lithosphere. The results show a highly tensional stress field, with maximum principal stresses of 5 to 6 kbar. North-south tension in the vicinity of present-day Panama is proposed to have been the cause for the fragmentation of the Farallon plate and the inception of spreading along the new Cocos-Nazca plate boundary. Because the kind of plate interaction that gave rise to the high level of tensional stresses in the Farallon plate is not restricted to the area of this study, the proposed mechanism seems to shed light on the problem of fragmentation of oceanic plates in general.**


## INTRODUCTION

In the past decade marine geophysical studies have elucidated many features of the apparently very complex Cenozoic history of the east-central Pacific (Herron, 1972; Handschumacher, 1976; Hey, 1977; Mammerickx and others, 1980). From these investigations the break-up of the former Farallon plate into the Cocos plate and the Nazca plate, which took place at about 25 to 30 m.y. B.P., emerges as a milestone in the tectonic evolution of this area. However, the amount of attention given so far to the mechanism that caused the splitting of the Farallon plate does not reflect the importance of this event. In fact, it is limited to some tentative suggestions. For example, Hey (1977) suggested that the Cocos-Nazca spreading center (or alternatively, the Galapagos spreading center) "was born about 25 m.y. B.P. when an old Pacific-Farallon fracture zone opened in response to a new stress pattern in this area." Lonsdale and Klitgord (1978) hypothesized that the Farallon plate was subject to divergent gravitational stresses from the Middle America Trench and the South American trench system. Furthermore, Van Andel and others (1971) postulated the splitting of an east-trending ridge (the "ancestral Carnegie Ridge") in an attempt to explain the origin of the young Panama Basin. Menard (1978) discussed the fragmentation of the Farallon plate, but he concentrated on the relative motion of the fragmented parts rather than on the fragmentation process itself.

In the present context it is important to be aware of the changes brought about by the approach of the Pacific-Farallon spreading center to the western margin of the North and South American continent. Not only did the approach cause a continuous change in geometry of the Farallon plate, but also it caused lateral and temporal variations in the age of the lithosphere present at the trench system along the eastern boundary of the plate. As will be discussed below, several important forces acting on a lithospheric plate are a strong function of the age of the lithosphere in or near a subduction zone. Therefore, the stress field in the Farallon plate was subject to temporal variations as well.

Here we investigate the state of stress in the Farallon plate at about 30 m.y. B.P.—that is, just prior to the breakup—in order to see whether the stress field provides a clue to understanding the fragmentation. To this purpose we use finite element methods and a reconstruction of regional plate boundaries and forces appropriate for 30 m.y. B.P. Modeling the plate as being elastic allows us to derive the state of stress directly from the instantaneous forces acting on the plate.

Results obtained in previous work (Vlaar and Wortel, 1976; England and Wortel, 1980; Wortel, 1980) led us to take into account, as a new feature in modeling the state of stress in lithospheric plates, that important driving forces such as the slab pull and the ridge push depend on the age of the oceanic lithosphere involved. Of particular interest are the results obtained by

England and Wortel (1980), who investigated the relation between the forces acting at a convergent plate boundary and the nature of the tectonic regime in the overriding plate above a subducted slab. In view of the strong dependence of the gravitational pull of a slab on the age of the descending lithosphere (see England and Wortel, 1980), they suggested that below a critical age the driving forces may not be able to overcome the resistive forces acting in the subduction zone or at the plate contact. If, in a changing pattern of plate motion, lithosphere younger than this critical age would arrive at an active trench, subduction would be continued only if the young lithosphere would actively be driven into the subduction zone by forces acting on adjacent segments of the plate or if the "upper" plate (usually of the continental type) would actively overthrust the young slab. In both cases a compressive regime is expected in the overriding plate. If the forces promoting subduction are great enough to overcome the resistive forces, there is no need for compression in the overriding plate and possibly a tensional regime may be observed, as a result of the retrograde motion of the subducting slab. From a compilation of observations, it was found that a transition from tensional to compressional regimes, corresponding to a net resistive force per unit width along the trench of $8 \times 10^{12}$ N/m, indeed takes place. The age at which this transition occurs varies from about 40 to 70 m.y., depending on the vertical velocity of the sinking slab.

As the intersections of the Pacific-Farallon spreading center with the trench system (see Fig. 1) implied lateral variations in the age of the lithosphere at the trench, these findings appear to be quite relevant to the problem of modeling the forces that acted on the Farallon plate. Preliminary results of this work were reported by Wortel and Cloetingh (1979).

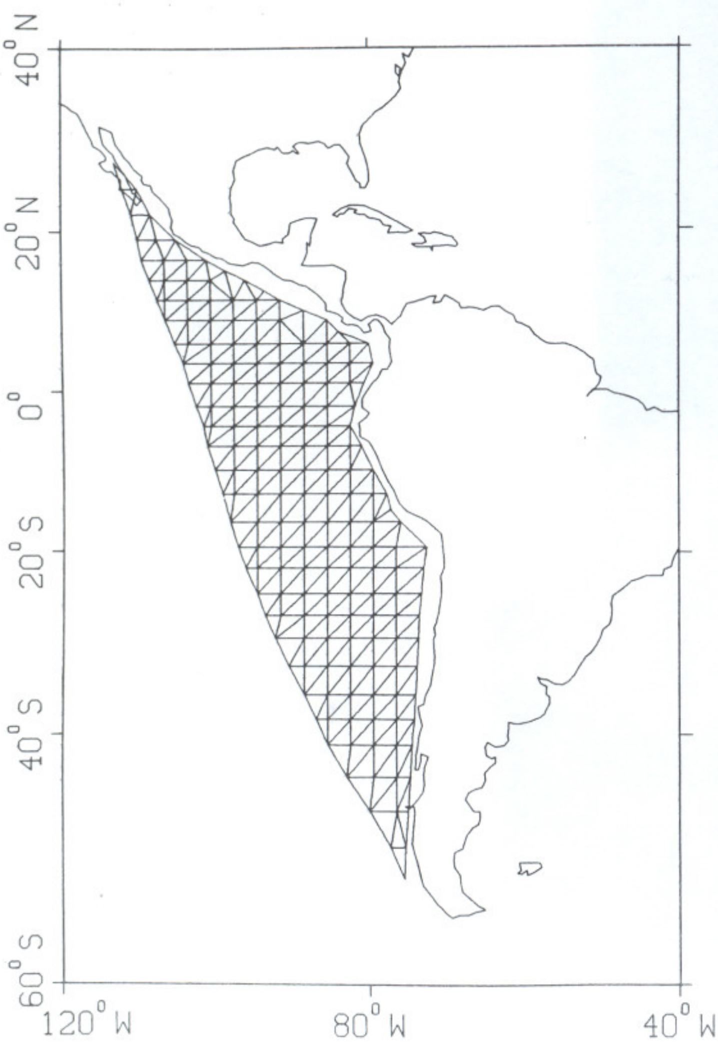


**Figure 1. Mesh used in finite element calculations of stress field of Farallon plate (approximate configuration of 30 m.y. B.P.). Mesh consists of 311 triangular membrane elements with a quadratic displacement field (linear strain).**

## MODEL

The plate boundaries adopted for the model of the Farallon plate at 30 m.y. B.P. and the mesh used in the calculations are shown in Figure 1. From present-day northwest Mexico to southern Chile we envisage the presence of a continuous trench system. This is justified because the subduction zones beneath Mexico and western South America have been active since at least the Late Cretaceous, whereas beneath Central America subduction began during the Eocene (see Malfait and Dinkelman, 1972). The spatial discrepancy between the mesh boundary and the coastline of northwestern Mexico is not relevant in the context of our model, because it is due to the opening of the Gulf of California, which took place *after* 30 m.y. B.P. Karig and others (1978) and Moore and others (1979) have presented strong evidence for truncation and accretion in some segments of the Middle America Trench; therefore, the boundary between the Farallon plate and Mexico–Central America may have been somewhat different from the one depicted in Figure 1. However, it will be shown below that the basic features of the model are not affected by these uncertainties. The location of the northern ridge-trench intersection at 30 m.y. B.P. is taken from Atwater (1970). The location of the southern intersection is somewhat uncertain. From various lines of evidence—for example, the plate boundaries reconstructed for 55 m.y. B.P. (Jurdy and Van der Voo, 1975) and the presence of a sediment-filled trench off western South America south of 45°S—the position indicated in Figure 1 may be taken as a reasonable estimate (see also Barker and Griffiths, 1972, for a discussion of this topic). Because we do not model the ridge push as a line force (see below), the detailed configuration of the ridge is not very important. Therefore, the ridge is modeled without any offsets along transform faults.

The model plate is taken to be elastic (Young's modulus $E = 7 \times 10^{10}$ N/m² and Poisson's ratio $\upsilon = 0.25$), with a thickness of 100 km. This thickness is only used as a reference value. As we use a plane stress approximation, the stresses in an elastic plate with a thickness different from this reference value can be derived directly from those obtained for the model plate: for all thicknesses for which the plane stress approximation is valid, the product of average stress and plate thickness is constant. The spherical surface was approximated by an assembly of 311 triangular membrane elements. The stress calculations were made with the ASKA package of finite element routines (Argyris, 1979), which employs a *quadratic* representation of the displacement field (linear strain).

Following Richardson and others (1979), we assume that the state of stress in a lithospheric plate is determined to a large extent by plate-tectonics forces. The forces considered to act on the plate are the driving forces $F_{sp}$ (slab pull) and $F_{rp}$ (ridge push) and the resistive forces $F_{tr}$ (resistance at the trench and in the subduction zone) and $F_{dr}$ (drag at the base of the lithospheric plate). The slab pull and the ridge push were calculated according to Richter and McKenzie (1978). It can be shown that per unit width along the trench, the slab pull $F_{sp}$, resulting from the density contrast between the cold descending slab and the surrounding upper mantle, depends on the thickness $L$ of the subducted slab according to $F_{sp} \propto L^3$. It is generally agreed that $L$ depends on the square root of the lithospheric age ($t$) for $t < 70$ m.y. (see, for example, Parsons and McKenzie, 1978). Therefore, for these ages, $F_{sp} \propto t^{3/2}$. Because of the reduced rate of thickening of $L$ for $t > 70$ m.y., the age dependence of $F_{sp}$ is somewhat weaker for old lithosphere. The possible contribution of the olivine-spinel phase change to the slab pull is neglected. As will be shown below, this does not seriously affect our results and conclusions. Similarly, it was found (Richter and McKenzie, 1978; England and Wortel, 1980) that for $t < 70$ m.y., the ridge push $F_{rp}$ (per unit width parallel to the ridge) depends linearly on the lithospheric age near the trench. This ridge push, acting on the oceanic lithosphere in the trench region, should be considered as the integrated value of a horizontal pressure gradient

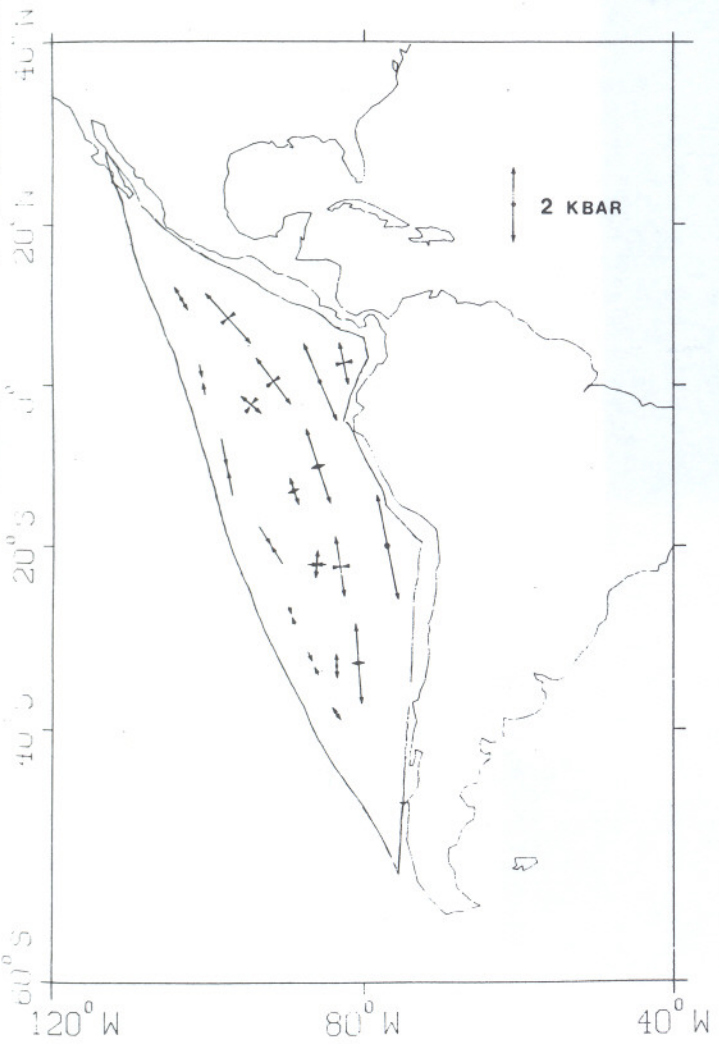


Figure 2. Results of modeling state of stress in Farallon plate under reconstructed conditions of 30 m.y. B.P., prior to break-up of Farallon plate. Stresses were calculated for elastic plate with thickness of 100 km (see text).

(Lister, 1975; Hager, 1978). Accordingly, in our model calculations the total ridge push was distributed over the area of the plate.

In view of the age dependence of both $F_{sp}$ and $F_{rp}$, we need to know the lithospheric age pattern in the Farallon plate, in particular the ages along the trenches. Because the geometry of our model is simplified (the offsets in the ridge are neglected), an assessment of only the gross features of the age pattern is warranted. Such an assessment was made by using Handschumacher's (1976) Oligocene rotation pole (70°N, 145°W) for the spreading along the Pacific-Farallon ridge in combination with the requirement that the age of the lithosphere at the trench off northern Chile had to be 75 to 80 m.y. The latter value is a conservative extrapolation of the results obtained by Wortel and Vlaar (1978). These authors showed that the age of the oceanic lithosphere at the South American trench system has been lower in the late Tertiary, owing to the fact that the convergence rate has been higher than the half-spreading rate at which the descending lithosphere was originally created at the Pacific-Farallon spreading center.

Furthermore, the slab pull $F_{sp}$ depends on the convergence rate $v_c$ (see Richter and McKenzie, 1978) and the dip angle $\phi$ of the descending slab as $F_{sp} \propto v_c \sin \phi$; thus, $F_{sp}$ varies linearly with $v_z$, the vertical velocity of the subducted slab. It was shown by Wortel (1980) that present-day subduction zones display the following characteristics: $2 \lesssim v_z \lesssim 3.5$ cm/yr for oceanic lithosphere younger than 65 m.y. and $4 \lesssim v_z < 6$ cm/yr for lithosphere older than 100 m.y. In our model we used 3 cm/yr and 5 cm/yr as representative values for these two age groups and linearly interpolated velocities for the intermediate ages.

In other studies of stress in the lithosphere (see Richardson and others, 1979), the resistive forces acting at a convergent plate boundary appeared to be most difficult to model. Various mechanisms may contribute to the plate interaction, and as yet no detailed model has been established. Therefore, we follow England and Wortel (1980) and take the total resistive force per unit width along the trench to be $8 \times 10^{12}$ N/m. The buoyancy effect of the stable petrological stratification of the oceanic lithosphere, according to Oxburgh and Parmentier's (1977) model, accounts for $4 \times 10^{12}$ N/m. The remaining resistance of $4 \times 10^{12}$ N/m is attributed to shearing forces acting along the plate contact and along the slab's interfaces.

To ensure mechanical equilibrium, the net torque on the plate is required to vanish. The drag at the base of the lithosphere is determined from the torque balance. Without having to adjust Handschumacher's (1976) pole position, we found that a constant resistive shear stress of 8 bar, acting at the base of the plate and in the direction derived from the position of the pole, balances the torques.

## RESULTS AND DISCUSSION

The resulting stress field in the Farallon plate under the reconstructed conditions of 30 m.y. B.P. is displayed in Figure 2. The accuracy of the finite element solution was checked and confirmed by convergence tests and an analysis of the internal reaction forces of the model. The high tensional stresses near the trench constitute the most conspicuous feature of the stress field.

In Figure 3 two mechanisms are indicated that may account for tensional stresses in a plate (labeled plate I) attached to a subducted slab. In Figure 3a the forces $F_A$, $F_B$, $F_C$ represent the downdip gravitational pull exerted by the descending lithosphere. If these slab-pull forces are not totally balanced by resistive forces acting on the dipping slab—that is, if a net pull is transferred to the horizontal part of the plate—they will cause tensional stresses in the plate. Similarly, if only, or predominantly, the driving forces in the direction of plate convergence are balanced by resistive forces (shearing forces parallel to the direction of relative motion), the components $F_{A2}$ and $F_{B2}$ give rise to tensional stresses as indicated in the figure. Thus, essentially the geometry of the convergent plate boundary determines the directions of the slab-pull forces $F_A$, $F_B$, and $F_C$. The divergence of these forces results in a tensional stress field, as was realized by Lonsdale and Klitgord (1978). Our modeling of plate-tectonics forces depending on lithospheric age implies a distribution of forces schematically shown in Figure 3b. Here, the descending lithosphere exerts a net pull on plate I in the central part of the subduction zone, but the younger lithopshere in the upper and lower regions (near A and D, corresponding to Mexico–Central America and southern Chile), where the ridge approaches the trench system, is too buoyant to overcome resistive forces. This situation causes a stress field in plate I with tension near the plate contact and compression farther away from the trench

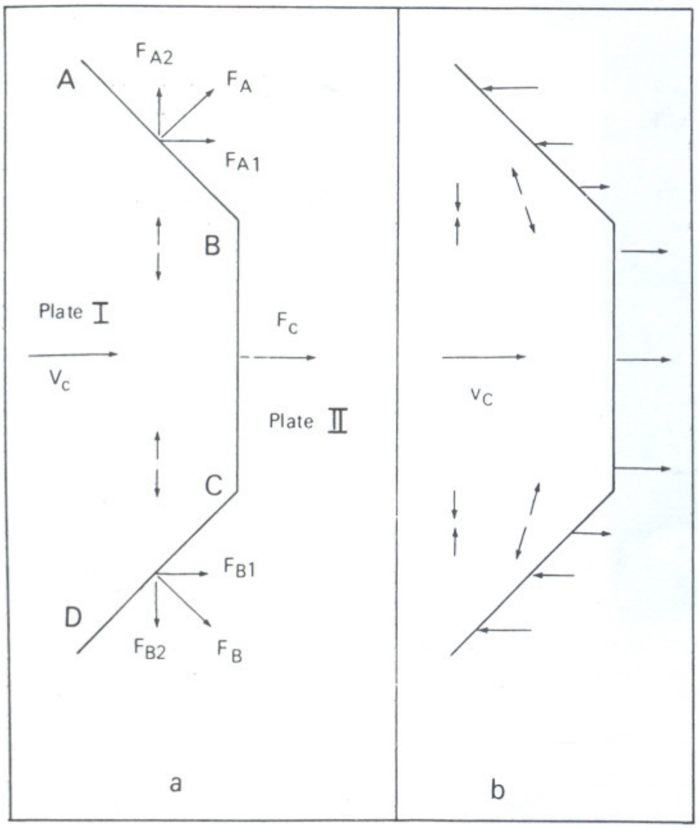


**Figure 3. Schematic representation of two mechanisms that produce tensional stresses in plate approaching subduction zone. Plate I underthrusts plate II. In case a, forces $F_A$, $F_B$, and $F_C$ represent pull exerted by descending slab. If only (or predominantly) components in direction of plate convergence are balanced by resistive forces (shearing forces parallel to direction of relative motion), components $F_{A2}$ and $F_{B2}$ give rise to tensional stresses as indicated in figure. In case b, descending slab exerts net pull on plate I in central part of subduction zone, but younger lithosphere in upper and lower regions (near A and D) is too buoyant to overcome resistive forces. This situation causes a stress field in plate I with tension near plate contact and compression farther away from trench.**

(see Figs. 3b and 2). Although the curved or angular geometry of the convergent plate boundary may play a role in creating lithospheric age differences along the strike of the trench system, the age differences themselves are of more fundamental importance. In many cases they result from large offsets in a spreading ridge or from other peculiarities in the spreading history of the plate which bear no direct relation to the curvature of the plate boundary. Even along a linear trench system, descending lithosphere of widely different ages—and, therefore, structures—could give rise to similar tensional stresses parallel to the trench. At this stage it may be realized that the pattern of forces acting on the Farallon plate (as sketched in Fig. 3b) is not affected seriously by the relatively minor uncertainties regarding the configuration of the Middle America Trench in Tertiary time.

The calculated stress field represents the nonhydrostatic state of stress in an elastic plate that was initially unstressed (Richardson, 1978). As noted earlier, the thickness of 100 km for the elastic model plate is only a reference value. Caldwell and Turcotte (1979) showed that a more appropriate model for the oceanic lithosphere is a division of the lithosphere into an elastic upper part and a plastic lower part. According to their model, the thickness of the elastic upper layer, which is presumably temperature-dependent, increases linearly with the square root of lithospheric age from a few kilometres for very young lithosphere to 40–50 km for lithosphere of about 80 m.y. Similar results were obtained by Bodine and others (1981). This implies that the magnitudes of the principal stresses plotted in Figure 2 (at some distance from the ridge) should be multiplied by a factor of 2 to 3 in order to get the stresses in the elastic upper layer. Thus, we obtain maximum principal stresses and also maximum differential stresses of 5 to 6 kbar. Assigning a yield stress of a few hundred bars to the lower part of the lithosphere or modeling this part as viscoelastic does not alter the above conclusion significantly (Kusznir and Bott, 1977). Neither is it to be expected that the incorporation of the body forces associated with an elevation of the olivine-spinel phase boundary would change the nature of our calculated stress field. Subduction of the young lithosphere ($<$70 m.y.) near the ridge-trench intersections probably does not cause such an elevation (Vlaar and Wortel, 1976; Wortel, 1980), whereas the increase in gravity pull experienced by the older parts of the slab (beneath present-day Peru and northern Chile) would lead only to even greater tensional stresses in the Farallon plate.

Unfortunately, the calculated stress field at 30 m.y. B.P. cannot be compared with observations. However, results of stress calculations for the present-day Nazca plate, based on the same approach, show good agreement with pertinent observational evidence (Wortel and Cloetingh, in prep.).

From laboratory experiments on olivine, the yield stress for the upper part of the lithosphere is inferred to be in the range of 3 to 10 kbar (Evans and Goetze, 1979; Kirby, 1980). Therefore, we propose that the Farallon plate failed in response to a stress field of the type depicted in Figure 2. This failure (in the stippled region of Fig. 4) resulted in two smaller plates, the Cocos plate and the Nazca plate (see Fig. 4), and gave birth to the Cocos-Nazca spreading center. A noteworthy feature of Hey's (1977) reconstruction of the Cocos-Nazca spreading center is that its *original* orientation was perpendicular to the strike of the Pacific-Farallon ridge. Later reorganizations in the spreading pattern led to the present east-west orientation of the spreading center.

From Figure 2 no particular preference can be inferred for failure in the region shown in Figure 4. Everywhere along the central part of the trench system high stresses prevail. If failure occurs in one part of the plate, however, the state of stress in the plate is relaxed, and the two new parts may change their rate and direction of motion. Their motion is no longer determined by the forces acting on all of the original plate but only by those acting on each of the smaller plates separately. The young lithosphere near the trench off northwest Mexico and southern Chile will initially cause the Cocos and Nazca plates to pivot around the intersections of the ridge and the trench. In this respect the postulated break-up (Fig. 4) may have had preference over other regions, because the new direction of the Cocos plate could easily be accommodated in the Central American trench system. The observed evidence for pivoting motion of the Cocos plate (see Menard, 1978) is considered to be in support of our force modeling (Fig. 3b). Much less pronounced is the pivoting motion of the Nazca plate (S. Cande, 1981, personal commun.), probably because the Nazca plate did not retain the original wedge-shaped geometry shown in Figure 4. Instead, it was affected by reorganizations in the system of spreading ridges in the east-central and South Pacific (Herron, 1972; Mammerickx and others, 1980), which changed the plate boundaries significantly.

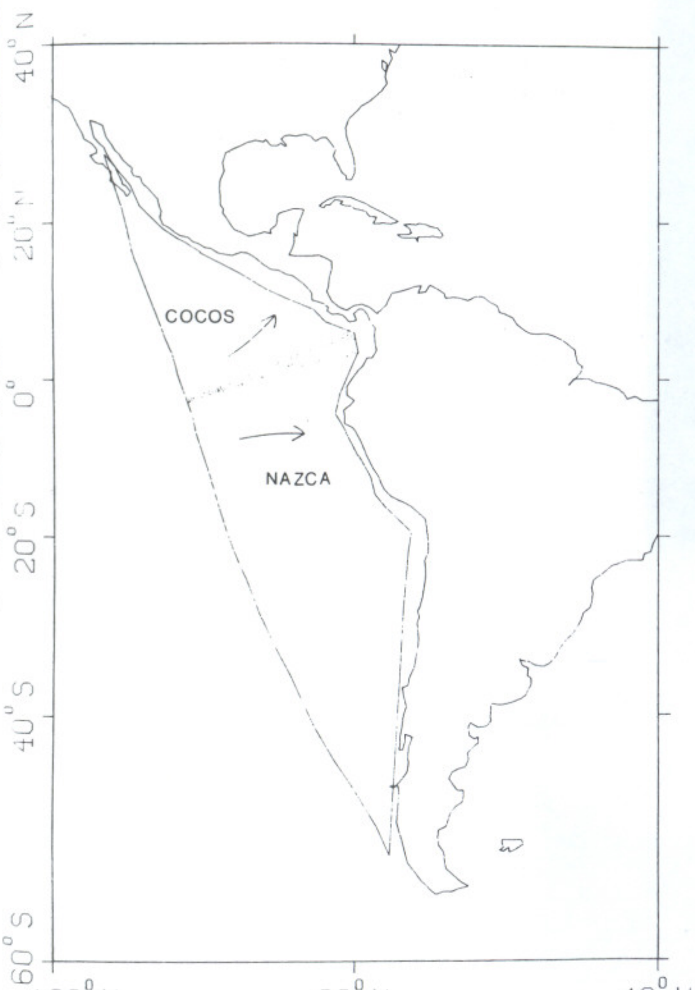


**Figure 4. Fragmentation of Farallon plate into Nazca plate and Cocos plate, supposedly as result of state of stress depicted in Figure 2 (stippled region indicates zone of failure). Age-dependent forces exerted by descending slab initially cause Cocos plate and Nazca plate to pivot around points of intersection of ridge and trenches off California-northwestern Mexico and southernmost Chile, respectively.**

## IMPLICATIONS

The kind of plate interaction that gave rise to the high tensional stresses in the Farallon plate is not restricted to the area of our case study. A curved or angular geometry of a trench system and significant lateral variations in the age of the oceanic lithosphere at the trench are encountered in several other regions. Also, in the earlier history of the Farallon plate (prior to 30 m.y. B.P.), when the Farallon plate extended farther north into the northeastern Pacific (see Handschumacher, 1976), situations quite similar to the one discussed here arose, and fragmentation repeatedly took place (Menard, 1978). For example, the Vancouver plate and the Guadalupe plate (Menard, 1978) were broken off the northern tip of the Farallon plate. We suggest that these fragmentations occurred in response to tensional stresses of the type discussed above.

The start of spreading along the new Cocos-Nazca plate boundary has caused an important change in the subduction process near present-day Panama. Prior to the break-up of the Farallon plate the subduction zone was consuming relatively old oceanic lithosphere, whereas after the break-up extremely young lithosphere arrived at the trench. In view of the important role (see Wortel, 1980) of the lithospheric age in the subduction process and associated geologic processes (such as volcanism), it is to be expected that taking into account this change may contribute to studies of the geology of Colombia and eastern Central America.

## CONCLUSIONS

Lateral variations in the age of the slab descending in a subduction zone may be the source of significant stresses in the plate to which the slab is attached. As such, they provide a possible cause for fragmentation of oceanic plates, in general, and the Farallon plate, in particular.

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