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A Mechanism for Fragmentation of Oceanic Plates

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To investigate the mechanism underlying the fragmentation of oceanic plates, we study the breakup of the Farallon plate into the Cocos plate and the Nazca plate, which took place 25 to 30 m.y. ago. Using finite element methods and a reconstruction of regional plate boundaries, we calculate the stress field in the Farallon plate at approximately 30 m.y. ago (just prior to the fragmentation). The resulting stress field is dominated by high tensional stresses (maximum principal stresses of 5 to 6 kbar). North-to-south tension near present-day Panama is proposed to have caused fragmentation of the Farallon plate and inception of spreading along the new Cocos-Nazca plate boundary. The plate interaction that allowed the high level of tensional stresses in the Farallon plate is not unique for our case study, and the proposed mechanism sheds light on the problem of fragmentation of oceanic plates. The preliminary results of stress field calculations for the present-day Nazca plate show interesting stress variations along the strike of the South American trench system.

The spreading activity of oceanic ridges has been documented extensively, but the processes underlying the fragmentation of lithospheric plates and the formation of new accreting plate boundaries are not completely known. We propose a mechanism for fragmentation of oceanic plates and the subsequent inception of spreading centres. This mechanism is based on a case study of the plate tectonic evolution of the east-central Pacific.

In the last decade, marine geophysical studies have clarified many features of the apparently complex Cenozoic history of this area (Herron, 1972; Handschumacher, 1976; Hey, 1977; Mammerrickx, Herron, and Dorman, 1980). These investigations show the breakup of the former Farallon plate into the Cocos plate and the Nazca plate (which took place approximately 25 to 30 m.y. ago) as a milestone in the tectonic evolution of the region. However, the amount of attention given to the mechanism causing 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 centre (or alternatively, the Galapagos spreading centre) "was born about 25 m.y. ago 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 et al (1971) postulated the splitting of an east-to-west trending ridge (the 'ancestral Carnegie Ridge') in attempting to explain the origin of the young Panama Basin. Finally, Menard (1978) discussed the fragmentation of the Farallon plate, concentrating on the relative motion of the fragmented parts rather than on the fragmentation process itself.

In the present context, it is important to realize the changes brought about by the Pacific-Farallon spreading centre approaching the western margin of the North American and South American continents. Not only did the approach imply a continuous change in geometry of the Farallon plate, but it also caused lateral and temporal variations in the age of the lithosphere at the trench systems along the eastern boundary of the plate. As is discussed below, several important forces acting on a lithospheric plate are strong functions 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.

We investigate the state of stress in the Farallon

plate at approximately 30 m.y. ago. (just prior to the breakup) to see whether the stress field assists in understanding the documented fragmentation. To do this, we use finite element methods and a reconstruction of regional plate boundaries and forces appropriate for 30 m.y. ago. We model the plate as elastic which 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) lead us to consider (as a new feature in numerical modelling of 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. 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 the subducted slab, are of particular interest. In view of the strong dependence of the gravitational slab pull on the age of the descending lithosphere, England and Wortel (1980) 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: 1) the young lithosphere was actively driven into the subduction zone by forces acting on adjacent segments of the plate, or 2) if the 'upper' plate, usually continental, 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, then there is no need for compression in the overriding plate and a tensional regime might be observed as a result of the retrograde motion of the subducting slab. A compilation of observations showed that a transition from tensional to compressional regimes, corresponding with a net resistive force per unit width along the trench of 8×10^{12} N/m, indeed takes place. The age at which this transition occurs varies from about 40 to 70 million years, depending on the vertical velocity of the sinking slab.

The intersections of the Pacific-Farallon spreading centre with the trench system (Figure 1) imply lateral variations in the age of the lithosphere at the trench and these findings appear relevant to modeling the forces which acted on the Farallon plate.

To test our modelling by observations, which is naturally impossible for the case of the Farallon plate, we also calculate the stress field for the present-day Nazca plate. Preliminary results of this work were reported earlier by Wortel and Cloetingh (1979).

MODEL

The plate boundaries adopted for the Farallon plate model at 30 m.y. ago and the mesh used in the cal-

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

culations 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 was initiated during the Eocene (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 since it is due to the opening of the Gulf of California, which took place after 30 m.y. ago. As Karig et al (1978) and Moore et al (1979) present strong evidence for truncation and accretion in some segments of the Middle America Trench, the boundary between the Farallon plate and Mexico/Central America may have been somewhat different from the one depicted in Figure 1. However, it is 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. ago is taken from Atwater (1970). The location of the southern intersection is somewhat uncertain. From various lines of evidence

(e.g. the plate boundaries reconstructed for 55 m.y. ago (Jurdy and Van der Voo, 1975), the presence of a sediment filled trench off western Southern America south of 45°S), the position indicated in Figure 1 may be taken as a reasonable estimate (see 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 modelled without any offsets along transform faults.

The model plate is considered elastic (Young's modulus $E = 7 \times 10^{10}$ N/m² and Poisson's ratio $\nu = 0.25$), with a thickness of 100 km. This thickness is only a reference value. We use a plane stress approximation, but stress 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, Solomon and Sleep (1979), we assume that the state of stress in a lithospheric plate is determined largely by plate tectonic 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 upon that L depends on the square root of the lithospheric age (t) for $t < 70$ million years (e.g. Parsons and McKenzie, 1978). Hence, for these ages, $F_{sp} \propto t^{3/2}$. Owing to the reduced rate of thickening of L for $t > 70$ million years, 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 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 $t > 70$ million years, the ridge push F_{rp} (per unit width parallel with 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 (over the distance from ridge to trench) value of a horizontal pressure gradient (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. Since the geometry of our model is simplified (the offsets in the ridge axis are neglected), an assessment of only the gross features of the age pattern is warranted. Such an assessment was made by combining Handschumacher's (1976) Oligocene rotation pole (70°N, 145°W) for the spreading along the Pacific-Farallon ridge with the requirement that the age of the lithosphere at the trench off northern Chile had to be 75 to 80 million years. 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 decreased in the Late Tertiary, due to the convergence rate being higher than the half-spreading rate at which the descending lithosphere was originally created at the Pacific-Farallon spreading centre.

Furthermore, the slab pull (F_{sp}) depends on the convergence rate v_c (Richter and McKenzie, 1978) and the dip angle (ϕ) of the descending slab as $F_{sp} \propto v_c \sin \phi$; hence, F_{sp} varies linearly with v_z , the vertical velocity of the subducted slab. In a comprehensive study of the subduction process of oceanic lithosphere, Wortel (1980) showed that present-day subduction zones display the following characteristics: $2 \leq v_z \leq 3.5$ cm/yr for oceanic lithosphere younger than 65 million years and $4 \leq v_z < 6$ cm/yr for lithosphere older than 100 million years. 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, for which no observational data were available.

In other studies of stress in the lithosphere (Richardson, Solomon, and Sleep, 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 8×10^{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 4×10^{12} N/m. The remaining resistance of 4×10^{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.

The relative importance of the forces F_{sp} , F_{rp} , F_{tr} , and F_{dr} is demonstrated in Table 1, in which these forces are specified (per unit width along the ridge or trench) for two cross sections from a spreading ridge to a trench system. In these examples, we assume that the ridge runs parallel with the trench; we consider the forces to be positive if they drive the oceanic plate

Table 1. Forces acting on oceanic lithosphere, calculated for two cross sections from ridge to trench. All forces are given per unit width along the trench. "Age" refers to the age of the oceanic lithosphere at the trench. $F_{\text{sum}} = F_{\text{rp}} + F_{\text{sp}} + F_{\text{tr}} + F_{\text{dr}}$ (see text for the explanation of these forces).

age (m.y.)	F_{rp} (10^{12} N/m)	F_{sp} (10^{12} N/m)	F_{tr} (10^{12} N/m)	F_{dr} (10^{12} N/m)	F_{sum} (10^{12} N/m)
30	+ 0.8	+ 3.2 ^(a)	- 8.0	- 0.6 ^(b)	- 4.6
70	+ 1.7	+ 12.9 ^(a)	- 8.0	- 1.4 ^(b)	+ 5.2

(a) Values taken for the vertical velocity v_z of the subducted slabs of 30 and 70 m.y. old are 3 cm/yr and 4 cm/yr, respectively.

(b) Based on a shear stress of 8 bar and a half-spreading rate (determining the relation between age at the trench and distance from ridge to trench) appropriate for the Farallon plate.

towards the trench. In the first cross section, the oceanic lithosphere near the trench is 30 m.y. old and the sinking velocity (v_z) of the subducted slab is 3 cm/yr. The sum of the forces appears to be negative. Hence, the resistance to plate motion (F_{tr} and F_{dr} , based on a shear stress of 8 bar) is greater than are combined driving forces F_{sp} and F_{rp} . As a result, the oceanic lithosphere is in a state of compression (principal stress in the direction from ridge to trench). In the second cross section, the lithosphere at the trench is 70 m.y. old and $v_z = 4$ cm/yr. Owing to the strong age-dependence of the slab pull (F_{sp}), the driving forces now outweigh the resistive forces, which leads to tensional stresses in the oceanic lithosphere. It can be shown that, in these examples, the transition from compression to tension takes place if the lithosphere at the trench is around 50 m.y. old. Realize that the net forces (unequal to zero) acting in cross sections of this type do not violate the required balance of forces or, on a spherical surface, the balance of torques. Such laws refer to the whole of the plate.

RESULTS AND ANALYSIS

Stress field in the Farallon plate

The resulting stress field in the Farallon plate under the reconstructed conditions of 30 m.y. ago 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 which 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 , and 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 (i.e. if a net pull is transferred to the horizontal part of the plate), they will cause tensional stresses in the plate. Similarly, if

Figure 2 — Calculated stress field in the Farallon plate under the reconstructed conditions of 30 m.y. ago, prior to the breakup of the Farallon plate. The thickness of the elastic plate is 100 km (see text).

only, or predominantly, the driving forces in the direction of plate convergence are balanced by resistive forces (shearing forces parallel with the direction of relative motion), the components F_{A2} and F_{B2} give rise to tensional stresses as indicated in the figure. Thus, 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) for the Farallon plate and earlier, in a more general context, by Solomon and Sleep (1974). Our modelling of plate tectonic 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 lithosphere in the upper and lower regions (near A and D, corresponding with 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 (Figures 3b and 2).

Figure 3 — Schematic representation of two mechanisms which produce tensional stresses in a plate approaching a subduction zone. Plate I underthrusts plate II. In a, the forces F_A , F_B , and F_C represent the pull exerted by the descending slab. If only, or predominantly, the components in the direction of plate convergence are balanced by resistive forces (shearing forces parallel with direction of relative motion), the components F_{A2} and F_{B2} give rise to tensional stresses as indicated in the figure. In b, the descending slab exerts a net pull on plate I in the central part of the subduction zone, but the younger lithosphere in the 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 the plate contact and compression further away from the trench.

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, from the presence of extinct spreading centres, 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 hence, different structures, could give rise to similar tensional stresses parallel with the trench. In short, the age-dependence of forces acting on a plate constitutes a factor which is essentially independent of the actual shape of the plate. At this stage, the pattern of forces acting on the Farallon plate (as sketched in Figure 3b) is not affected seriously by the relatively minor uncertainties regarding the configuration of the Middle America Trench in Tertiary times.

The calculated stress field represents the non-hydrostatic state of stress in an elastic plate which 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 kilometers for very young lithosphere to 40 to 50 km for lithosphere of about 80 m.y. old. Similar results were obtained by Bodine, Steckler, and Watts (1981). This implies that the magnitudes of the principal stresses plotted in Figure 2 (at some distance from the ridge) should be multiplied by 2 to 3 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 modelling this part as visco-elastic does not alter the above conclusion significantly (Kusznir and Bott, 1977). Incorporation of the body forces associated with an elevation of the olivine-spinel phase boundary is not expected to change the nature of our calculated stress field. Subduction of the young lithosphere (< 70 million years) near the ridge-trench intersections probably does not cause such an elevation (Vlaar and Wortel, 1976), whereas the increase in gravity pull experienced by the older parts of the slab (beneath present-day Peru and northern Chile) would only lead to even greater tensional stresses in the Farallon plate.

Note that our modeling procedure is closely constrained by extensive data sets. The model for the oceanic lithosphere, used in the evaluation of the slab pull (F_{sp}) and ridge push (F_{rp}) and in the interpretation of the stress field, satisfies oceanic heat flow and bathymetry data (Wortel, 1980) and deformation of oceanic lithosphere data (Caldwell and Turcotte, 1979). The modelling of forces is constrained by observational data on the stress regime in the lithosphere above subducted slabs (England and Wortel, 1980). In our approach of calculating intraplate stress fields, we prefer to use the internally consistent parameters and results derived from these studies to making a variable parameter study.

Stress field in the Nazca plate

The maximum values of the stresses in Figure 2 are considerably higher than those calculated by Richardson, Solomon, and Sleep, (1979) for the present-day system of lithospheric plates (several hundreds of bars). For direct comparison, we calculated the stress field for the present-day Nazca plate employing the same modelling procedure as we did for the Farallon plate. Our finite element mesh for the Nazca plate and the computational results are displayed in Figures 4 and 5, respectively. More detailed work on the state of stress in the Nazca plate, in which specific local factors are incorporated, is in progress (Wortel and Cloetingh, in preparation). In the Nazca plate, the stress level appears to be significantly lower than in the Far-

Figure 4 — Mesh used in the finite element calculation of the present-day stress field in the Nazca plate (see Figure 5).

allon plate. Taking into account the difference between the thickness of the elastic model plate (100 km) and the elastic thickness of the lithosphere, we find the stresses in the eastern part of the plate to typically range from 500 to 700 bar, the maximum stress being close to 1 kbar. Thus, in comparable situations, the stresses are of the same magnitude as found by Richardson, Solomon, and Sleep (1979). Our results for the Nazca plate exhibit another noteworthy feature: a transition from approximately east-west compression near the northern segment of the South American trench system, via tension off northern Chile, to compression again along the southern part of the trench. Various data on the deformational characteristics of trench deposits and of the adjacent oceanic crust provide evidence for such a lateral variation along the South American trench system, and in particular for the presence of east-west compression (Prince and Kulm, 1975; Hussong et al, 1976; Kulm, Schweller, and Masias, 1977; Schweller and Kulm, 1978). In Richardson's (1978) modelling of the state of stress in the Nazca plate, he used the focal mechanism solution of an intraplate earthquake (east-west compression, epicentre indicated by open circle in Figure 5) determined by Mendiguren (1971) as the most important con-

Figure 5 — Calculated stress field in the present-day Nazca plate. Note that the stresses were calculated for an elastic plate with a thickness of 100 km.

straint. However, the extensive marine geophysical evidence cited above might provide a much more useful constraint in numerical modelling of the state of stress in the lithosphere. From the difference in stress level between the present-day Nazca plate (and other plates; see Richardson, Solomon, and Sleep, 1979) and the Farallon plate at 30 m.y. ago, we infer that, just prior to its fragmentation, the Farallon plate attained unusually high intraplate stresses.

Fragmentation of the Farallon plate

From laboratory experiments on olivine, the yield stress for the upper part of the lithosphere is inferred to range from 3 to 10 kbar (Ashby and Verrall, 1978; 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 resulted in two smaller plates, the Cocos plate and the Nazca plate (see Figure 6) and gave birth to the Cocos-Nazca spreading centre. An interesting feature of Hey's (1977) reconstruction of the Cocos-Nazca spreading centre is that its original orientation was perpendicular with the strike of the Pacific-Farallon ridge. Later, reorganizations in the spreading pattern

led to the present east-west orientation of the spreading centre.

From Figure 2 no particular preference can be inferred for failure in the region shown in Figure 6. Everywhere along the central portion 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 breakup (Figure 6) may have had preference over other regions as 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 support our force modelling (Figure 3b). The pivoting motion of the Nazca plate (S. Cande, personal communication, 1981) is much less pronounced. This is probably due to the fact that the new Nazca plate did not retain the original wedge-shaped geometry shown in Figure 6. Instead, it was affected by reorganizations in the system of spreading ridges in the east-central and South Pacific (Herron, 1972; Mammerickx, Herron, and Dorman, 1980) which changed the plate boundaries significantly.

Finally, we draw attention to implications for the geology of continental margins which are adjacent to a region of (oceanic) plate fragmentation. The start of spreading along the new Cocos-Nazca plate boundary has caused important changes in the subduction process near present-day Panama. Prior to breakup of the Farallon plate, the subduction zone was consuming relatively old oceanic lithosphere. After breakup, extremely young lithosphere arrived at the trench. In view of the important role of the lithospheric age in the subduction process (Wortel, 1980) and associated geological processes (De Long and Fox, 1977), we expect that accounting for this change may contribute to studies of the geology of Colombia, eastern Central America, and adjacent continental margins (e.g. Lu and McMillen, this volume).

CONCLUSION

The plate interaction that gave rise to the high tensional stresses in the Farallon plate is not restricted to our case study area. 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. ago), when the Farallon plate extended farther north into the northeastern Pacific (Handschomacher, 1976), situations have arisen which are quite similar to the one studied in this paper, and fragmentation has repeat-

Figure 6 — Fragmentation of the Farallon plate into the Nazca plate and the Cocos plate, supposedly resulting from the state of stress depicted in Figure 2 (the stippled region indicates the zone of failure). The age-dependent forces exerted by the descending slab initially cause the Cocos plate and the Nazca plate (see text) to pivot around the points of intersection of the ridge and the trenches off California/northwest Mexico and southernmost Chile, respectively.

edly taken place (Menard, 1978; see also Riddihough, 1977). For example, the Vancouver plate and the Guadelupe plate (Menard, 1978) were broken off the northern part of the Farallon plate. We suggest that these fragmentations occurred in response to tensional stresses of the type discussed.

Intraplate stresses associated with plate tectonic forces (such as those considered in this paper) have tentatively been advanced as a cause for intraplate volcanism (e.g. Jackson and Shaw, 1975; Watts, Bodine, and Ribe, 1980). Our numerical results indicate that tensional stresses may reach a level which is sufficient to cause failure of oceanic plates. Since inception of intraplate volcanism probably requires lower tensional stresses than creation of spreading centres, we conclude that for explaining the origin of volcanic island chains, stress fields of the type calculated for the Farallon plate provide a sound alternative to hypotheses based on postulated hot spots.

We conclude that 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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