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by

Han-Shou Liu

ABSTRACT

The observed boundary system of the major tectonic plates on the surface of the earth lends fresh support to the hypothesis of polar wandering. In this paper a dynamic model of the outer shell of the earth under the influence of polar shift is developed. The analysis falls into two parts: (1) deriving equations for stresses caused by polar shifting; (2) deducing the pattern according to which the fracture of the shell can be expected. For stress analysis, the theory of plates and shells is the dominant feature of this model. In order to determine the fracture pattern, the existence of a mathematical theorem of plasticity is recalled: it says that the plastic flow begins to occur when a function in terms of the differences of the three principal stresses surpasses a certain critical value. By introducing the figures for the geophysical constants, this model generates stresses which could produce an initial break in the lithosphere. The fracture pattern of plastic deformation in the outer shell of the earth due to shift of poles shows a remarkable correlation to the existing systems of the tectonic plate boundaries.

ON THE BREAKUP OF TECTONIC PLATES BY POLAR WANDERING

INTRODUCTION

Convection currents in the interior of the earth (Pekeris, 1935) are capable of producing polar wandering, (Runcorn, 1959). For the explanation of how a relatively thin shell has managed to slide a full 90° with respect to the underlying mantle, Goldreich and Toomre (1969) have proposed a hypothesis that large angular displacement of the earth's poles has shifted on a geological time scale owing to the gradual redistribution of density inhomogeneities within the earth by the process of convection. Such a shift of polar axis with regard to the mantle must cause stresses and deformation of the thin shell because it would adjust its shape to the change of the flattening (Jeffreys, 1962). Therefore, the stresses and deformation generated by polar shift may provide a mechanism for the original breakup of the shell into several major tectonic plates. In the present paper, the equations for the stresses in a homogeneous shell of uniform thickness caused by a shift of the axis of rotation are derived. The magnitude of these stresses reaches a maximum value of the order of 10^9 dyn cm^{-2} which is sufficient for explaining a tectonic breakup. In order to deduce the fracture pattern according to which the breakup of tectonic plates can be expected, we shall apply the theory of plastic deformation of shells (Hencky, 1924; Bijlaard, 1936; Van Iterson, 1943). The analysis of this pattern gives an explanation of the existing boundary systems of the major tectonic plates as described by Morgan (1968), LePichon (1968) and Isacks, et al. (1968).

STRESSES IN A SHELL

Let r denote the radius of the earth, h the thickness of the shell, α and β polar coordinates, σ_α , σ_β and σ_r the normal components of stresses and τ the shear stress. For an element prism as shown in Fig. 1, extending over the full thickness of the shell and bounded by two planes through the coordinate axis enclosing an angle $d\alpha$ and two conic surfaces described around the axis with angle differing $d\beta$, the conditions of equilibrium can be expressed by (Love, 1944; Timoshenko and Woinowsky-Krieger, 1959)

$$\sigma_\alpha \, hr \cos\beta d\beta d\alpha - \frac{\partial \sigma_\beta}{\partial \beta} hr \sin\beta d\beta d\alpha - \sigma_\beta \, hr \cos\beta d\beta d\alpha - \frac{\partial \tau}{\partial \alpha} hr \, d\beta d\alpha = 0, \tag{1}$$

$$\frac{\partial \sigma_\alpha}{\partial \alpha} hr \, d\beta d\alpha - \frac{\partial \tau}{\partial \beta} hr \sin\beta d\beta d\alpha - \tau \, hr \cos\beta d\beta d\alpha - \tau \, hr \cos\beta d\beta d\alpha = 0, \tag{2}$$

$$\sigma_r \, r^2 \sin\beta d\beta d\alpha + \sigma_\beta \, hr \sin\beta d\beta d\alpha + \sigma_\alpha \, hr \sin\beta d\beta d\alpha = 0. \tag{3}$$

The third terms appear in equations (1) and (2) because the lateral sides of the element shown in Fig. 1 have a trapezoidal form due to the curvature of the shell. By simplifying these equations, we obtain

$$
\begin{aligned}
&(\sigma_\alpha - \sigma_\beta) \cos \beta - \frac{\partial \sigma_\beta}{\partial \beta} \sin \beta + \frac{\partial \tau}{\partial \alpha} = 0, \\
&\frac{\partial \sigma_\alpha}{\partial \alpha} - \frac{\partial \tau}{\partial \beta} \sin \beta - 2\tau \cos \beta = 0, \qquad (4) \\
&\sigma_r + \frac{h}{r} (\sigma_\alpha + \sigma_\beta) = 0.
\end{aligned}
$$

The relations between stresses and displacements are

$$
\begin{aligned}
&\sigma_\beta - \nu \sigma_\alpha = \frac{E}{r} \left(\frac{\partial U_\beta}{\partial \beta} + U_r \right), \\
&\sigma_\alpha - \nu \sigma_\beta = \frac{E}{r} \left(U_\beta \operatorname{Cot} \beta + \frac{\partial U_\alpha}{\partial \alpha} \operatorname{Csc} \beta + U_\beta \right), \qquad (5) \\
&\tau = \frac{E}{2(1 + \nu) r} \left(\frac{\partial U_\beta}{\partial \alpha} \operatorname{Csc} \beta - \frac{\partial U_\alpha}{\partial \beta} + U_\alpha \operatorname{Cot} \beta \right),
\end{aligned}
$$

in which E is Young's modulus, ν is Poisson's ratio and U_α, U_β and U_r are components of displacement in the elements of the shell.

For the case of a change of the flattening, U_α and τ are zero in these coordinates and equations (4) and (5) reduce to

$$\frac{\partial \sigma_\beta}{\partial \beta} = (\sigma_a - \sigma_\beta)\,\mathrm{Cot}\,\beta,$$

$$\sigma_r = -\frac{h}{r}(\sigma_a + \sigma_\beta),$$

$$\sigma_\beta - \nu\,\sigma_a = \frac{E}{r}\left(\frac{\partial U_\beta}{\partial \beta} + U_r\right), \tag{6}$$

$$\sigma_a - \nu\,\sigma_\beta = \frac{E}{r}(U_\beta\,\mathrm{Cot}\,\beta + U_r).$$

If we assume that the flattening of the earth's figure diminishes by an amount δ and that the volume of the earth remains constant, U_r can be formulated by (Jeffreys 1962)

$$U_r = \delta r\left(\mathrm{Cos}^2\,\beta - \frac{1}{3}\right). \tag{7}$$

By substituting equation (7) into equation (6), the results are

$$\sigma_a = \frac{\delta E}{\nu + 5}\left(3\cos^2\beta - \frac{5}{3}\right),$$

$$\sigma_\beta = \frac{\delta E}{\nu + 5}\left(\cos^2\beta + \frac{1}{3}\right),$$

$$\sigma_r = -\frac{4\delta E}{\nu + 5}\,\frac{h}{r}\left(\cos^2\beta - \frac{1}{3}\right), \tag{8}$$

$$U_\beta = -\frac{2(\nu + 1)\,\delta r}{\nu + 5}\,\mathrm{Sin}\,\beta\,\mathrm{Cos}\,\beta.$$

It is noted that σ_r is small with respect to σ_α and σ_β because the ratio 4 h/r is about 6×10^{-2}.

EFFECT OF POLAR SHIFT

For deriving the stresses and deformation caused by a shift of the poles, we require the expression for the displacement U_r in terms of latitude and polar motion before and after the event. As shown in Fig. 2, we consider the pole after the movement to point P_n at an angular distance θ from its initial position P'_n. Denoting latitude by φ, we may represent the radius of the earth by

$$r = a\,(1 - \Delta\,\mathrm{Sin}^2\,\varphi). \tag{9}$$

If the earth has to adjust its shape entirely to the equilibrium figure after polar shift, the displacement U_r becomes

$$\begin{aligned} U_r &= \Delta a\,[\mathrm{Sin}^2\,\varphi - \mathrm{Sin}^2\,(\phi - \theta)] \\ &= \Delta a\,\mathrm{Sin}\,\theta\,\mathrm{Sin}\,(2\phi - \theta). \end{aligned} \tag{10}$$

U_r reaches maximum value $\Delta a \sin\theta$ at $\phi = \pi/4 + \theta/2$ and minimum value $-\Delta a \sin\theta$ at $\phi = -\pi/4 + \theta/2$. The deformation of the outer shell due to polar shift can be obtained by the superposition of two special cases of deformations given by equation (7). The first case is the one with the axis coinciding with the direction $\phi = \pi/4 + \theta/2$, and the second case is the one with the axis coinciding with the direction $\phi = -\pi/4 + \theta/2$. Therefore, if we introduce successively $\beta = \phi - (\pi/4 + \theta/2)$ and $\beta = \phi - (-\pi/4 + \theta/2)$ in equation (7), we find

$$U_r = \Delta r \operatorname{Sin}\theta \left\{ \operatorname{Cos}^2 \left[\phi - \left(\frac{\pi}{4} + \frac{\theta}{2}\right)\right] - \operatorname{Cos}^2 \left[\phi - \left(-\frac{\pi}{4} + \frac{\theta}{2}\right)\right]\right\}$$

$$= \Delta r \operatorname{Sin}\theta \operatorname{Sin}(2\phi - \theta). \tag{11}$$

which is identical with equation (10) to the first order of Δ. This result shows that we may derive the solution of our problem simply from equation (7). For this purpose we introduce a new system of polar coordinates ψ and λ with its axis coinciding with the axis of rotation. Thus the origin of this system lies in the equator. We define ψ from the great circle through the origin and the pole in its final position as shown in Fig. 3. According to equations (5) and (6), the position A_1 and A_2 in the original system of deformation have latitudes of $\pi/4 + \theta/2$ and $-\pi/4 + \theta/2$ with regard to the initial position of the equator. Their latitudes with regard to its final position are $\pi/4 - \theta/2$ and $-\pi/4 - \theta/2$. Therefore, the coordinates of A_1 and A_2 in the new system are

$$A_1 \left(\lambda = \frac{\pi}{2},\ \psi = \frac{\pi}{4} + \frac{\theta}{2}\right),$$

$$A_2 \left(\lambda = \frac{\pi}{2},\ \psi = \frac{3\pi}{4} + \frac{\theta}{2}\right).$$

By introducing $\delta = \Delta \sin\theta$ in equation (7) and (8), we obtain

$$\sigma_m = \frac{1}{2}(\sigma_\beta + \sigma_a) = \frac{2}{\nu + 5} \Delta E \operatorname{Sin}\theta \left(\frac{2}{3} - \operatorname{Sin}^2 \beta\right),$$

$$\sigma_d = \frac{1}{2}(\sigma_\beta - \sigma_a) = \frac{1}{\nu + 5} \Delta E \operatorname{Sin}\theta \operatorname{Sin}^2 \beta. \tag{12}$$

The general formula for stresses in a plane enclosing an angle γ with that of the principal stresses are

$$\sigma_\lambda = \sigma_m + \sigma_d \operatorname{Cos} 2\gamma,$$

$$\sigma_\psi = \sigma_m - \sigma_d \operatorname{Cos} 2\gamma, \tag{13}$$

$$\tau = \sigma_d \operatorname{Sin} 2\gamma.$$

We denote β_1 and γ_1 for the system A_1 and β_2 and γ_2 for the system A_2. The results of σ_λ, σ_ψ and τ for the combined system A_1 and A_2 in the new coordinates are

$$\sigma_\lambda = -\frac{2}{\nu + 5}\,\Delta E\,\mathrm{Sin}\,\theta(\mathrm{Sin}^2\,\beta_1 - \mathrm{Sin}^2\,\beta_2)$$

$$+\frac{1}{\nu + 5}\,\Delta E\,\mathrm{Sin}\,\theta(\mathrm{Sin}^2\,\beta_1 \mathrm{Cos}\;2\gamma_1 - \mathrm{Sin}^2\,\beta_2\,\mathrm{Cos}\;2\gamma_2),$$

$$\gamma_\psi = -\frac{2}{\nu + 5}\,\Delta E\,\mathrm{Sin}\,\theta(\mathrm{Sin}^2\,\beta_1 - \mathrm{Sin}^2\,\beta_2) \qquad (14)$$

$$-\frac{1}{\nu + 5}\,\Delta E\,\mathrm{Sin}\,\theta(\mathrm{Sin}^2\,\beta_1\,\mathrm{Cos}\;2\gamma_1 - \mathrm{Sin}^2\,\beta_2\,\mathrm{Cos}\;2\gamma_2),$$

$$\tau = \frac{1}{\nu + 5}\,\Delta E\,\mathrm{Sin}\,\theta(\mathrm{Sin}^2\,\beta_1\;\mathrm{Sin}\;2\gamma_1 - \mathrm{Sin}^2\,\beta_2\;\mathrm{Sin}\gamma_2).$$

Since angle $QOA_1 = (\pi/4) - \psi + (\theta/2)$ and angle $QOA_2 = (3\pi/4) - \psi + (\theta/2)$, we can derive

$$\mathrm{Sin}\,\beta_1\;\mathrm{Sin}\,\gamma_1 = \mathrm{Sin}\left(\frac{\pi}{4} - \psi + \frac{\theta}{2}\right),$$

$$\mathrm{Sin}\,\beta_2\;\mathrm{Sin}\;\gamma_2 = \mathrm{Sin}\left(\frac{3\pi}{4} - \psi + \frac{\theta}{2}\right) = \mathrm{Sin}\left(\frac{\pi}{4} + \psi - \frac{\theta}{2}\right),$$

$$\mathrm{Sin}\,\beta_1\;\mathrm{Cos}\,\gamma_1 = -\,\mathrm{Cos}\,\lambda\;\mathrm{Cos}\left(\frac{\pi}{4} - \psi + \frac{\theta}{2}\right), \qquad (15)$$

$$\mathrm{Sin}\,\beta_2\;\mathrm{Cos}\,\gamma_2 = -\,\mathrm{Cos}\,\lambda\;\mathrm{Cos}\left(\frac{3\pi}{4} - \psi + \frac{\theta}{2}\right) = \mathrm{Cos}\,\lambda\;\mathrm{Cos}\left(\frac{\pi}{4} + \psi - \frac{\theta}{2}\right).$$

By substituting equation (15) into equation (14), the results are

$$\sigma_\lambda = \frac{1}{\nu + 5} \Delta E \operatorname{Sin} \theta (\operatorname{Sin}^2 \lambda + 2) \operatorname{Sin} (2\psi - \theta),$$

$$\sigma_\psi = \frac{1}{\nu + 5} \Delta E \operatorname{Sin} \theta (3 \operatorname{Sin}^2 \lambda - 2) \operatorname{Sin} (2\psi - \theta), \qquad (16)$$

$$\tau = - \frac{2}{\nu + 5} \Delta E \operatorname{Sin} \theta \operatorname{Cos} \lambda \operatorname{Cos} (2\psi - \theta).$$

Equations in (16) are stresses in the outer shell of the earth caused by a shift of the poles over an angle θ.

BREAKUP PROBLEM

Equation (16) shows that σ_λ and σ_ψ vanish in two great circles through the origin given by $\psi = \theta/2$ and $\psi = \pi/2 + \theta/2$. Shear stress τ in these circles reaches maximum value at the origin where the two circles intersect at right angles. The maximum value of τ is

$$\tau_{max} = \frac{2}{\nu + 5} \Delta E \operatorname{Sin} \theta. \qquad (17)$$

For the shell of the earth, we adopt $\nu = 0.25$ and $E = 10^{12}$ dyn cm^{-2}. (Gutenberg, 1959). At present the flattening of the earth Δ is 1/298. (Jeffreys, 1962). Therefore, we have $\tau_{max} = 1.3 \times 10^9$ dyn cm^{-2} for $\theta = (\pi/2)$. This shear stress is quite considerable, and we may imagine that the outer shell of the earth will yield under this effect.

For $\lambda = \pi/2$, $\psi = \pi/4 + \theta/2$ and $\psi = -\pi/4 + \theta/2$, we conclude from equation (16) that $\tau = 0$. We further find that $\sigma_\lambda = 3\,\sigma_\psi$ everywhere in the meridian

$\lambda = (\pi/2)$. The maximum absolute value σ_λ is found in the crossings of the meridian $\lambda = (\pi/2)$ with two great circles $\psi = \pi/4 + \theta/2$ and $\psi = -\pi/4 + \theta/2$. For the first case it is a maximum tension and for the second case a maximum compression. The absolute values in both cases amount to

$$|\sigma_\lambda|_{max} = \frac{3}{\nu + 5} \Delta E \operatorname{Sin} \theta. \tag{18}$$

which gives $|\sigma_\lambda|_{max} = 1.9 \times 10^9$ dyn cm^{-2} for $\theta = \pi/2$. This result also implies that the outer shell of the earth could not resist the stresses caused by a larger shift of the poles.

At an early date of the earth's history the stresses generated by polar shift must have been even larger because the flattening must have been greater at that time. Using the value $\Delta = 1/210$ for a date 1.6×10^9 years ago (Jeffreys, 1962), we have $\tau_{max} = 1.8 \times 10^9$ dyn cm^{-2} and $|\sigma_\lambda|_{max} = 2.7 \times 10^9$ dyn cm^{-2}. Therefore, from the estimation of the stresses due to polar shifting, it is unlikely that the outer shell of the earth was able to stand them without fracturing.

ENERGY OF DEFORMATION

The deformation energy which is required for the increase of the stresses caused by polar shift can be expressed by the following formula (Timoshenko and Goodier, 1951)

$$V = \frac{\nu + 1}{2E} (\sigma_x^2 + \sigma_y^2 + \sigma_z^2) + \frac{\nu + 1}{E} (\tau_x^2 + \tau_y^2 + \tau_y^2) - \frac{\nu}{2E} (\sigma_x + \sigma_y + \sigma_z)^2 . \tag{19}$$

where σ_x , σ_y and σ_z are components of normal stress, and τ_x, τ_y and τ_z are components of shear stress in the rectangular coordinate system. For our case, equation (19) becomes

$$V = \frac{\nu + 1}{2E} (\sigma_\lambda^2 + \sigma_\psi^2) + \frac{\nu + 1}{E} \tau^2 - \frac{\nu}{2E} (\sigma_\lambda + \sigma_\psi)^2 . \qquad (20)$$

By substituting equation (16) into equation (20) and integrating over the shell, we obtain

$$V = \frac{32}{15} \cdot \frac{1}{\nu + 5} \pi \Delta^2 \, Eh \, r^2 \, \mathrm{Sin}^2 \, \theta. \qquad (21)$$

Differentiating equation (21) with respect to θ, the moment of force required to shift the poles is

$$T = \frac{32}{15} \cdot \frac{1}{\nu + 5} \pi \Delta^2 \, Eh \, r^2 \, \mathrm{Sin} \, 2\theta. \qquad (22)$$

The maximum value of T occurs for $\theta = \pi/4$. Introducing $\nu = 0.25$, $E = 10^{12}$ dyn cm^{-2}, $\Delta = 1/298$, $h = 10^7$ cm and $r = 6.37 \times 10^8$ cm, we find $T_{max} = 5.6 \times 10^{31}$ dyn cm. Therefore, the total drift moment of the convection currents in the upper mantle, as studied by Ichiye (1971) and Richter (1973), would be adequate to overcome the elastic counter forces within the shell accompanying shift of the shell around the earth.

GLOBAL FRACTURE PATTERN

We consider now the problem of how the outer shell of the earth will deform and along which lines we may expect this to occur. For these deductions we apply the theory of plastic deformation of shells developed by Hencky (1924), Bijlaard (1936), and Van Iterson (1943). According to this theory the plastic flow begins to occur when the stress σ_p given by

$$\sigma_p = \left\{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2]\right\}^{1/2}. \qquad (23)$$

surpasses a critical value σ_c. In equation (23) σ_1, σ_2 and σ_3 are principal stresses. Bijlaard (1936), and Turcotte and Oxburgh (1973) have already applied the theory of plasticity for crustal problems and discussed its validity in such cases. Introducing the stresses σ_λ, σ_ψ and τ instead of σ_1, σ_2 and σ_3 in equation (23), we find

$$\sigma_p = \left[\frac{(\sigma_\lambda + \sigma_\psi)^2}{4} + \frac{3(\sigma_\lambda - \sigma_\psi)^2}{4} + 3\tau^2\right]^{1/2}. \qquad (24)$$

By introducing equation (16) in (24), the result is

$$\sigma_p = \sigma_o \; [\mathrm{Cos}^2 \lambda + \frac{7}{12} \mathrm{Sin}\,(2\psi - \theta)\, \mathrm{Sin}^4 \lambda]^{1/2} \qquad (25)$$

where

$$\sigma_o = \frac{2\sqrt{3}\Delta E \,\mathrm{Sin}\,\theta}{\nu + 5}.$$

Since plastic deformation is characterized by conditions of flow the value of ν in this case is about 0.5.

Equation (25) describes the distribution of σ_p in the outer shell of the earth for each value of θ. It gives an idea about the zones of the shell that must first be liable to plastic flow. The value of σ_o is 2.1 x 10^9 dyn cm^{-2} for $\theta = 80°$. If we adopt the critical stress σ_c = 1.6 x 10^9 dyn cm^{-2}, the stress ratio I is

$$I = \frac{\sigma_p}{\sigma_c} = \frac{2.1}{1.6}\left[\mathrm{Cos}^2\,\lambda + \frac{7}{12}\,\mathrm{Sin}\,(2\psi - \theta)\,\mathrm{Sin}^4\,\lambda\right]^{1/2}. \quad (26)$$

Plastic fracture occurs when σ_p approaches σ_c. Therefore, equation (26) describes the plastic fracture lines in the outer shell of the earth caused by the shift of poles for I = 1. The fracture lines for I = 1 have been computed by means of equation (26) and have been drawn in stereographic projection as shown in Fig. 4. Fig. 4 can be changed over into another projection; we have transformed it onto a map in Fig. 5 for a shift of poles over 80° along the meridian of 75° W. This fracture pattern follows directions roughly in the N-E and N-W direction on the northern hemisphere and in the S-E and S-W direction on the southern hemisphere. Therefore the directions and locations of the fracture lines in Fig. 5 disclose the trend of the existing boundary system of six major tectonic plates (Eurasian, Indian, Pacific, North American, South American, African) as described by Morgan (1968) LePichon (1968) and Isacks et al. (1968). After the original splitting of the outer shell of the earth as the first stage of sea floor spreading (Richter, 1973), the major tectonic plates possibly became subject to further breakup by plate motions. Because the fracture lines are based upon the simplifying assumptions of the uniform thickness and the homogeneity of the earth's shell which are certainly not absolutely true, we have to expect that the boundary of tectonic plates will not accurately follow the mathematical fracture lines which have been deduced. Taking this into account in the investigation of the correlation between the boundary features of plates and the fracture lines, we may consider them in good harmony. Since the choice of the magnitude and direction of the polar shift determines the position and direction of the fracture lines, the locations of plate boundaries at earlier stages in the earth's history may be investigated by following the path of polar wandering.

CONCLUDING REMARKS

A correlation has been found between the global boundary system of tectonic plates and polar wandering. The stress analysis in the present paper shows that the relationship of the fracture of the outer shell of the earth with respect to the shift of poles is influenced by geophysical parameters such as the flattening of the earth's figure, angular shift of the axis of earth's rotation, modulus of elasticity, and Poisson's ratio of the crust material of the earth. This and the previous convection results, as obtained by Richter (1973) and Ichiye (1971) can only have necessarily vague explanations of a tectonic catastrophe owing to almost complete lack of understanding of the breakup mechanism. They are, however, not unexpected if plasticity arguments are accepted. Based on theories for the originating of plastic deformation in elastic media, the resulting fracture lines over the surface of the earth have been determined. These lines show a remarkable correlation to the boundary system of the major tectonic plates. If this correlation is not fortuitous, and this does not appear probable, we have to suppose that the outer shell of the earth at some moment of its history has indeed undergone a corresponding plate-breaking in the process of polar wandering.

The magnitude and direction of polar shift would alter the locations of fracture zones. In this case the breaking mechanism of plates would become dependent on the path of polar wandering. The problem of determination of the date for original breakup of the outer shell of the earth must therefore wait for detailed study of the evolution of plate motions.

ACKNOWLEDGMENT

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FIGURE CAPTIONS

Figure 1. Stresses in spherical shell

Figure 2. Effect of the shift of the earth's axis of rotation.

Figure 3. The coordinate system ψ and λ .

Figure 4. Stress intensity I in stereographic projection of the half-sphere for shift of the poles over θ . The solid lines for I = 1 are fracture lines.

Figure 5. Fracture lines for a shift of the poles over 80° along the meridian of 75°W. The boundary system of six major tectonic plates coincides with the directions of these lines.

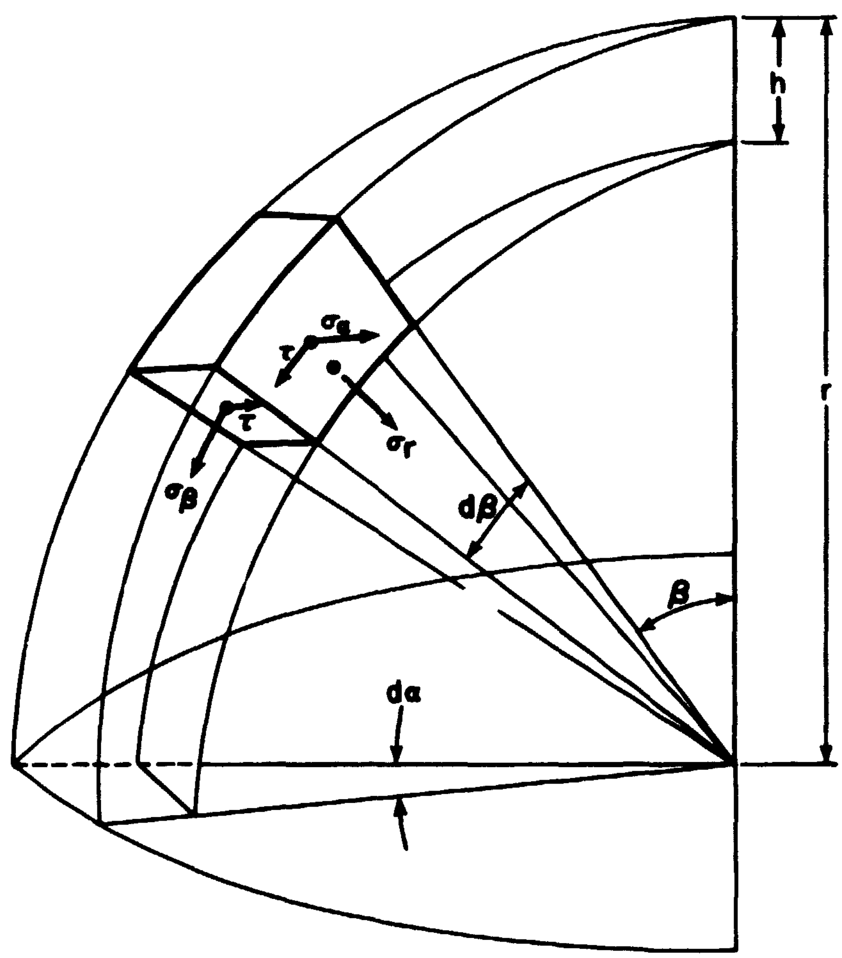


Figure 1. Stresses in spherical shell.

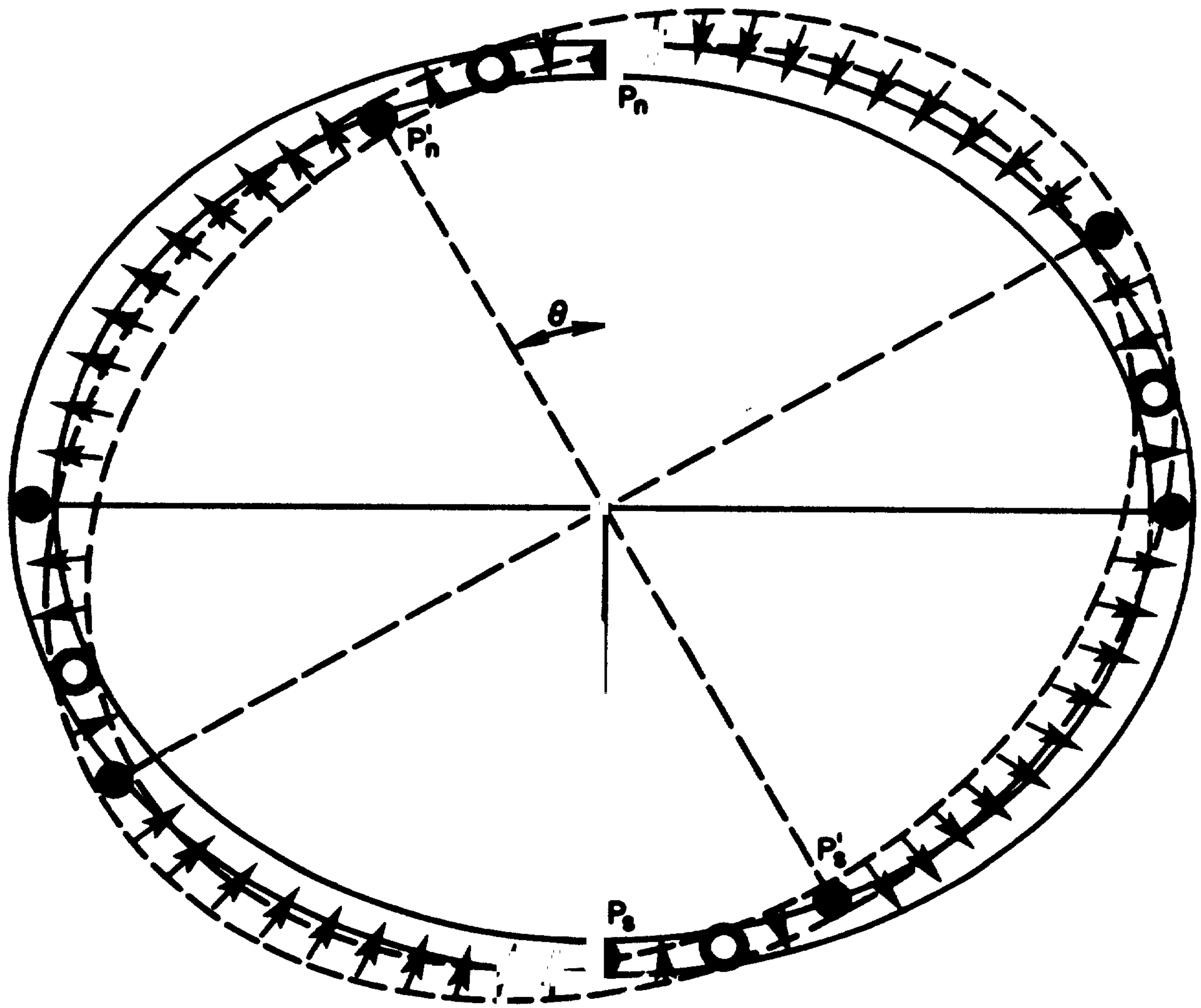
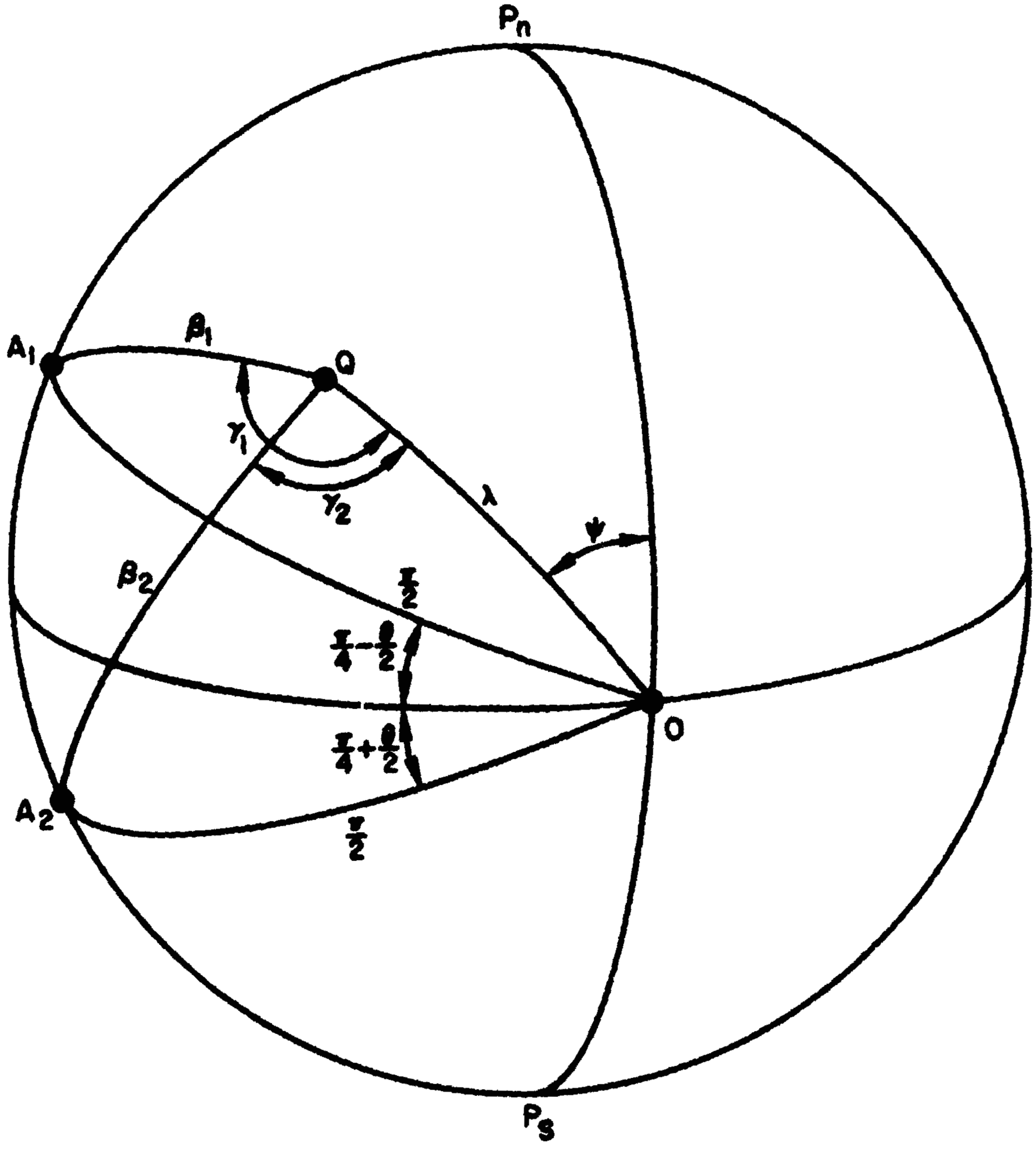


Figure 2. Effect of the shift of the earth's axis of rotation.



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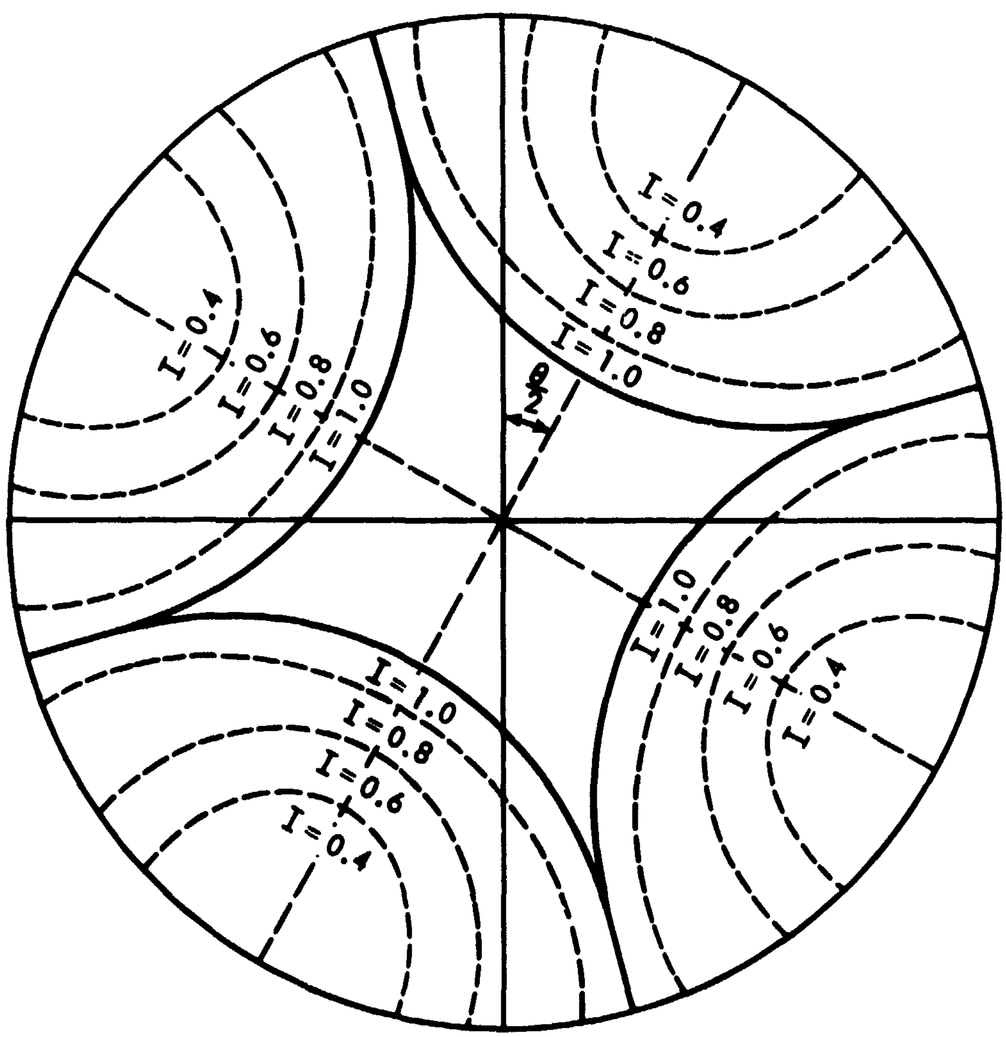

Figure 4. Stress intensity I in stereographic projection of the half-sphere for shift of the poles over θ. The solid lines for I = 1 are fracture lines.

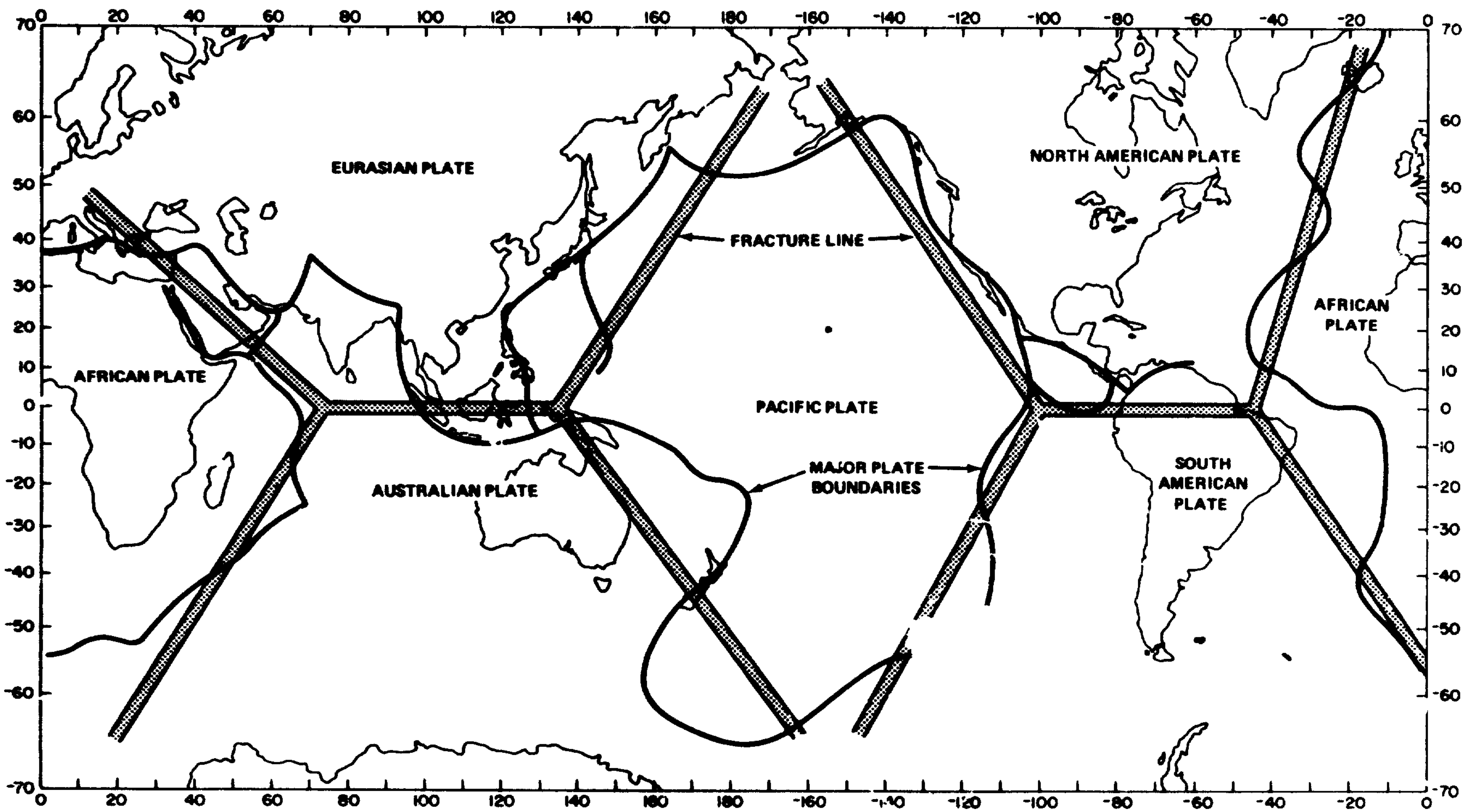

Figure 5. Fracture lines for a shift of the poles over 80 ° along the meridian of 75 ° W. The boundary system of six major tectonic plates coincides with the directions of these lines.