Lithospheric Flexure at Fracture Zones

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Bathymetric profiles across six major fracture zones (FZ's) in the North Pacific are used to demonstrate the absence of vertical slip on the fossil fault planes. The scarp heights on these FZ's are constant with age and equal to the initial vertical offsets at the ridge-transform fault-FZ intersections. Because of the frozen-in scarp and the differential subsidence of lithosphere far from the FZ, the lithosphere bends in the vicinity of the FZ. This flexure results in a characteristic ridge-rough topographic FZ signature. The flexural amplitude, which is the difference between the scarp height and the overall change in depth across the FZ, increases with age. Good fits to the bathymetric profiles across the Mendocino and Pioneer FZ's are obtained by modelling the topography as the flexure of a thin elastic plate with an age-dependent effective elastic thickness. Results of the modelling indicate that the base of the elastic lithosphere is approximately defined by the 450°C isotherm. Maximum bending stresses at FZ's are on the order of 100 MPa, substantially less than the stresses encountered at subduction zones. Because the Mendocino and Pioneer FZ's are separated by less than a flexural wavelength, they are elastically coupled.

INTRODUCTION

Flexure of the oceanic lithosphere is commonly observed in the bathymetry across subduction zones and around islands and large seamounts [Turet, 1979]. The trench and outer rise topography at a subduction zone is the flexural response of the elastic lithosphere to a vertical end load and bending moment applied at the trench axis [Gunn, 1937, 1947; Hanks, 1971; Watts and Talwani, 1974; Caldwell et al., 1976; Parsons and Molnar, 1976]. The moat and outer rise topography surrounding many islands and seamounts is the flexural response of the elastic lithosphere to the isolated vertical load [Gunn, 1943; Walcott, 1970; Watts and Cochran, 1974; Watts, 1978]. The wavelength of the flexural topography is a function of the effective elastic thickness $h_e$ of the lithosphere, while the amplitude of the flexure depends on both $h_e$ and the applied bending moment or vertical load.

Recent flexure studies of subducting oceanic lithosphere and lithosphere loaded by the Hawaiian-Emperor chain have shown that the effective elastic thickness of the lithosphere is approximately proportional to (age)$^{1/2}$ [Watts, 1978; Caldwell and Turcotte, 1979; Watts et al., 1980; Bodine et al., 1981]. This behavior basically reflects the age-dependent thermal structure of the lithosphere and the strong temperature dependence of the creep processes which tend to relieve flexural stresses. To a first approximation, the uppermost portion of the lithosphere has a viscous relaxation time that is greater than the age of the lithosphere, and it therefore exhibits elastic behavior; the lower portion of the lithosphere is hotter, less viscous, and relieves stresses on a much shorter time scale [Caldwell and Turcotte, 1979]. The division between the upper elastic and lower viscous portions of the lithosphere occurs at a temperature between 300°C and 600°C according to Watts et al. [1980], while Caldwell and Turcotte [1979] suggest a temperature of 700°C.

In this paper we demonstrate that lithospheric flexure also occurs at an oceanic fracture zone (FZ) as a consequence of the difference in subsidence rates on either side of the FZ and the permanence of the initial bathymetric step across the FZ. Figure 1 illustrates why this flexure occurs. Initially a FZ separates newly created lithosphere (0 Myr) from older lithosphere (20 Myr) (see A-A' in Figure 1). As these two segments of lithosphere move away from the ridge crest from A-A' to B-B', the depth far from the FZ on the older lithospheric segment increases at a higher rate than the depth far from the FZ on the older segment [Menard and Atwater, 1969; Delong et al., 1977; Sibuet and Mascle, 1978]. This effect is shown by the two subsidence curves in the middle of Figure 1. By the time the two segments have evolved to B-B', the overall change in depth across the FZ, $h_B$, is less than the initial value $h_A$. We propose, however, that the FZ does not slip during its evolution. Therefore the height of the scarp at the fracture zone will remain at its initial value $h_A$. The lithosphere must flex to satisfy both of these requirements as shown in the lower portion of Figure 1. The amplitude of this flexure $\delta h$ is the change in the differential subsidence from A to B, i.e., $h_A - h_B$. Further evolution from B to C increases the flexural amplitude to $\delta h$. The shape of this flexural topography depends upon the effective elastic thickness $h_e$ of the lithosphere. Since $h_e$ is proportional to (age)$^{1/2}$, the flexure is asymmetric about the FZ with the younger lithosphere flexing at a shorter wavelength than the older lithosphere.

The major objectives of this study are to demonstrate that lithospheric flexure occurs across the Pioneer and Mendocino FZ's and that this flexural topography is a primary topographic expression at these FZ's. This is accomplished by modelling the flexure and comparing the predicted depths with five bathymetric profiles crossing the two FZ's at different ages. In addition, we show that the flexure model is consistent with bathymetric profiles crossing four other north Pacific FZ's, the Clipperton, Clarion, Molokai, and Murray FZ's. The model for computing the flexure utilizes a thin elastic plate overlying an incompressible fluid half space. The model also incorporates a temperature-dependent effective elastic thickness. The ages on each side of the FZ determine both the initial bathymetric step across the FZ.
the Juan de Fuca ridge and 150°W because it contains identified magnetic anomalies [Atwater and Menard, 1970]. These anomalies were dated by using the magnetic time scale of Ness et al. [1980]. The Mendocino FZ has an age offset which varies between 30 Myr at 128°W and 25 Myr at 140°W. To the west of 140°W, the Mendocino divides and the age offset gradually shifts from the northern branch to the southern branch. However, only the total age offset across both FZ’s is known, since the lithosphere between these two FZ’s does not contain identified magnetic anomalies. The Pioneer FZ runs subparallel to the Mendocino FZ and has an age offset which varies between 8 Myr at its eastern end and 4 Myr at 104°W.

Five N-S trending bathymetric profiles crossing both FZ’s were chosen for this study and are shown in Figure 2. A few other continuous N-S profiles are available; however, these additional profiles lie within 100 km of the five we have chosen, and they therefore contain redundant information. The depths along each of the profiles were obtained from the sounding charts used to construct the ‘Bathymetry of the Northeast Pacific’ contour map [Mammerickx and Smith, 1981]. The spacings between soundings varied from 1 to 2 min of latitude. Because of this rather coarse sampling the shortest wavelength topography is aliased, but the longer wavelength topographic features are unaffected.

The bathymetry along each of the profiles A–E in Figure 2 is shown in Figure 3 together with the ages of each lithospheric segment. The dashed lines are the bathymetric profiles predicted by the depth-age relation (equation (1) of the following section) and the parameter values in Table 1. The predicted depths are in approximate agreement with the data for locations more than 1° (111 km) away from each of the FZ’s (marked by arrows in Figure 3). However, in the vicinity of each FZ there are large systematic differences between the predicted and observed depths. In each case, the ocean floor is anomalously shallow on the younger side of the FZ, while on the older side it is generally deeper than expected. We will show that the depth anomalies in Figure 3 are a consequence of lithospheric flexure.

**MODEL**

As the oceanic lithosphere ages, it cools and subsides according to the depth-age relation [Parker and Oldenburg,

![Fig. 2. Map of the northwest Pacific showing the locations of the five bathymetric profiles A–E crossing the Mendocino and Pioneer FZ's. The Mendocino FZ divides into north and south branches west of 140°W. Modified from Mammerickx [1982].](image)
The definitions of the parameters, and their values, are given in Table 1. Thus the benthic step $h_A$ across the youngest part of the FZ, section A-A’ in Figure 1, is given by

$$h_A = d(t_{A'}) - d(0) = \frac{2\alpha \rho_m (T_m - T_s)}{(\rho_m - \rho_w)} \left( \frac{\kappa}{\pi} \right)^{1/2}$$  \hspace{1cm} (2)

where $t_{A'}$ is the age offset across the FZ and $t_A = 0$. This benthic step is assumed to be frozen-in on the fossil fault plane as the FZ ages. However, the overall change in depth across the FZ decreases with age; along section B-B’ in Figure 1 it is $h_B$, where

$$h_B = d(t_{B'}) - d(t_B) = \frac{2\alpha \rho_m (T_m - T_s)}{(\rho_m - \rho_w)} \left( \frac{\kappa}{\pi} \right)^{1/2} (t_B^{1/2} - t_{B'}^{1/2})$$  \hspace{1cm} (3)

and $t_B$ and $t_{B'}$ are the ages of the lithosphere at section B-B’. The amplitude of the flexure at B-B’ is

$$\delta_B = h_A - h_B = \frac{2\alpha \rho_m (T_m - T_s)}{(\rho_m - \rho_w)} \left( \frac{\kappa}{\pi} \right)^{1/2} \cdot \{(t_{B'} - t_B)^{1/2} + t_{B'}^{1/2} - t_B^{1/2}\}$$  \hspace{1cm} (4)

where $t_{A'} = t_{B'} - t_B$. A contour plot of this flexural amplitude is shown in Figure 4 in terms of the age of the younger side of the FZ and the age offset. While flexural amplitude increases continuously with age, the rate of increase declines with age, and most of the amplitude is acquired while the FZ is young.

The wavelength of the flexure $\lambda$ is given by

$$\lambda = 2\pi \left( \frac{4D}{g(\rho_m - \rho_w)} \right)^{1/4}$$  \hspace{1cm} (5)

where $D$, the flexural rigidity, is

$$D = \frac{Eh_e^3}{12(1 - \nu^2)}$$  \hspace{1cm} (6)

### Table 1. Definitions and Values of Parameters and Functions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>$a$</td>
<td>thermal expansion coefficient</td>
<td>$3.1 \times 10^{-5}$ K$^{-1}$</td>
<td>Parsons and Sclater [1977]</td>
</tr>
<tr>
<td>$d_{ref}$</td>
<td>ridge crest depth</td>
<td>2500 m</td>
<td>Parsons and Sclater [1977]</td>
</tr>
<tr>
<td>$E$</td>
<td>Young’s modulus</td>
<td>$6.5 \times 10^4$ MPa</td>
<td>Parsons and Sclater [1977]</td>
</tr>
<tr>
<td>$g$</td>
<td>acceleration of gravity</td>
<td>9.82 m s$^{-2}$</td>
<td>Parsons and Sclater [1977]</td>
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<tr>
<td>$kappa$</td>
<td>thermal diffusivity</td>
<td>$8 \times 10^{-7}$ m$^2$ s$^{-1}$</td>
<td>Parsons and Sclater [1977]</td>
</tr>
<tr>
<td>$nu$</td>
<td>Poisson’s ratio</td>
<td>0.25</td>
<td>Parsons and Sclater [1977]</td>
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<tr>
<td>$rho_m$</td>
<td>mantle density</td>
<td>3330 kg m$^{-3}$</td>
<td>Parsons and Sclater [1977]</td>
</tr>
<tr>
<td>$rho_w$</td>
<td>seawater density</td>
<td>1025 kg m$^{-3}$</td>
<td>Parsons and Sclater [1977]</td>
</tr>
<tr>
<td>$T_c$</td>
<td>stress relaxation temperature</td>
<td>450°C</td>
<td>Watts et al. [1980]</td>
</tr>
<tr>
<td>$T_m$</td>
<td>mantle temperature</td>
<td>1365°C</td>
<td>Parsons and Sclater [1977]</td>
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<tr>
<td>$T_s$</td>
<td>surface temperature</td>
<td>0°C</td>
<td>Parsons and Sclater [1977]</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Function</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$</td>
<td>ocean floor depth</td>
<td>meters</td>
</tr>
<tr>
<td>$\delta$</td>
<td>flexural amplitude</td>
<td>meters</td>
</tr>
<tr>
<td>$D$</td>
<td>flexural rigidity</td>
<td>newton-meters</td>
</tr>
<tr>
<td>$h$</td>
<td>overall change in depth across a fracture zone</td>
<td>meters</td>
</tr>
<tr>
<td>$h_e$</td>
<td>effective elastic thickness</td>
<td>meters</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>flexural wavelength</td>
<td>meters</td>
</tr>
<tr>
<td>$\sigma_{xx}$</td>
<td>bending stress</td>
<td>megapascals</td>
</tr>
<tr>
<td>$\sigma_{zz}$</td>
<td>shear stress</td>
<td>megapascals</td>
</tr>
<tr>
<td>$w$</td>
<td>flexural topography</td>
<td>meters</td>
</tr>
</tbody>
</table>
The effective elastic thickness \( h_e \) is related to age \( t \) by [Caldwell and Turcotte, 1979]

\[
h_e = 2(\kappa t)^{1/2} \text{erfc}^{-1}\left(\frac{T_m - T_e}{T_m - T_s}\right)
\]

where \( \text{erfc}^{-1} \) is the inverse complimentary error function. Upon combining (5)–(7) we obtain

\[
D = \frac{2E(\kappa t)^{3/2}}{3(1 - \nu^2)} \left\{ \text{erfc}^{-1}\left(\frac{T_m - T_e}{T_m - T_s}\right) \right\}^3
\]

and

\[
\lambda = 2\pi \left(\frac{8E}{3g(\rho_m - \rho_w)(1 - \nu^2)}\right)^{1/4} \cdot (\kappa t)^{3/8} \left\{ \text{erfc}^{-1}\left(\frac{T_m - T_e}{T_m - T_s}\right) \right\}^{3/4}
\]

The lithosphere on the younger side of the FZ flexes with a shorter wavelength than the lithosphere on the older side of the FZ because \( \lambda \propto t^{3/4} \). In addition, the flexural wavelength on either side of the FZ increases as the FZ ages.

In calculating the flexural topography as a function of age along a FZ we have approximated the continuous time dependences of \( \delta \) and \( \lambda \) by using discrete 1 Myr time steps. Because the flexural problem is linear, the total flexural topography is the sum of the incremental contributions over all of the steps up to the age of the FZ.

The separation distance between the Pioneer and Mendocino FZ's (150-220 km) is less than one flexural wavelength when the age of the lithosphere between the two FZ's is greater than about 10 Myr. This produces a coupling of the FZ's and requires that the flexural problem be formulated so as to explicitly include the interaction. We have actually modelled the most general case in which \( N + 1 \) segments of lithosphere are separated by \( N \) FZ's. This configuration of FZ's is shown in Figure 5 for the case \( N = 2 \). The \( i \)th segment of lithosphere has a flexural rigidity \( D_i \) that depends upon its age \( t_i \) according to (8). The \( i \)th FZ is located at \( x_i \), and the flexural topography between the \( i \)th and \( (i + 1) \)th FZ's is \( w_{i+1}(x) \). The flexural amplitude at the \( i \)th FZ is \( \delta_i \); it is a function of the ages of the adjacent lithospheric segments and the duration of the time step since the previous increment of flexure.

The \( N + 1 \) homogeneous differential equations governing the flexural topography are

\[
D_1 \frac{d^4 w_1}{dx^4} + g(\rho_m - \rho_w)w_1 = 0 \quad x < x_1
\]

\[
D_i \frac{d^4 w_i}{dx^4} + g(\rho_m - \rho_w)w_i = 0 \quad x_{i-1} < x < x_i
\]

\[
D_{N+1} \frac{d^4 w_{N+1}}{dx^4} + g(\rho_m - \rho_w)w_{N+1} = 0 \quad x_N < x
\]

Their solutions are

\[
w_i(x) = e^{-2\pi \lambda_i} \left\{ A_i \sin\left(\frac{2\pi x}{\lambda_i}\right) + B_i \cos\left(\frac{2\pi x}{\lambda_i}\right) \right\}
\]

\[
+ e^{2\pi \lambda_i} \left\{ C_i \sin\left(\frac{2\pi x}{\lambda_i}\right) + D_i \cos\left(\frac{2\pi x}{\lambda_i}\right) \right\}
\]

for \( x_{i-1} < x < x_i \), where \( \lambda_i \) is given by (9) with \( \nu = t_i \). The coefficients \( A_i, B_i, C_i, \) and \( D_i \) are determined from the boundary conditions and matching conditions discussed below.

For \( N + 1 \) lithospheric segments there are \( 4(N + 1) \) coefficients to be determined. The boundary conditions require that the flexural topography must vanish as \( x \to \pm \infty \). This condition is satisfied if the four coefficients \( A_1, B_1, C_{N+1}, D_{N+1} \) are zero. The remaining \( 4N \) coefficients are determined from four matching conditions at each of the \( N \) FZ's. At the \( i \)th FZ the displacement must be discontinuous by the amount \( \delta_i \), while the slope, moment, and shear force must all be continuous. The matching conditions at \( x = x_i \) are therefore

\[
w_i - w_{i+1} = \delta_i
\]

\[
\frac{dw_i}{dx} - \frac{dw_{i+1}}{dx} = 0
\]

\[
-D_i \frac{d^2 w_i}{dx^2} + D_{i+1} \frac{d^2 w_{i+1}}{dx^2} = 0
\]

\[
D_i \frac{d^3 w_i}{dx^3} + D_{i+1} \frac{d^3 w_{i+1}}{dx^3} = 0
\]

We have solved these \( 4N \) equations by a method similar to the Thompson-Haskell technique [Haskell, 1953] used to determine the eigenfunctions and eigenfrequencies for Rayleigh and Love waves in a layered half space.

Once the coefficients have been determined, the flexural

\[
w(x)
\]

Fig. 5. Model used to calculate the flexural topography \( w(x) \) across multiple FZ's. Two FZ's are located at \( x_1 \) and \( x_2 \) and have flexural amplitudes \( \delta_1 \) and \( \delta_2 \). The flexural rigidity is different for each segment of lithosphere.
Fig. 6. Comparisons between theoretical bathymetric profiles computed from flexure models assuming no slip on the FZ's (dashed lines) and the observed bathymetric profiles A–E (solid lines). The asymmetric flexure predicted by the model across each FZ is a consequence of the increase in flexural wavelength with age according to (9). The apparent tilt in the bathymetry between the Pioneer and Mendocino FZ's occurs because the flexural wavelength is greater than their separation distance.

Topography can be calculated from (11). Other quantities of interest are the maximum bending stresses \( \sigma_{xx} \) and the average shear stresses \( \sigma_{xz} \) in the elastic lithosphere. The maximum bending stress at the top of the \( i \)th lithospheric segment is

\[
\sigma_{xx}(x) = \frac{-Eh_c}{2(1-\nu^2)} \frac{d^2w_i}{dx^2}(x) = \frac{6M_i(x)}{h_c^2}
\]

(16)

where \( M_i(x) \) is the bending moment

\[
M_i(x) = -D_i \frac{d^2w_i}{dx^2}(x)
\]

(17)

The average shear stress \( \sigma_{xz} \) is the shear force divided by \( h_c \)

\[
\sigma_{xz}(x) = \frac{-D_i}{h_c} \frac{d^2w_i}{dx^2}(x)
\]

(18)

The total bathymetry across a FZ is found by calculating the flexural topography for each time step from zero to the age of the FZ, summing the flexure over all of the time steps, and finally adding this flexural topography along each lithospheric segment to the depths calculated from the depth-age relation.

RESULTS

Figure 6 shows comparisons between model depths (dashed lines) and the five bathymetric profiles (solid lines). The values of the thermal parameters \( \alpha \), \( \kappa \), and \( T_m \) used in these model calculations are compatible with the depth-age and heat flow–age relations from the North Pacific [Parsons and Sclater, 1977]. The value of the stress relaxation temperature \( T_r \) was adjusted until good fits were obtained for all five profiles. The models shown in Figure 6 were calculated using \( T_r = 450^\circ \text{C} \) although reasonable fits were also obtained for values of \( T_r \) ranging from 350°C to 600°C.

The model predicts many of the features that appear in the observed profiles. In nearly every case the observed flexural amplitude is well matched by the model. This agreement
large flexural amplitudes (about 1 km) that must be sustained by stresses transmitted across the fossil transform faults for periods of greater than 50 Myr.

The maximum bending stress $\sigma_{xx}$ (measured at the top of the elastic layer) and the average shear stress $\sigma_{xz}$ along each profile have been calculated from the flexure model by summing (16) and (18) over the time increments. The largest stresses occur along profile E, and these are shown in Figure 7. The locations of the three FZ's are also marked in this figure. Relative minima and maxima of $\sigma_{xx}$ occur at points lying about 10–20 km to the south and north of each FZ, respectively. The largest maximum bending stress of $-120$ MPa occurs just south of the Mendocino S. FZ. The largest average shear stress of 28 MPa is found at the Mendocino N. FZ. The maximum values of $|\sigma_{xz}|$ and $|\sigma_{xx}|$ attained along the other profiles are summarized in Table 2.

To test whether lithospheric flexure occurs at other major Pacific FZ's, we have modelled bathymetric profiles crossing the Clipperton, Clarion, Molokai, and Murray FZ's. The most complete N-S bathymetric coverage in the North Pacific occurs at 140°W where a number of cruises span the latitudes between 4°N and 41°N [Mannerickx and Smith, 1981]. The locations of two of these ship tracks are shown in Figure 8a (dashed lines) together with the locations of the major FZ's (solid lines). The modelling of these bathymetric profiles requires that the age of each lithospheric segment be known. North of the Molokai FZ ages were determined from identified magnetic anomalies. South of the Molokai FZ there are no identified anomalies. However, along 140°W there are a number of deep-sea drilling sites which can be used to constrain basement ages. Site 162, which lies just to the south of the Clarion FZ, reached basement with an age of $49.5 \pm 3.6$ Myr [Van Andel and Bukry, 1973]. Other sites which did not reach basement were used to place minimum bounds upon ages and sediment thicknesses. For example, sites 70 and 71 lie just to the north and south of the Clipperton FZ, respectively, and have minimum age/sediment thickness of 46 Myr/338 m and 37 Myr/558 m, respectively. Where ages are uncertain (annotated by question marks in Figure 8b), we chose the age that would match the average seafloor depth away from the FZ based on the age/depth relation of Parsons and Sclater [1977]. At the Clipperton FZ, however, sediment thickness exceeds 300 m. Along this profile, ages were based upon seafloor depths corrected for sediment loading.

Figure 8b shows a comparison of the flexure model profiles (dashed lines) with each of the observed bathymetric profiles (solid lines). Except for the Clipperton FZ and the south side of the Murray FZ, the flexure model is compatible

<table>
<thead>
<tr>
<th>TABLE 2. Maximum Stresses (Megapascals)</th>
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<tr>
<td>Profile</td>
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<tr>
<td></td>
</tr>
<tr>
<td>A</td>
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<td>C</td>
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<tr>
<td>D</td>
</tr>
<tr>
<td>E</td>
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</table>

In every case the maximum shear stress $|\sigma_{xz}|$ occurs at the FZ. The maximum of $|\sigma_{xx}|$ occurs 10–20 km north of each FZ except for the Mendocino S. on profile E where it occurs 20 km south of the FZ.
with the observations. From these comparisons alone, however, one cannot determine if any slip has occurred on the fracture zones. The important result is that the observations do not disagree with the flexural model for the Clipperton, Clarion, Molokai, and Murray FZ’s and the agreement between the model and the data is again quite good across the Mendocino FZ where the age offset is greatest.

**Effects of Horizontal Heat Conduction**

In this section we demonstrate that horizontal conduction of heat across the FZ has only a minor influence upon the bathymetry and that it is valid to neglect this effect in computing the model bathymetric profiles of Figure 6. In writing the depth-age relation (1) we assumed that the thermal structure of the FZ is given by the half-space cooling model

\[ T(z, t) = (T_m - T_s) \operatorname{erf} \left( \frac{z}{2(kt_B)^{1/2}} \right) + T_s \]  

(19)

where \( z \) is the depth beneath the ocean floor and \( t \) is the age of the half space. This gives a step change in temperature across the FZ as a consequence of the age offset. Actually, the temperature will vary in a continuous manner across the FZ because of horizontal heat conduction [Louden and Forsyth, 1976]. The deviations in temperature from the step variation implied by (19) are responsible for buoyancy forces on the lithosphere which flex the younger lithosphere down and the older lithosphere up. The sense of this additional flexure is opposite to that of the flexure caused by the difference in subsidence rates. (The two effects were separated to avoid a numerical solution to the complete problem.)

The two-dimensional temperature structure along B-B' in Figure 1 is derived in Appendix A:

\[ T(x, z) = T_s + \frac{(T_m - T_s)}{2} \left\{ \operatorname{erfc} \left( \frac{x}{2(kt_B)^{1/2}} \right) \operatorname{erf} \left( \frac{z}{2(kt_B)^{1/2}} \right) + \operatorname{erfc} \left( \frac{-x}{2(kt_B)^{1/2}} \right) \operatorname{erf} \left( \frac{z}{2(kt_B)^{1/2}} \right) \right\} \]  

(20)

The temperature due solely to horizontal heat conduction \( \Delta T(x, z) \) is found by constructing the step variation from (19)
and subtracting it from (20):

\[
\Delta T(x, z) = \frac{(T_m - T_s)}{2} \left\{ \text{erfc} \left( \frac{-x}{2(\kappa t_f)} \right)^{1/2} - 2H(x) \right\} \cdot \left[ \text{erfc} \left( \frac{z}{2(\kappa t_f)} \right)^{1/2} - \text{erfc} \left( \frac{z}{2(\kappa t_f)} \right)^{1/2} \right] \quad (21)
\]

where \(H(x)\) is the Heaviside step function. The buoyancy forces arising from these temperature differences exert a pressure on the base of the lithosphere \(p(x)\) given by

\[
p(x) = -g \alpha \rho_m \int_0^z \Delta T(x, z) \, dz \quad (22)
\]

where \(\alpha\) is the coefficient of thermal expansion. Upon substituting (21) into (22) and performing the integration we find

\[
p(x) = -g \alpha \rho_m (T_m - T_s) \left( \frac{\kappa}{\pi} \right)^{1/2} (t_f)^{1/2}
\]

\[
- (t_f)^{1/2} \left\{ 2H(x) - \text{erfc} \left( \frac{-x}{2(\kappa t_f)} \right)^{1/2} \right\} \quad (23)
\]

The pressure force is measured positive downward to be consistent with our sign convention for the flexural topography \(w\).

The deflection of the lithosphere produced by this pressure is found by solving the equation for the thin elastic plate model [Turcotte, 1979]:

\[
D \frac{d^4 w}{dx^4} + g(\rho_m - \rho_w)w = p(x) \quad (24)
\]

subject to the conditions that \(w\) and \(dw/dx\) approach zero as \(x\) tends to \(\pm \infty\). To avoid the necessity of resorting to a numerical solution of (24), we will assume that \(D\) is constant across the FZ and has the value appropriate to the age of the lithosphere on the younger side of the FZ according to (8). This is a conservative assumption for the value of \(D\), since it actually overestimates the flexural topography caused by lateral heat conduction.

Equation (24) is most easily solved by taking its Fourier transform [Banks et al., 1977]. We obtain

\[
W(k) = \left( 1 + \frac{D|k|^4}{g(\rho_m - \rho_w)} \right)^{-1} \frac{2\alpha \rho_m(T_m - T_s)}{(\rho_m - \rho_w)} \left( \frac{\kappa}{\pi} \right)^{1/2} \cdot \left[ (t_f)^{1/2} - (t_f)^{1/2} \right] \cdot \frac{i}{k} \left[ 1 - \exp \left( -k^2 \kappa t_f \right) \right] \quad (25)
\]

where \(k\) is the wave number and \(W(k)\) is the Fourier transform of \(w(x)\). To obtain the topography \(w(x)\), we invert (25) numerically using a fast Fourier transform procedure. The age dependence of \(D = D(t_f)\) is accounted for by applying (25) to discrete 1-Myr time intervals using the value of \(D\) appropriate to the interval and incrementing the plate deflection throughout the evolution of the FZ.

Figure 9 shows the topography due to horizontal heat conduction across a FZ with a 20-Myr age offset when the age of the younger side of the FZ is 5, 15, and 45 Myr. The magnitude of this flexural topography increases with the age of the FZ. The effects of horizontal heat conduction on the topography extend progressively farther from the FZ as it ages. The flexural amplitude does not decrease as the thermal contrast (21) across the FZ decreases with age because each increment of flexural topography becomes frozen in as the elastic lithosphere thickens from below. We have seen in the model section that the flexural wavelength increases with age proportionately to \(t_f^{1/2}\), while the thermal diffusion distance increases as \(t_f^{1/2}\). Horizontal heat conduction does not change the flexural amplitude given by (4); it tends only to broaden the topographic profile. This is because the scarp height on the FZ is frozen in and the differential subsidence far from the FZ is unaffected by heat conduction across the FZ. In agreement with this, the topography in Figure 9 is zero both at \(x = 0\) and \(x = \pm \infty\).

The amplitude of the topography in Figure 9 is about 150 m. This is to be compared with the observed flexural amplitude of 500 m on profiles B–E in Figure 6. It should be remembered that the topography of Figure 9 significantly overestimates the effect of horizontal heat conduction on the older side of the FZ and may slightly overestimate it on the younger side because of our approximation to \(D\). Therefore while flexure due to horizontal heat conduction is small, it is not entirely negligible. In fact it may be responsible for the dips in the bathymetric profiles B–E on the north side of the Mendocino FZ (Figure 6).

DISCUSSION AND CONCLUSIONS

Global, regional, and local seismicity studies indicate that FZ’s do not slip over periods of time short enough to generate seismic disturbances. The majority of earthquakes with magnitudes greater than about 5 occur along plate boundaries including subduction zones, spreading centers, and transform faults [Barazangi and Dorman, 1969]. Large intraplate earthquakes rarely occur. A regional study of smaller intraplate earthquakes (magnitude greater than about 4) in the south central Pacific showed that only one earthquake out of about 100 occurred at a FZ [Okal et al., 1980]. Local studies of microseismicity at the intersections of transform faults, spreading ridges, and fracture zones demonstrate that while numerous microearthquakes occur along the transform faults and spreading ridges, the FZ’s are seismically inactive [Reid, 1976; Francis et al., 1978; Forsyth and Rowlett, 1979; Rowlett, 1981].

Our study indicates that at least two major FZ’s do not slip
over a time scale of $10^7$ yr, ruling out the possibility of aseismic slip on the FZ’s. The models of the flexural topography across profiles A–E (Figure 6) predict that the fossil transform faults must maintain shear stresses of up to 30 MPa. These stresses are more than twice as large as the stress drops derived from studies of major earthquakes [Brune, 1968]. If a FZ were a zone of weakness, then it should slip, like other faults, to relieve these large shear stresses. We conclude, therefore, that a FZ is not a zone of weakness; the fractured crust is only a remnant surface expression of past tectonic activity along the transform fault and spreading ridges. Beneath this fractured surface layer lies coherent oceanic lithosphere that is not significantly weaker than the surrounding lithosphere. This is not surprising when one considers the evolution of a FZ. The lithosphere on the younger side of the FZ is created by upwelling of hot mantle material along the ridge crest which terminates at the end of the transform fault (see Figure 1). The material upwelling at this intersection cools rapidly because of its proximity to the older segment of lithosphere. Thus the two segments of lithosphere fuse together at this intersection. The mechanical bond continues to increase in strength as the FZ ages. At depth, the FZ is not a structural boundary; instead it is a zone of large horizontal temperature gradients.

Our observation that the Pioneer and Mendocino FZ’s have not slipped significantly during their evolutions has implications for FZ’s with much smaller age offsets and for FZ’s situated on very old lithosphere. In both cases, the ridge and trough features predicted by our model should have sufficient amplitude to appear on large-scale bathymetric charts with 100- to 200-m contour intervals.

Consider the older portions of the Mendocino FZ separating lithospheric segments of ages 135 Myr and 140 Myr [Mammerickx, 1982]. The overall change in depth across this FZ is only 30 m according to the empirical depth-age relation of Parsons and Scater [1977]. If this were the only topographic expression of the FZ, then it would not be apparent on a bathymetric chart with a 100-m contour interval. However, the FZ is clearly delineated on the map of this region. Furthermore, the step in the bathymetry across a 500-km segment of this FZ lying between the Hawaiian-Emperor ridge and the Mapmaker Seamounts varies from 300 to 700 m (see Figure 3 of Mammerickx [1982]). Our model predicts a step amplitude of 715 m along this portion of the Mendocino FZ. The agreement, although not perfect, indicates that this portion of the Mendocino FZ has not slipped significantly for over 130 Myr.

FZ’s with very small age offsets should also be visible on bathymetric charts with a 100-m contour interval even when the overall change in ocean floor depth far from the FZ is less than 100 m. For example, (4) predicts that the bathymetric step across a FZ separating lithospheric segments with ages of 30 and 31 Myr is more than 300 m (see Figure 2). The overall change in ocean floor depth far from the FZ is only 32 m in this case.

Fracture zones with both large and small age offsets can be traced for thousands of kilometers across the ocean floor. If FZ’s slipped completely during their evolutions, then their topographic expressions would diminish with age. However, the FZ topography persists on lithosphere with ages greater than 100 Myr. Some of this topography may be the result of fracturing in the transform fault environment. However, the major topographic expression of Pacific FZ’s (i.e., the ridge and trough) is a consequence of the freezing in of the bathymetric step at the intersection of the transform fault with the ridge crest.

From an examination of Atlantic bathymetric charts it is evident that the ridges and troughs that are characteristic of Pacific FZ’s are not the dominant topographic expression of Atlantic FZ’s. Atlantic FZ’s generally consist of a narrow deep central valley surrounded by bordering ridges [Van Andel et al., 1971]. Our flexural model cannot explain this type of topography which apparently forms within the active transform fault environment. Furthermore, the amplitude of the topography along large age offset Atlantic FZ’s is generally 1–3 km (see Figure 4 of Feden et al. [1973]). This is greater than the expected flexural amplitude (<1 km), and therefore it may mask any flexure that has occurred along Atlantic FZ’s. Detection of flexural topography associated with Atlantic FZ’s is also made difficult by the roughness of the seafloor. The seafloor of the Atlantic is generally rougher than Pacific seafloor perhaps because of the difference in spreading rates [Menard, 1967]. As a consequence of the general roughness of the Atlantic seafloor and the large valleys and hills that are formed within Atlantic transform faults it may be impossible to observe any flexure along Atlantic FZ’s.

Lithospheric flexure at the Mendocino and Pioneer FZ’s is qualitatively similar to the bending of the lithosphere at subduction zones and around large seamounts. The main difference is that the maximum bending stresses inferred from subduction zone and seamount studies are usually greater than 500 MPa, while the stresses at FZ’s are substantially lower, about 100 MPa. Experimental and theoretical studies of lithospheric rheology indicate that the largest stresses inferred from purely elastic subduction zone models ($\sim10^3$ MPa) cannot be maintained [Kirby, 1980]. Accordingly, flexure at subduction zones has been reinterpreted with more realistic elastic-plastic rheologies [Turcotte et al., 1978; McDougal et al., 1978; Chapple and Forsyth, 1979; Forsyth, 1980; M. K. McNutt and H. W. Menard, unpublished manuscript, 1981]. In these models, the lithosphere behaves elastically until the yield stress is reached, at which point further increases in strain do not increase the stress (plastic behavior). Yield stress depends on temperature, overburden pressure, stress rate, and the sign of the stress (i.e., tension or compression). In contrast to the situation at subduction zones, the maximum bending stresses at FZ’s are probably smaller than the yield stresses and purely elastic models of the bending should suffice. The most important rheological consideration for modelling of lithospheric flexure at FZ’s is the increase of effective elastic thickness with age. Our attempts to match the observed flexural topography at FZ’s with a constant $h_e$ were not successful.

Our major conclusions are as follows:

1. There is no significant slip on the fossil fault planes of the Mendocino and Pioneer FZ’s. The bathymetric steps on these FZ’s are constant with age and equal to the initial vertical offsets at the ridge–transform fault–FZ intersections.

2. As a consequence of the frozen-in scarp and the differential subsidence of lithosphere far from the FZ, the lithosphere bends in the vicinity of the FZ. This flexure results in a characteristic ridge-trough topographic signature. The flexural amplitude, which is the difference between the scarp height and the overall change in depth across the FZ, increases with age.

3. Good fits to the bathymetric profiles across the Mendocino and Pioneer FZ’s can be obtained by modelling the
topography as the flexure of a thin elastic plate with an age-dependent effective elastic thickness.

4. Results of the modelling indicate that the base of the elastic lithosphere is approximately defined by the 450°C isotherm. Maximum bending stresses are on the order of 100 MPa, substantially less than the stresses encountered at subduction zones.

5. Because the separation of the Mendocino and Pioneer FZ’s is less than a flexural wavelength, there is elastic coupling between them.

APPENDIX: TEMPERATURES IN THE VICINITY OF A FRACTURE ZONE

The two-dimensional thermal structure near a FZ is found by solving the time-dependent heat conduction equation

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\kappa} \frac{\partial T}{\partial t}$$  \hspace{1cm} (A1)

where $z$ is depth and $x$ is distance from the fossil transform fault. The initial temperature distribution $T(x, z, t_A)$ is that appropriate to the lithosphere lying beneath A-A' in Figure 1 [Louden and Forsyth, 1976]

$$T(x, z, t_A) = T_m \hspace{1cm} x < 0$$  \hspace{1cm} (A2)

$$T(x, z, t_A) = T_s + (T_m - T_s) \text{erf} \left( \frac{z}{2(\kappa t_A)^{1/2}} \right) \hspace{1cm} x > 0$$  \hspace{1cm} (A2)

The boundary condition is

$$T(x, 0, t) = T_s$$  \hspace{1cm} (A3)

The solution to this problem for an arbitrary initial temperature distribution can be expressed as a two-dimensional convolution of the initial temperature with a line source Green's function

$$T'(x, z, t) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} T'(x_0, z_0, t_A) G(x - x_0, z - z_0, t - t_A) \, dx_0 \, dz_0$$  \hspace{1cm} (A4)

where $T' = T - T_s$ and the Green's function is [Carslaw and Jaeger, 1959]

$$G(x - x_0, z - z_0, t - t_A) = \frac{1}{4\pi \kappa (t - t_A)}$$

$$\cdot \{ \exp \left[ -(x - x_0)^2 + (z - z_0)^2 / 4\kappa (t - t_A) \right] - \exp \left[ -(x - x_0)^2 + (z + z_0)^2 / 4\kappa (t - t_A) \right] \}$$  \hspace{1cm} (A5)

After inserting (A2) into (A4) and integrating over $x_0$ and $z_0$ we find

$$T'(x, z, t) = \frac{(T_m - T_s)}{2}$$

$$\cdot \left[ \text{erfc} \left( \frac{x}{2[\kappa(t - t_A)]^{1/2}} \right) \, \text{erf} \left( \frac{z}{2[\kappa(t - t_A)]^{1/2}} \right) + \text{erfc} \left( \frac{-x}{2[\kappa(t - t_A)]^{1/2}} \right) \, \text{erf} \left( \frac{z}{2(\kappa t)^{1/2}} \right) \right]$$  \hspace{1cm} (A6)

where $t - t_A$ is the age of the lithosphere on the younger side of the FZ and $t$ is the age on the older side. The actual temperature is obtained by adding $T_s$ to $T'$.

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REFERENCES


Gunn, R., Quantitative aspects of juxtaposed ocean deeps, mountain chains, and volcanic ranges, Geophysics, 12, 238–255, 1947.


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