Mechanisms of normal fault development at mid-ocean ridges

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[1] Slow spreading ridge segments are characterized not only by small, closely spaced faults that develop near the segment center but also by large, widely spaced faults that develop near the segment ends, typically at the inside corner of a ridge-offset intersection. In this study we investigate the competing effects of stress accumulation in the lithosphere and the yield strength of the lithosphere in controlling the location of normal fault formation and direction of propagation. Seismic velocity models from the Mid-Atlantic Ridge in the Oceanographer-Hayes region and 29°N and the East Pacific Rise at 9°N were used to estimate the along-axis change in dynamic Young's modulus. Corresponding thermal and rheologic models were calculated to estimate the along-axis variation in yield strength. We then develop a thin-plate model to calculate the predicted location of fault initiation or reactivation and the subsequent propagation direction for different combinations of linear along-axis gradients in Young's modulus and yield strength. On the basis of this model we define two modes of normal fault development at slow spreading segments: mode C (center) faults, which develop at the segment center and propagate outward, and mode E (end) faults, which develop at the segment ends and propagate inward. Mode C faults are predicted to form at ridges where the along-axis variation in yield strength dominates the along-axis accumulation of stress. Conversely, mode E faults are predicted to develop at ridges where stress accumulation toward segment ends overcomes the high yield strength in these locations. In addition to the accumulation of stress caused by along-axis gradients in Young's modulus, we illustrate that shear stresses resisting relative plate motion along a transform fault will generate higher effective stress at inside corners, possibly concentrating mode E faulting in these locations. At fast spreading ridges, where along-axis gradients in stress and lithospheric strength are relatively small, more uniform patterns of faulting are predicted. The results of this study quantify how the interplay between the along-axis variations in stress state and the mechanical properties of the lithosphere controls the style of fault development at mid-ocean ridge segments. *INDEX TERMS:* 8164 Tectonophysics: Stresses—crust and lithosphere; 8159 Tectonophysics: Rheology—crust and lithosphere; 3035 Marine Geology and Geophysics: Midocean ridge processes; 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; *KEYWORDS:* mid-ocean ridge processes, normal faults, oceanic lithosphere, lithosphere dynamics, stresses, elastic properties

1. Introduction

[2] The structure of oceanic crust formed at a ridge axis is controlled by the interplay between magmatic and tectonic processes. To first order, the relative importance of tectonic extension by faulting in seafloor spreading appears to increase with decreasing spreading rate [*Edwards et al.*, 1991; *Carbotte and Macdonald*, 1994; *Goff et al.*, 1997]. Furthermore, the style of tectonic faulting also varies with spreading rate. Faults formed at slow spreading ridges are generally longer, with greater throw and larger spacing than faults formed at faster spreading rates [e.g., *Searle and Laughton*, 1981; *Macdonald*, 1982]. Systematic variations in faulting are also observed along individual segments of the slow spreading Mid-Atlantic Ridge (MAR) [e.g., *Shaw*, 1992; *Shaw and Lin*, 1993; *Escartín et al.*, 1999]. Near segment centers, where negative residual gravity anomalies [e.g., *Kuo and Forsyth*, 1988; *Lin et al.*, 1990; *Detrick et al.*, 1995] and seismic velocity structure [e.g., *Tolstoy et al.*, 1993; *Hooft et al.*, 2000] indicate crustal thickness to be greatest, faults are observed to be linear and closely spaced, with relatively small throws. Toward segment offsets, however, faults become more oblique, fault spacing increases, and the amount of throw on an individual fault is observed to increase (see Figure 1) [e.g., *Shaw and Lin*, 1993; *Searle et al.*, 1998; *Escartín et al.*, 1999]. In Figure 2 we present a geologic map of the MAR segment at 25°10′N (segment 6 of *Purdy et al.* [1990]) based on a combination of

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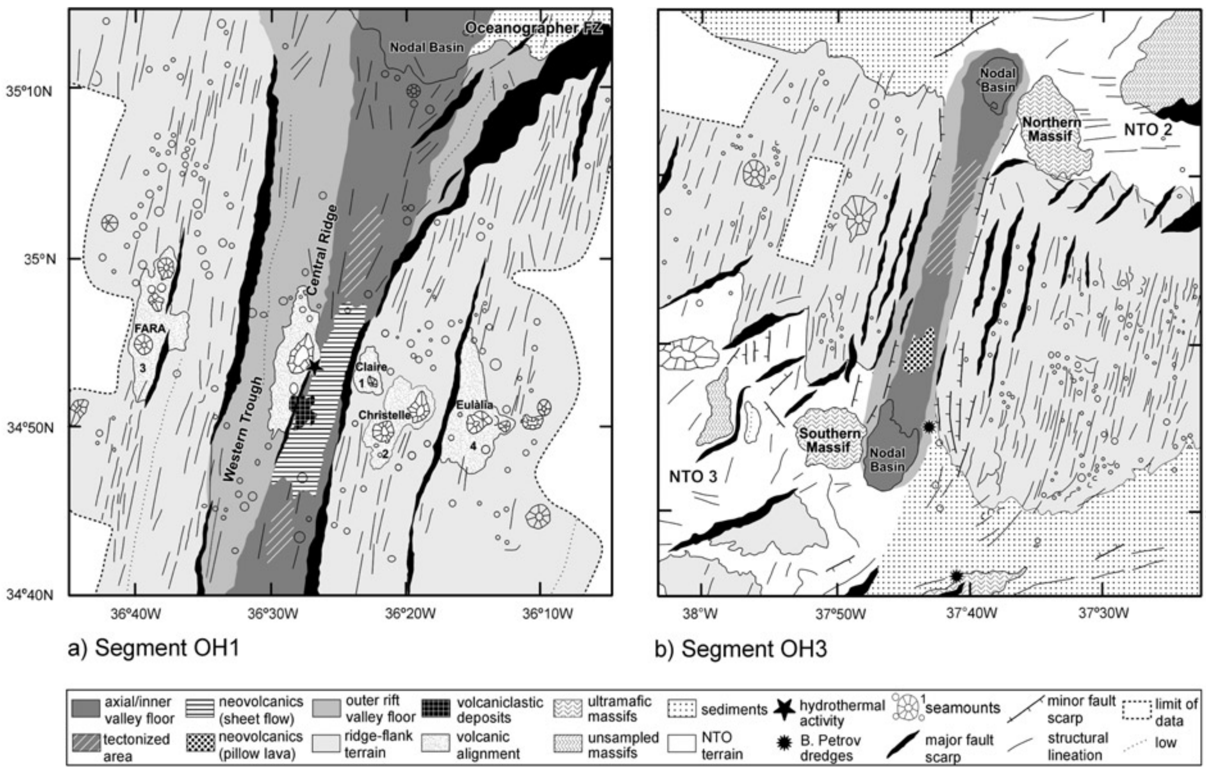


Figure 1. Geologic maps from *Gràcia et al.* [1999] of (a) MAR segment OH-1 and (b) segment OH-3 based on a combination of bathymetry, acoustic backscattering, submersible observations, and rock samples. Major fault scarps are shown in black. At both segments, faults appear to develop not only near segment center (mode C faults) but also toward segment ends (mode E faults). Note the asymmetry in faulting toward the segment ends, with most major faults forming on the inside-corner crust near the Oceanographer fracture zone (in Figure 1a) and nontransform offsets NTO2 and NTO3 (in Figure 1b).

multibeam bathymetry data [*Purdy et al.*, 1990; *Smith et al.*, 1995] and Towed Ocean Bottom Instrument (TOBI) side-scan sonar data [*Smith et al.*, 1995]. Fault throw was mapped along individual faults on the basis of strike-perpendicular bathymetry profiles, spaced every 1 km. Stars mark the locations of maximum throw along those faults for which it was possible to confidently determine throw along the entire length of the fault scarp.

[3] *Malinverno and Cowie* [1993] and *Shaw and Lin* [1996] attributed the first-order dependence of fault style on spreading rate to changes in the mechanical strength of the lithosphere caused by the difference in thermal state between fast and slow spreading ridges. Moreover, the observed change in fault throw and spacing along individual slow spreading segments has been hypothesized to reflect segment-scale variations in the strength of the brittle lithosphere [*Shaw*, 1992; *Shaw and Lin*, 1996]. Near segment centers, where warmer temperatures and thicker crust are predicted, yield strength calculations show lithospheric strength to be significantly reduced relative to the segment ends [*Shaw and Lin*, 1996; *Hirth et al.*, 1998].

[4] The symmetry of faulting is also observed to vary along individual slow spreading segments. At the segment center, faulting is generally symmetric across-axis, often with several inward dipping faults nested to form the median valley [e.g., *Macdonald*, 1982]. Toward the segment ends, however, the crust becomes highly asymmetric with large throw, widely spaced faults concentrated on the elevated crust of the inside corner of a ridge-transform intersection and smaller more closely spaced faults at the outside corner [*Severinghaus and Macdonald*, 1988; *Tucholke and Lin*, 1994; *Allerton et al.*, 1995; *Escartín et al.*, 1999]. Many of the faults formed on inside-corner crust are observed to have their maximum throw at or near the segment end (Figure 2). This observation suggests that these faults have initiated, or are preferentially reactivated, in these locations rather than at the segment center.

[5] These observations raise a fundamental question regarding the mechanics of faulting at mid-ocean ridges. Namely, if thicker crust and elevated temperatures indicate a weaker plate at segment centers, why are many faults observed to initiate, or preferentially reactivate, in the stronger lithosphere near segment ends, particularly on inside-corner crust? One potential explanation is that at certain times, stress accumulation in the lithosphere is enhanced toward the segment ends. Such an along-axis gradient in stress could be achieved if stress is preferentially released near the segment center due to greater magmatic extension in these areas [*Karson and Winters*, 1992; *Gràcia et al.*, 1999] while continuing to accumulate at the segment ends. Alternatively, variations in the elastic properties of the lithosphere [e.g., *Campbell*, 1978] or the geometry of a ridge-transform intersection [e.g., *Phipps Morgan and Parmentier*, 1984; *Pollard and Aydin*, 1984; *Grindlay and Fox*, 1993] could generate higher stresses toward segment ends.

[6] Here we present the results of a modeling study to quantify the competing effects of stress accumulation in the lithosphere and the mechanical strength of the brittle plate in order to predict the style of normal fault development and propagation. We show that at fast spreading ridges the lack of strong along-axis gradients in stress and lithospheric strength leads to relatively uniform fault patterns. In contrast, at slow spreading segments, significant along-axis variations in these two parameters generate a more complex pattern of faulting depending on the relative importance of stress and the mechanical properties of the plate. These and other

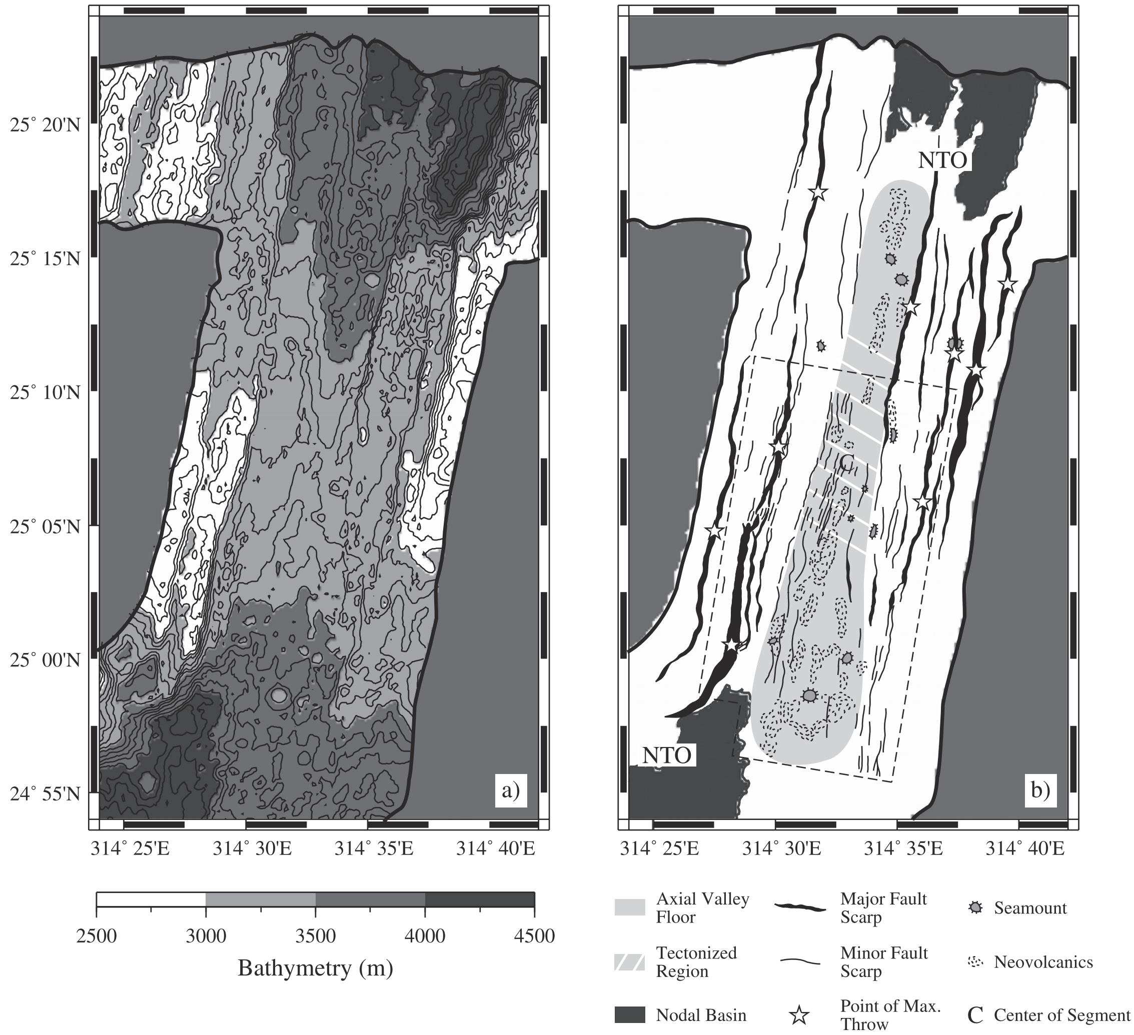


Figure 2. (a) Multibeam bathymetry from *Purdy et al.* [1990] and *Smith et al.* [1995] for the MAR segment at 25°10′N. Note the hourglass-shaped morphology of the axial valley, which is characteristic of many magmatically robust slow spreading segments. (b) Geologic map of the 25°10′N segment based on the multibeam bathymetry data in Figure 2a and TOBI side-scan sonar data from *Smith et al.* [1995]. Dashed box delineates the area within which the TOBI data are available. Throw of faults was measured along major fault scarps, and location of maximum throw is marked with a star. Note that major faults develop not only at the segment center (mode C faults) but also near the segment ends (mode E faults), particularly on inside-corner crust.

predictions are compared with observations, and the implications for different styles of fault development at fast and slow spreading ridges are discussed.

2. Rheology of a Mid-ocean Ridge Spreading Segment

[7] In order to understand how the state of stress and the mechanical strength of the lithosphere vary at a typical spreading segment, we first examine the constraints on these parameters at mid-ocean ridge spreading centers.

2.1. Young's Modulus and State of Stress

[8] Stress accumulation in the lithosphere is influenced by the elastic properties of the brittle layer. Hooke's law dictates that stress in an elastic body is directly proportional to the strain applied on the body and the Young's modulus of material. Therefore bodies with a greater Young's modulus will experience higher stress for a given strain than bodies with a lower modulus. Numerous laboratory studies have estimated the static elastic properties of rocks typically found on mid-ocean ridges [e.g., *Bass*, 1995, and references therein]. However, because laboratory experiments can only be performed on small rock samples, they are highly dependent on local heterogeneities in the sample. To avoid this problem, we take advantage of the fact that seismic velocity is a function of the elastic properties of the medium, and we use *P* wave velocity models to estimate the dynamic Young's modulus of the lithosphere [e.g., *Cheng and Johnston*, 1981; *Eissa and Kazi*, 1988]. The relationship between static and dynamic Young's modulus is somewhat complex, particularly at low confining pressures. However, laboratory and in situ studies have found that in general, the ratio of static to dynamic Young's modulus is between 1 and 2 [*Eissa and Kazi*, 1988; *Gudmundsson*, 1988; *Forslund and Gudmundsson*, 1991].

[9] Rewriting the equation for *P* wave velocity gives the following expression for dynamic Young's modulus [*Jaeger and Cook*, 1979]:

$$E = \frac{v_p^2(1+\nu)(1-2\nu)\rho}{(1-\nu)}, \tag{1}$$

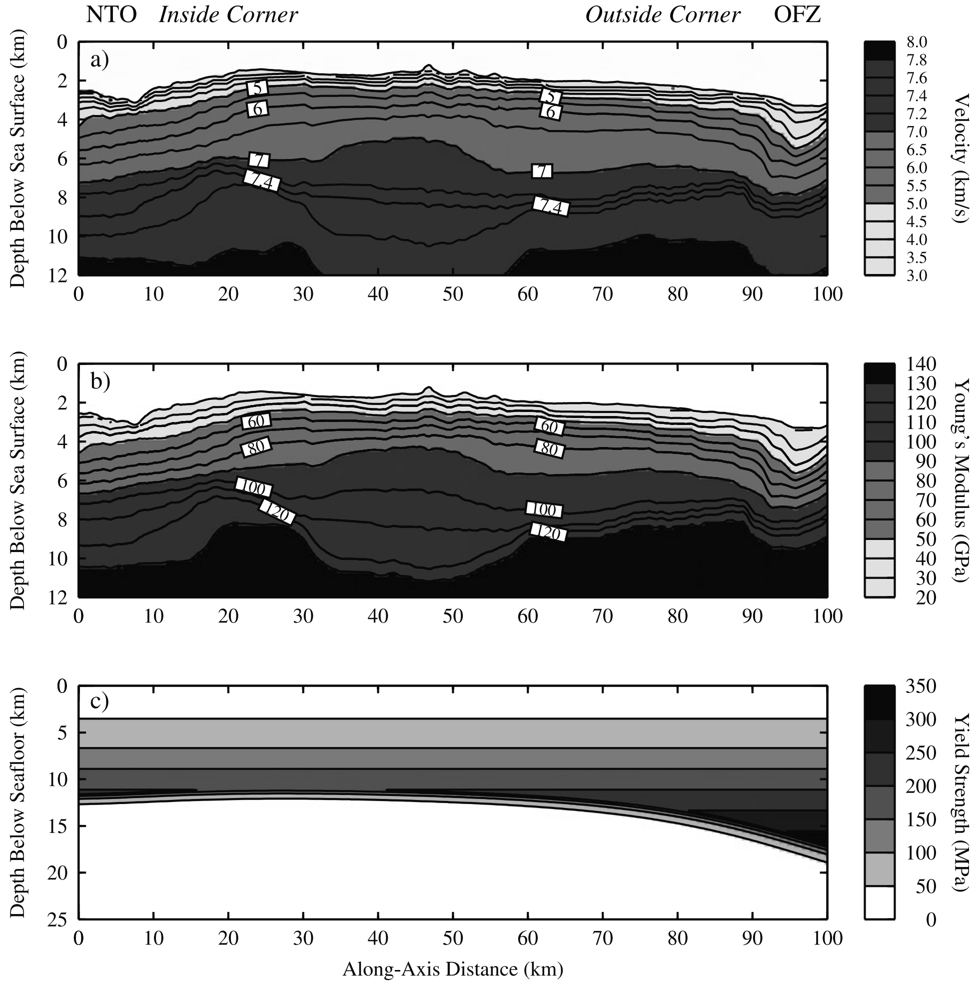
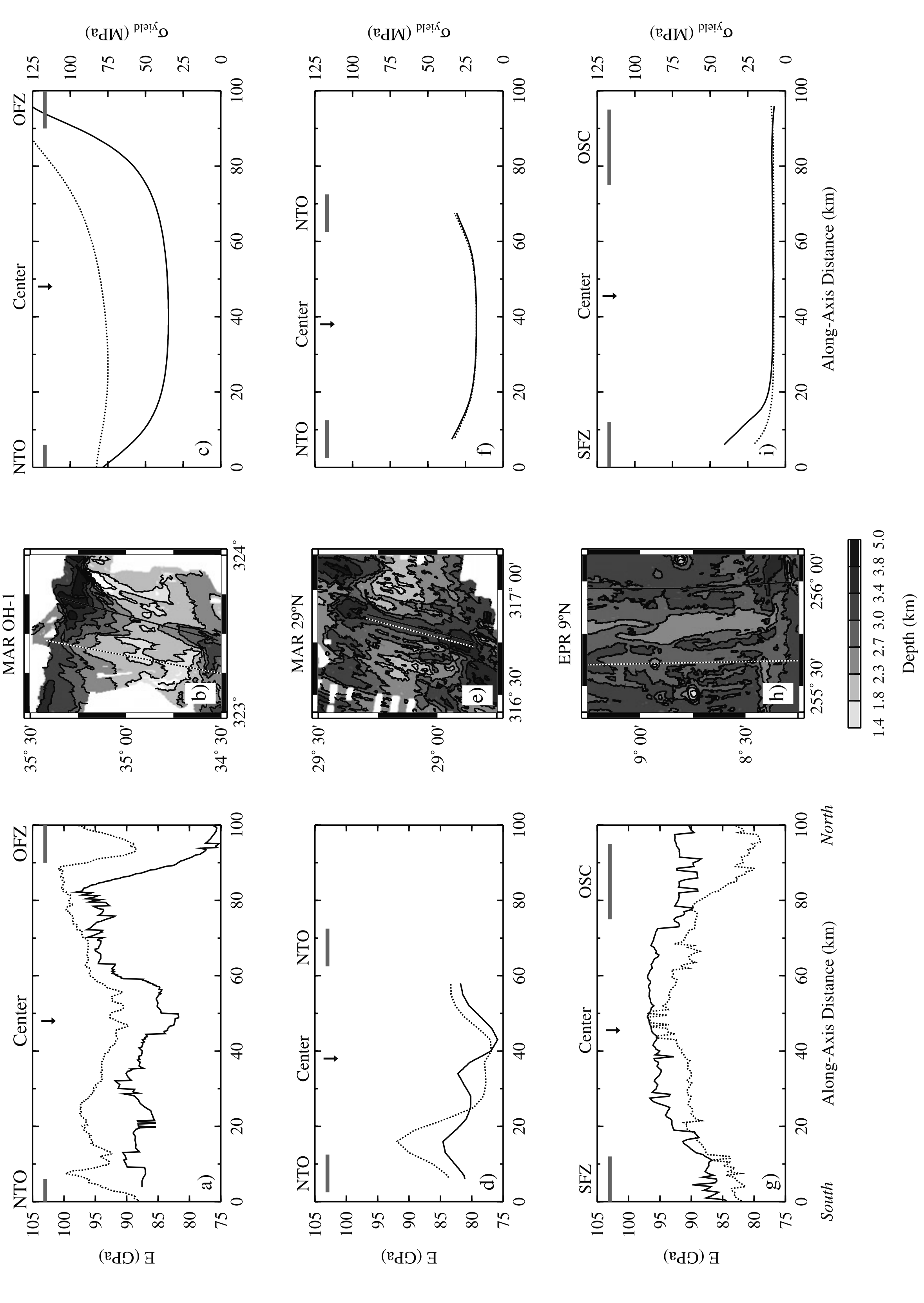


Figure 3. (a) Seismic *P* wave velocity model of *Canales et al.* [2000b] along the western rift mountains of MAR segment OH-1 (see Figure 4 for location). Segment is bounded to the south by a nontransform offset (NTO) and to the north by the Oceanographer fracture zone (OFZ). (b) Calculated dynamic Young's modulus with depth along the OH-1 segment, based on the *P* wave velocity and density models of *Canales et al.* [2000b] and assuming a Poisson's ratio of 0.30. See text for description of dynamic Young's modulus calculation. (c) Calculated yield strength depth section along the OH-1 segment. Yield strength is based on Byerlee's rule with a constant coefficient of friction $\mu = 0.85$ above the brittle-ductile transition and the ductile flow law below the brittle-ductile transition. We assume the dry diabase flow law of *Mackwell et al.* [1998] for the crust and the dry dunite flow law of *Chopra and Paterson* [1984] for the mantle. The thermal structure for the OH-1 segment was calculated using *Phipps Morgan and Forsyth*'s [1988] passive flow model with a half rate of 1.1 cm yr^{-1} and a mantle temperature of 1350°C at a depth of 100 km.

where v_p^2 is the *P* wave velocity, ν is the Poisson's ratio, and ρ is the density. Applying (1) to the *P* wave velocity model of *Canales et al.* [2000b] for the western rift mountains of MAR segment OH-1 (35°N), we calculated a corresponding Young's modulus model (Figure 3). The crustal and mantle densities were taken from the model of *Canales et al.* [2000b], which is based on the velocity-to-density relationships of *Horen et al.* [1996] and *Miller and Christensen* [1997] and constrained by

Figure 4. (opposite) (a) Along-axis variation in the calculated Young's modulus averaged to a depth of 8 km based on the seismic refraction profiles of *Canales et al.* [2000b] (dashed) and *Hooft et al.* [2000] (solid). (b) Location of *Canales et al.* [2000b] and *Hooft et al.* [2000] seismic lines. (c) Along-axis variation in the calculated yield strength averaged to a depth of 15 km along the *Canales et al.* [2000b] and *Hooft et al.* [2000] seismic lines. See Figure 3 for description of parameters used in calculation of yield strength. Shaded bars illustrate the location of the nontransform offset (NTO) and Oceanographer fracture zone (OFZ) bounding the OH-1 segment to the south and north, respectively. Small arrow shows segment midpoint. (d, e, and f) Calculated Young's modulus, location, and yield strength, respectively, for two profiles through the 3-D tomographic *P* wave inversion of *Wolfe et al.* [1995] at 29°N on the MAR. (g, h, and i) Calculated Young's modulus, location, and yield strength, respectively, for two seismic refraction profiles (J. Canales et al., submitted manuscript, 2001) on ~300-kyr-old crust at 9°N along the East Pacific Rise (EPR). Note that the two MAR segments display significant along-axis gradients in both Young's modulus (0.2–0.3 GPa km^{-1}) and yield strength (0.1–1.0 MPa km^{-1}), with the lowest values found at the center of the segment. In contrast, the EPR segment shows little variation in either Young's modulus or yield strength along axis, except within the Siqueiros fracture zone (SFZ) and overlapping spreading center (OSC) at the segment ends.


MAR OH-1
MAR 29°N
EPR 9°N
Depth (km)
1.4 1.8 2.3 2.7 3.0 3.4 3.8 5.0
E (GPa)
σyield (MPa)
Along-Axis Distance (km)
Center
NTO
OFZ
SFZ
OSC
South
North
a)
b)
c)
d)
e)
f)
g)
h)
i)

the observed gravity. Estimates of Poisson's ratio in oceanic crust range from 0.25 to 0.32 [e.g., *Christensen and Smewing*, 1981; *Bratt and Solomon*, 1984; *Collier and Singh*, 1998]. We choose an average value of 0.30 for Poisson's ratio and assign an uncertainty of ±15% to our calculations of Young's modulus.

[10] In order to incorporate the observed variations in Young's modulus into a thin-plate model of a ridge segment we assume that at any point the plate behaves in relation to the depth-averaged value of its rheologic properties. The dashed line in Figure 4a illustrates Young's modulus averaged to a depth of 8 km, which is the maximum depth of reasonable seismic resolution, along the *Canales et al.* [2000b] profile shown in Figure 3b. The depth-averaged value of Young's modulus increases from segment center toward the distal ends with an approximate gradient of 0.15–0.25 GPa km^{-1} and then decreases by $\sim$10 GPa within the offsets bounding the segment to the north and south. We performed a similar calculation along the axis of segment OH-1 using the *P* wave velocity model of *Hooft et al.* [2000] (solid line in Figure 4a). This calculation suggests that while the along-axis gradient in depth-averaged Young's modulus is similar both on and off axis, the off-axis profile is shifted to higher moduli by a constant value of 5–8 GPa. This would predict an across-axis gradient in Young's modulus of $\sim$0.15 GPa km^{-1}.

[11] We also calculated depth-averaged Young's modulus along the MAR segment at 29°N (Figure 4d) and the East Pacific Rise (EPR) segment at 9°N (Figure 4g) using the seismic velocity models of *Wolfe et al.* [1995] and J. Canales et al. (Segment-scale variations in crustal structure of 150- to 300-k.y.-old fast spreading oceanic crust (East Pacific Rise, 8°15′N–10°15′N) from wide-angle seismic refraction profiles, submitted to *Geophysical Journal International*, 2001, hereinafter referred to as J. Canales et al., submitted manuscript, 2001), respectively. The 29°N segment of the MAR shows a gradient similar to that of the OH-1 segment, while the EPR segment shows little along-axis variation in Young's modulus outside the fracture zone and overlapping spreading center at the segment ends. These results imply that the increase in depth-averaged Young's modulus toward the ends of a slow spreading segment is caused by thinner crust in these locations, resulting in a greater portion of the brittle plate being composed of high Young's modulus mantle rocks, such as olivine and pyroxene. In contrast, at fast spreading ridges the observed variations are much smaller except locally near major ridge offsets.

[12] An alternative approach is to average Young's modulus to the depth of the brittle-ductile transition, as opposed to a constant depth along the entire segment. The effect of this calculation would be to average to greater depths at the segment ends where the brittle-ductile transition is deeper (see Figure 3c), incorporating more high Young's modulus rocks of the lower crust and mantle and increasing the along-axis gradient. This approach was used along the OH-1 segment, and the resulting gradient was calculated to be $\sim$0.5 GPa km^{-1}, approximately twice the value calculated when averaging to a constant depth of 8 km. Thus it is possible that the depth-averaged values shown in Figures 4a, 4d, and 4g underestimate the true along-axis gradients in Young's modulus.

2.2. Yield Strength

[13] The mechanical strength of the lithosphere is often modeled using a strength-versus-depth profile ("yield strength envelope"), in which strength in the shallow, brittle regime is controlled by a frictional resistance law [e.g., *Byerlee*, 1978], while strength in the deeper, ductile regime is limited by power law creep [e.g., *Goetze and Evans*, 1979; *Brace and Kohlstedt*, 1980] (Figure 5).

[14] Depth-averaged yield strength was calculated along the OH-1, MAR 29°N, and EPR 9°N segments. Using the technique of *Phipps Morgan and Forsyth* [1988], we consider conductive and advective heat transfer in mantle flow driven solely by separating surface plates. Thermal models were calculated for each of the three spreading segments on the basis of the appropriate spreading rate and ridge-offset geometry. Along each of the available seismic lines, strength-versus-depth profiles were computed (e.g., Figure 3c) and averaged to a depth of 15 km, below which changes are negligible. The resulting depth-averaged yield strengths for the three segments are shown in Figure 4. Because a constant coefficient of friction, μ = 0.85, was used in all calculations, the along-axis gradients in depth-averaged yield strength are primarily thermally controlled.

[15] Because of the thermal cooling effect of ridge offsets, along-axis changes in depth-averaged yield strength are highly dependent on the length of the bounding offset. At MAR 29°N, for example, where the offsets at either end of the segment are $\sim$15 km in length, the predicted along-axis gradient in yield strength is $\sim$0.3 MPa km^{-1}. In contrast, at the MAR OH-1 segment, where the northern end of the segment is bounded by the 100-km Oceanographer fracture zone, the predicted along-axis gradient in yield strength is >2.0 MPa km^{-1}. The along-axis variation in yield strength is also strongly dependent on spreading rate, with higher rates having smaller along-axis changes. Note that even though the southern end of the EPR 9°N segment is bounded by the 75-km-long Siqueiros fracture zone, the depth-averaged yield strength remains relatively constant up to distances of <10 km from the offset.

[16] The *Phipps Morgan and Forsyth* [1988] model neglects the effects of hydrothermal cooling in the shallow crust and the heat of magma emplacement at the ridge axis, which were considered in the models of *Shaw and Lin* [1996] (Figure 5a). Hydrothermal circulation preferentially cools those portions of the lithosphere where open cracks permit fluid flow beneath the seafloor. *Shaw and Lin* [1996] suggest that this process would be enhanced toward segment ends, intensifying the cooling effect of ridge offsets and further increasing the mechanical strength of the lithosphere in these locations (Figure 5d). Magma injection, on the other hand, would tend to increase temperatures near the center of a slow spreading segment, where gravity and seismic models suggest greater crustal emplacement. This would decrease the mechanical strength of the lithosphere at the segment center (Figure 5b) and, when combined with the effect of hydrothermal cooling, lead to stronger along-axis gradients in depth-averaged yield strength. We compare depth-averaged yield strength calculated at the center and end of a 50-km-long northern MAR segment using the *Phipps Morgan and Forsyth* [1988] and *Shaw and Lin* [1996] models. The results suggest that the addition of hydrothermal cooling and the heat of magma emplacement, as included in the *Shaw and Lin* [1996] model, may increase the along-axis gradient in yield strength by $\sim$50%.

[17] In contrast, the effect of serpentinization may partially offset these effects. Serpentinized peridotites are observed to outcrop preferentially toward the end of slow spreading segments, in particular, at the inside corner of a ridge-offset intersection [*Karson et al.*, 1987; *Tucholke and Lin*, 1994; *Cannat et al.*, 1995]. *Escartín et al.* [1997] observed that serpentinites have a low coefficient of friction, $\mu \sim 0.3$, and thus can reduce the integrated strength of the lithosphere up to 30% toward the segment ends (Figure 5d). Therefore, if the coefficient of friction decreases from the center to the ends of a spreading segment due to the effects of serpentinites, it may reduce the along-axis gradient in yield strength.

[18] In summary, our calculations indicate that the along-axis gradients in depth-averaged Young's modulus and yield strength are in the range of 0.15–0.5 GPa km^{-1} and 0.2–2.5 MPa km^{-1}, respectively, along the slow spreading MAR. In contrast, at the fast spreading EPR, there appears to be little variation in either of these two parameters along a spreading segment, with the possible exception of a narrow (5–10 km) zone adjacent to a major offset. Because of the uncertainties involved, we use these estimates only as qualitative limits on the variations along an individual spreading segment. We then parameterize a thin-plate deformation model

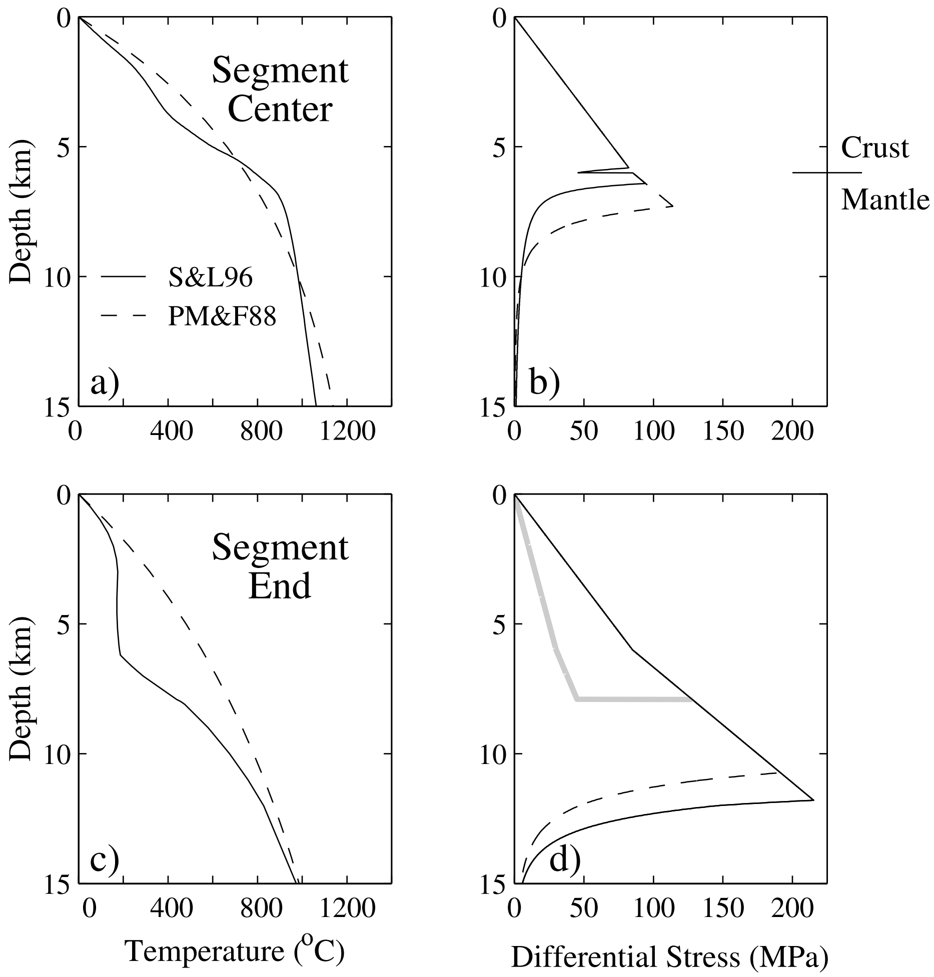


Figure 5. (a) Two temperature-depth profiles calculated at the center of a 50-km-long northern MAR segment. Dashed line (PM&F88) shows temperatures calculated from the passive flow model of *Phipps Morgan and Forsyth* [1988], assuming a half rate of 1 cm yr^{-1} and a mantle temperature of 1350°C at a depth of 100 km. Solid line (S&L96) illustrates the NMARL thermal model of *Shaw and Lin* [1996] for similar parameters but incorporates the effects of hydrothermal cooling in the crust and the heat of magma emplacement with variable crustal thickness. (b) Yield strength envelopes computed from thermal models in Figure 5a. Yield strength is calculated using Byerlee's rule with a constant coefficient of friction, $\mu = 0.85$, above the brittle-ductile transition and the ductile flow law below the brittle-ductile transition. We assume the dry diabase flow law of *Mackwell et al.* [1998] for the crust and the dry dunite flow law of *Chopra and Paterson* [1984] for the mantle. A strain rate of 10^{-14} s^{-1} was used for all calculations. (c and d) Thermal profiles and corresponding yield strength envelopes calculated at the end of the NMARL segment. Thick shaded line illustrates the predicted effect of serpentinization on the brittle regime above the 400°C isotherm when using the coefficient of friction for serpentinite ($\mu = 0.3$) from *Escartín et al.* [1997]. Note that the *Shaw and Lin* [1996] thermal model predicts lower strength at the segment center and greater strength at the segment ends relative to the model of *Phipps Morgan and Forsyth* [1988].

using linear gradients in Young's modulus and yield strength from the segment center to the distal ends.

3. Model Setup

[19] To date, most studies of faulting at mid-ocean ridges have focused on deformation in cross sections through the lithosphere [e.g., *Tapponnier and Francheteau*, 1978; *Phipps Morgan et al.*, 1987; *Chen and Morgan*, 1990; *Lin and Parmentier*, 1990; *Shaw and Lin*, 1996; *Buck and Poliakov*, 1998; *Poliakov and Buck*, 1998]. However, in this study we attempt to quantify the spatial pattern of normal fault development along a ridge segment. We construct a thin-plate model for a single ridge segment. A plane stress approximation is adopted, in which the vertical tectonic stresses are assumed to be negligible relative to the horizontal stresses in the lithosphere and there is no stress coupling between the lithosphere and its underlying ductile asthenosphere. As illustrated in Figure 4, both the depth-averaged Young's modulus and the yield strength are expected to vary along mid-ocean ridge segments, with the gradient a function of spreading rate and other factors. To parameterize the observed increase in Young's modulus E and yield strength σ_{yield} from segment center to the distal ends, we impose linear gradients in these two parameters (dE/dy and $d\sigma_{\text{yield}}/dy$, respectively) along the ridge axis (Figures 6b and 6c). We also impose an across-axis gradient in yield strength ($d\sigma_{\text{yield}}/dx$) twice the magnitude of the along-axis gradient in order to account for the thermal thickening of the lithosphere with age [e.g., *Watts et al.*, 1980] (see Table 1 for complete list of model parameters). Although Figure 4a suggests that an across-axis gradient in Young's modulus may be present at a typical

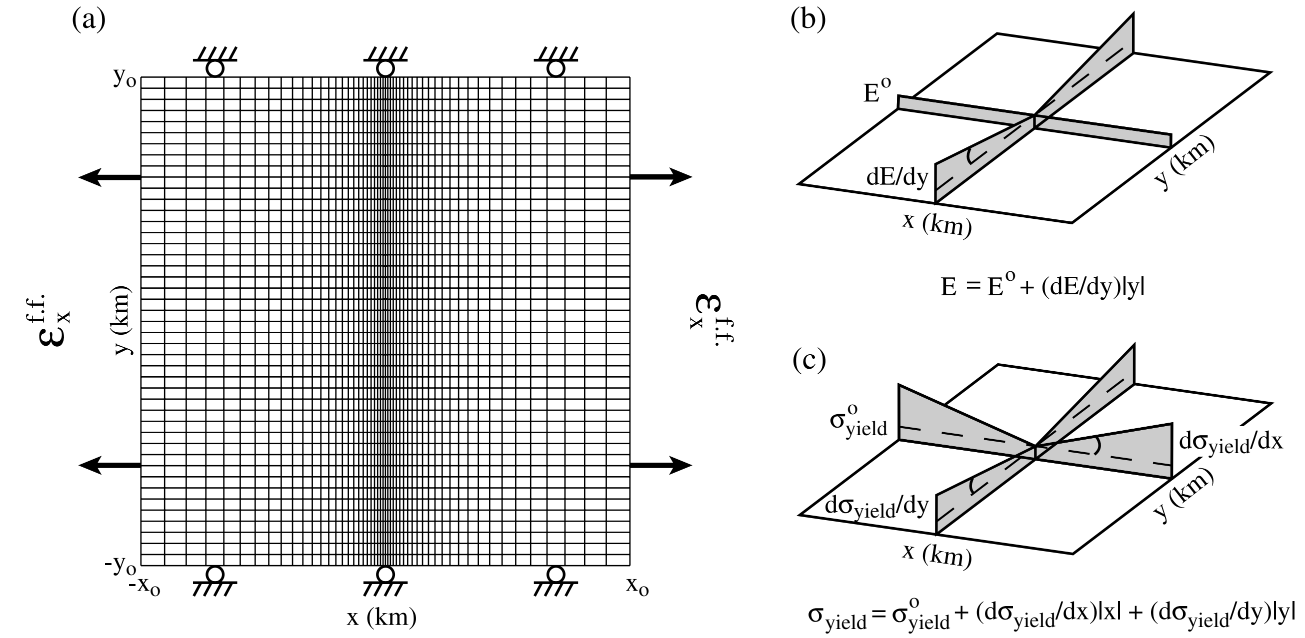


Figure 6. (a) The lithosphere at a mid-ocean ridge segment is modeled as a thin plate in plane stress undergoing uniaxial extension. The model space is 100 km × 100 km, with finer grid spacing toward the ridge axis. The north and south edges of the model are assigned to be free-slip boundaries with no displacement in the *y* direction. (b and c) Each element is assigned a Young's modulus *E* and a yield strength value σ_{yield}, which are allowed to vary linearly along and across axis.

slow spreading ridge segment, our calculations show that this gradient does not significantly influence the results of our model (see Appendix A for complete discussion), and thus we assume Young's modulus to be constant in the across-axis direction (Figure 6b).

[20] A gradually increasing extensional strain is applied at far-field model boundaries (left and right) to simulate spreading and the resulting stresses are calculated analytically throughout the model domain (see Appendix A). The far-field strain, ε_x^{ff}, is increased until the effective stress in the plate, defined as

$$\sigma_{eff} = \left\{\frac{1}{2}\left[\sigma_x^2 + \sigma_y^2 + \left(\sigma_x - \sigma_y\right)^2 + 6\tau_{xy}^2\right]\right\}^{1/2},$$

exceeds the material yield stress at some location in the model domain. Once yielding occurs, the elastic-plastic finite element model, ADINA [*Bathe*, 1996], is used to calculate the stresses and

Table 1. Model Parameters

	Meaning	Value	Units
ν	Poisson's ratio	0.3	
ρ	density		kg m^{-3}
μ	coefficient of friction	0.85	
v_p	*p* wave velocity		m s^{-1}
$x_\circ$	across-axis model space half width	50	km
$y_\circ$	along-axis model space half width	50	km
Δu_x	far-field half dispacement		km
ε_x^{ff}	far-field strain in *x* direction	$\Delta u_x/x_\circ$	
$\varepsilon_{\text{at yield}}^{ff}$	far-field strain at initial yielding		
E	Young's modulus		GPa
E°	Young's modulus at segment center		GPa
dE/dx	across-axis gradient in Young's modulus		GPa km^{-1}
dE/dy	along-axis gradient in Young's modulus		GPa km^{-1}
σ_{yield}	yield strength		MPa
$\sigma^\circ_{\text{yield}}$	yield strength at segment center		MPa
$d\sigma_{\text{yield}}/dx$	across-axis gradient in yield strength	$2{*}d\sigma_{\text{yield}}/dy$	MPa km^{-1}
$d\sigma_{\text{yield}}/dy$	along-axis gradient in yield strength		MPa km^{-1}
σ_{eff}	effective stress		MPa
$d\sigma/dy$	additional gradient in σ_{eff} to switch modes of faulting		MPa km^{-1}
σ_R	tensile stress resisting plate separation at ridge axis	$\sigma^\circ_{\text{yield}}$	MPa
σ_T	shear stress resisting plate motion along offset		MPa
$\Delta\sigma_{RT}$	change in σ_{eff} due to ridge-transform intersection		MPa

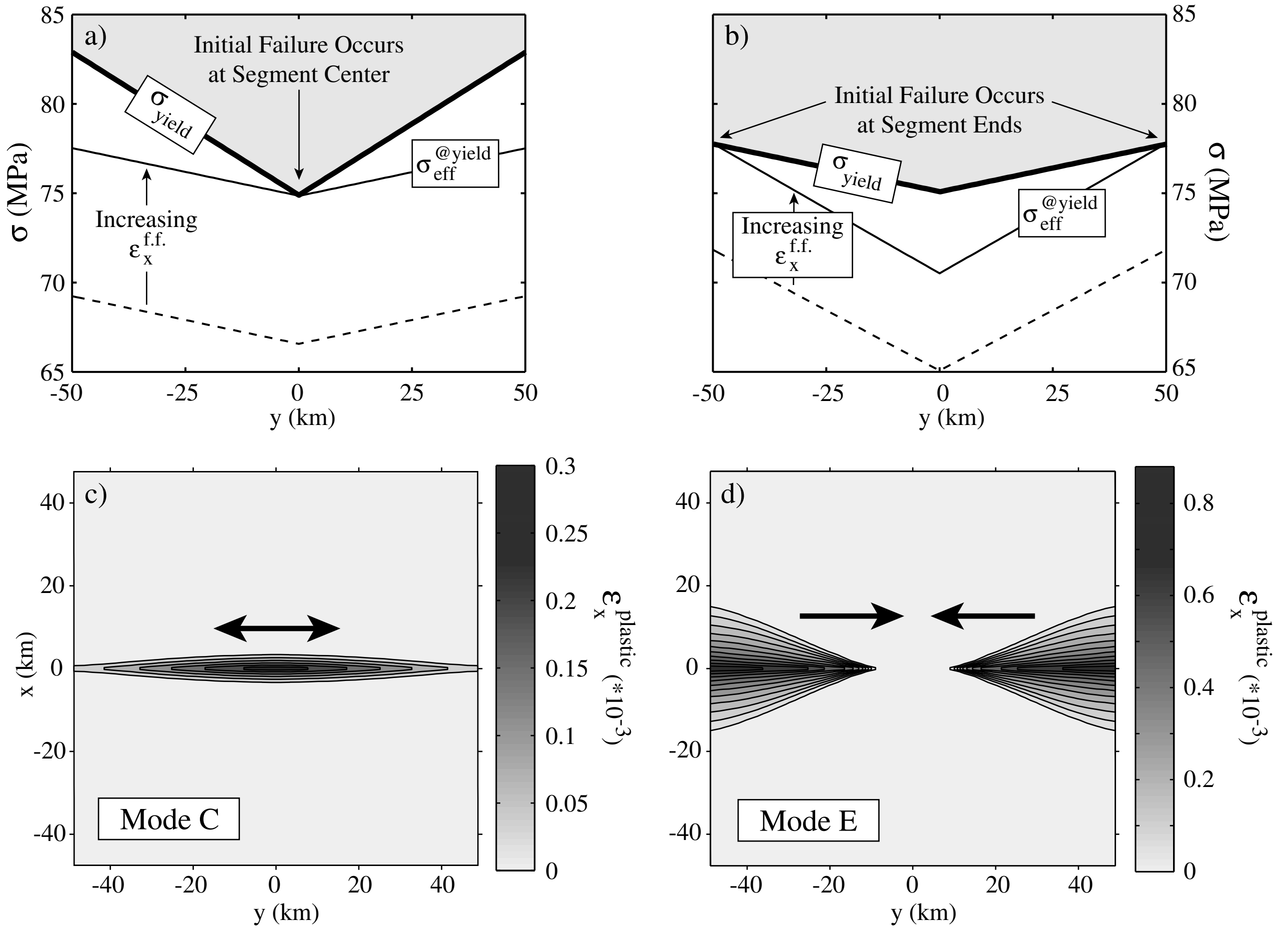


Figure 7. (a and b) Illustration of the relationship between effective stress (thin line) versus yield stress (thick line) at the ridge axis. Failure will occur if the effective stress is greater than the yield stress at any point. Mode C faults (Figure 7a) develop when the effective stress exceeds the yield stress first at the ridge center. Dashed line illustrates the effective stress for a value of ε_x^{ff} before yielding. Mode E faults (Figure 7b) develop if the effective stress exceeds the yield strength first at the segment ends. The relative magnitude of the along-axis gradient in Young's modulus (which controls the gradient in effective stress for a given far-field strain) and yield strength dictate whether mode C or mode E faults will develop. (c) Calculated plastic strain associated with mode C faults (propagation from the center of a segment toward its ends) calculated using the ADINA finite element model. Arrows indicate direction of fault propagation. (d) Calculated plastic strain associated with mode E faults (propagation from the segment ends toward the segment center). Note that the calculated plastic yield zone associated with mode E faults is wider than for mode C faults.

strains numerically throughout the model domain. We assume that after yielding, the plate behaves as a perfectly plastic material, and we examine the evolution of the plastic yield zone to provide a qualitative description of the resulting region of normal faulting at the ridge axis.

4. Model Results

[21] As the far-field extensional strain increases, stress will accumulate throughout the model space, until the effective stress exceeds the yield stress and failure occurs. Because the yield strength increases off axis, initial failure is expected to occur at a point along the ridge axis. Because of the higher Young's modulus toward the segment ends, stress builds up more rapidly in these regions under elastic extension of the plate. Competing with this stress accumulation pattern is the positive gradient in yield strength from segment center to the distal ends, which favors yielding to occur first at the segment center where the yield strength of the plate is minimum.

[22] On the basis of this model we define two modes of fault development at ridge segments: faults that develop at the segment center and propagate outward, called mode C (center) faults (Figures 7a and 7c), and faults that develop at the segment ends and propagate inward, called mode E (end) faults (Figures 7b and 7d). Mode C faults are expected to form at ridges where the along-axis variation in yield strength dominates the along-axis accumulation of stress. Conversely, mode E faults are expected to develop in environments where the stress accumulation associated with the along-axis gradient in Young's modulus overcomes the variation in yield strength (Figures 7b and 7d). Therefore, in our linear model it is the interplay between dE/dy and $d\sigma_{yield}/dy$ that determines whether failure is preferred at the segment center (Figures 7a and 7c) or at the segment ends (Figures 7b and 7d). Figure 8 shows calculation results illustrating how the relationship between dE/dy and $d\sigma_{yield}/dy$ controls the transition from mode C to mode E faults. The values for Young's modulus and yield strength at the segment center (E° = 75 GPa and σ°_{yield} = 50 MPa) are based on the depth-averaged Young's modulus and yield strength from the MAR OH-1 segment (Figures 4a and 4c).

[23] The relation between dE/dy and $d\sigma_{yield}/dy$ also plays an important role in controlling the evolution of the plastic yield zone after failure (Figure 9). In the case where enhanced accumulation of stress toward the segment ends perfectly balances the along-axis

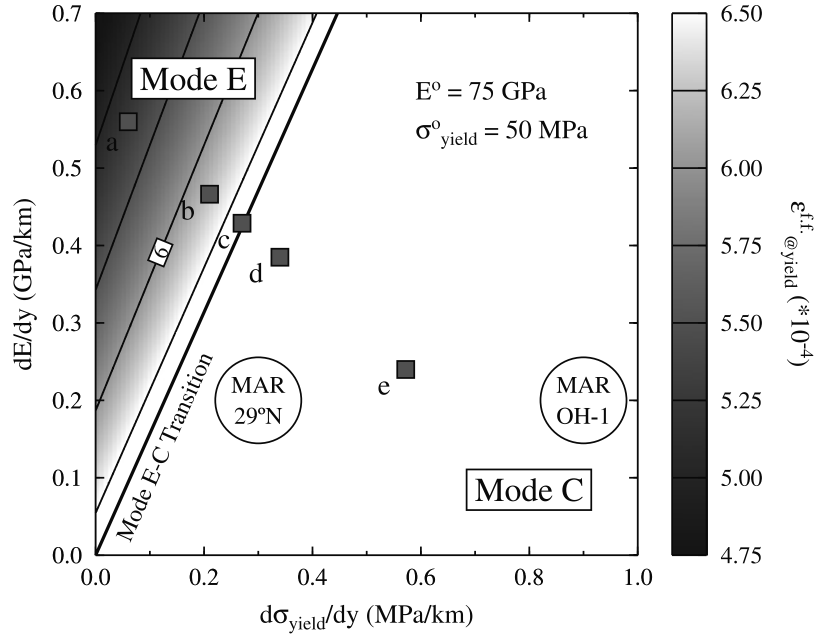


Figure 8. The ratio dE/dy versus $d\sigma_{\mathrm{yield}}/dy$ phase space showing the mode boundary between mode E and mode C faults (thick solid line). Shaded contours illustrate the far-field strain necessary for initial yielding. The values of Young's modulus and yield strength at the center of the segment are E° = 75 GPa and $\sigma^\circ_{\mathrm{yield}}$ = 50 MPa, respectively. Shaded squares show parameters used in the five cases shown in Figure 9. Approximate parameter values of the OH-1 and MAR 29°N segments are shown based on the values of dE/dy and d_{yield}/dy calculated in Figure 4. Note that when the along-axis gradient in yield strength dominates, mode C faults are predicted. Conversely, when the along-axis gradient in Young's modulus dominates over the gradient in yield strength, mode E faults are predicted.

gradient in yield strength, the plate will break uniformly along the entire ridge axis (Figure 9c). However, as dE/dy increasingly dominates $d\sigma_{\mathrm{yield}}/dy$, the plastic zone associated with mode E faults becomes more triangular in shape and propagates less toward the segment center for a given value of ε_x^{ff} (Figures 9a and 9b). In contrast, as $d\sigma_{\mathrm{yield}}/dy$ is increased relative to dE/dy, it becomes increasingly difficult for mode C faults to propagate outward toward the segment ends (Figures 9d and 9e).

[24] Another interesting prediction of this model is that the calculated plastic zone related to mode E faults is significantly wider in across-axis dimension than the plastic zone associated with mode C faults. This calculation suggests that mode E faults would tend to initiate and remain active over a broader across-axis region than mode C faults. Several segments of the slow spreading MAR have been documented to exhibit hourglass-shaped rift valleys [e.g., *Sempéré et al.*, 1993; *Detrick et al.*, 1995; *Weiland et al.*, 1996]. Although there is little geologic evidence constraining the width of the zone of fault initiation at ridge segments, *Bohnenstiehl and Kleinrock* [1999] used estimates of the amount of strain on individual faults to conclude that fault initiation is primarily confined within the median valley of a slow spreading segment. If correct, this observation suggests that segments with hourglass-shaped rift valleys may be characterized by wider zones of fault initiation at the segment ends than at the center. Furthermore, *Shaw* [1992] and *Shaw and Lin* [1993] observed that faults near segment ends are typically characterized by greater amounts of throw than faults at segment centers. This observation could be explained if mode E faults remain active, continuing to accumulate slip for a longer time period than mode C faults.

[25] The results of our model are moderately sensitive to the base values chosen for Young's modulus E° and yield strength $\sigma^\circ_{\mathrm{yield}}$ at the segment center. The observed variations in these parameters with spreading rate and offset length (Figure 4) suggest the need to test the importance of E° and $\sigma^\circ_{\mathrm{yield}}$ in influencing the transition from mode C to mode E faults. Figure 10 shows the mode C–E transition in dE/dy versus $d\sigma_{\mathrm{yield}}/dy$ phase space for four different combinations of E° and $\sigma^\circ_{\mathrm{yield}}$. Note that as $\sigma^\circ_{\mathrm{yield}}$ is decreased relative to E°, the slope of the mode C–E transition increases and the region of phase space for mode E faults decreases. In addition, the amount of far-field extensional strain required for initial yielding increases with increasing $\sigma^\circ_{\mathrm{yield}}$ and decreasing E°.

5. Discussion

5.1. Observations of Mode E Faults

[26] At slow spreading ridges, new normal faults typically initiate within the rift valley where the lithosphere is thinnest [*Searle*, 1984; *Bicknell et al.*, 1987; *Carbotte and Macdonald*, 1990]. Once formed, these faults grow in the along-axis direction through a combination of lateral propagation and linkage with other faults [e.g., *Cowie*, 1998], while simultaneously being rafted off-axis due to the injection of dikes at the ridge axis. The point of maximum throw on a fault scarp represents the location at which the fault is preferentially reactivated over time by slip events of higher frequency or larger magnitude. Several authors have argued that the location of maximum throw can be used as a proxy for the point of fault initiation [*Barnett et al.*, 1987; *Walsh and Watterson*, 1987]. If correct, this implies that many of the large faults observed toward the end of slow spreading segments may not only accumulate slip preferentially in these locations but may also initiate at or near the segment ends.

[27] Figure 1a illustrates an excellent example of a large mode E fault on inside-corner crust of the MAR OH-1 segment (oriented N45°E from 35°N to 35°10′N), with maximum throw near the segment end and tapering toward the segment center. Similarly, a series of discrete mode E faults (oriented N45°E just south of 34°N) can be seen on the inside-corner crust of segment OH-3 (Figure 1b). Another MAR segment that displays several prominent mode E faults is at 25°10′N (Figure 2). Here

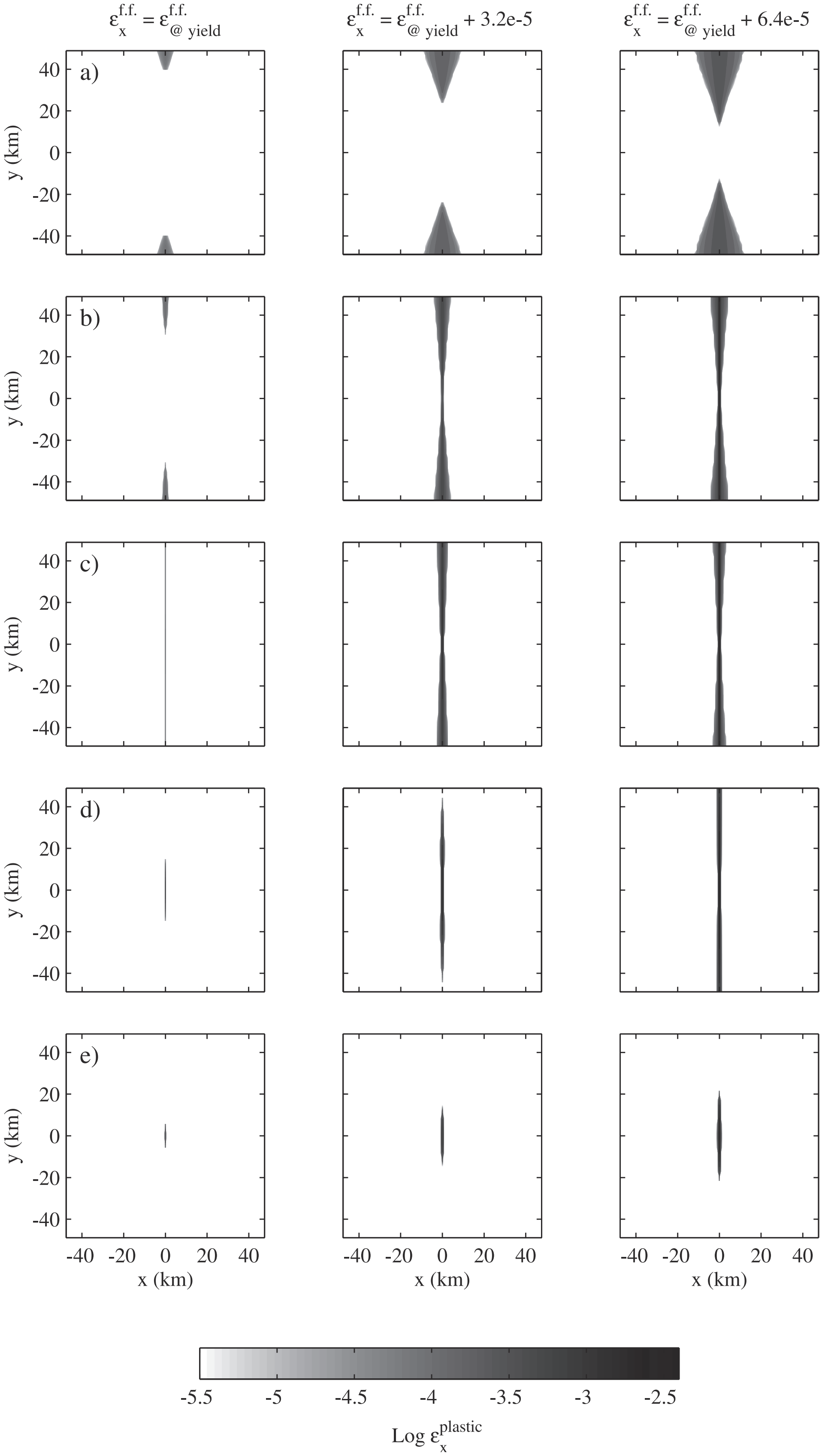


Figure 9. Plastic strain calculated using ADINA with increasing far-field strain for the five sets of parameters illustrated in Figure 8. (a and b) Mode E faults. (c) Uniform failure along the entire segment. (d and e) Mode C faults. For a given ε_x^{ff} the plastic deformation zone propagates a greater distance along-axis for the parameters in Figures 9b and 9d than in Figures 9a and 9e.

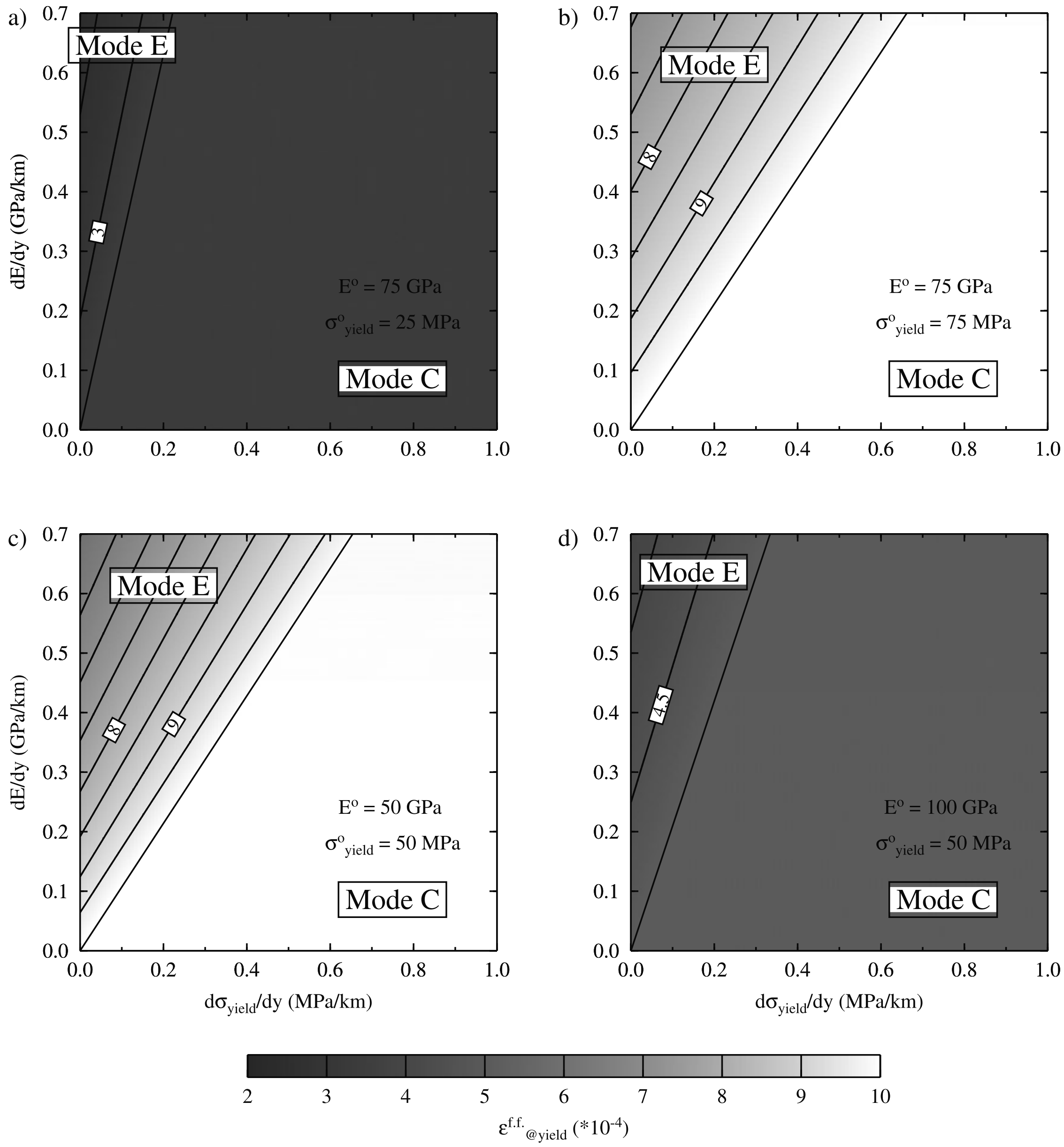


Figure 10. Mode boundary between mode E and mode C faults (thick solid line) for four different values of Young's modulus and yield strength at the segment center. (a) E° = 75 GPa, σ°_{yield} = 25 MPa. (b) E° = 75 GPa, σ°_{yield} = 75 MPa. (c) E° = 50 GPa, σ°_{yield} = 50 MPa. (d) E° = 100 GPa, σ°_{yield} = 50 MPa. Shaded contours illustrate the far-field strain necessary for initial yielding. Note the decrease in size of the mode E phase space as the value of E° becomes larger relative to the value of σ°_{yield}.

faults are observed to accumulate maximum slip at different locations along the segment, not only at the center and ends but also in between. However, toward the ends of the segment large faults appears to be preferred on inside-corner crust. Other examples of mode E faults have been documented elsewhere along the MAR [*Smith et al.*, 1995; *Searle et al.*, 1998; *Escartín et al.*, 1999; *Briais et al.*, 2000].

5.2. Factors Favoring the Generation of Mode E Faults

[28] Figures 8 and 10 show the conditions under which along-axis changes in Young's modulus can generate large enough gradients in stress to overcome the increased lithospheric strength of the segment ends, thus forming mode E faults. We note that the observed values of dE/dy along the MAR OH-1 and MAR 29°N segments are insufficient to generate the stress gradients necessary to produce the observed mode E faults in these locations (Figure 8). Figure 11 shows the additional gradient in effective stress that is required to switch from mode C to mode E faulting as a function of dE/dy and $d\sigma_{yield}/dy$. Note that the closer a segment plots to the mode C–E transition in Figure 11, the smaller the additional along-axis gradient in stress that is necessary to switch from one mode of faulting to the other.

[29] However, changes in Young's modulus are not the only source of along-axis variations in stress at a ridge segment. Furthermore, segments are rarely characterized by just one mode of faulting, as would be predicted if variations in dE/dy and $d\sigma_{yield}/dy$ were the only parameters controlling fault development at a ridge segment. This observation suggests that temporal variations in stress must also play an important role in the

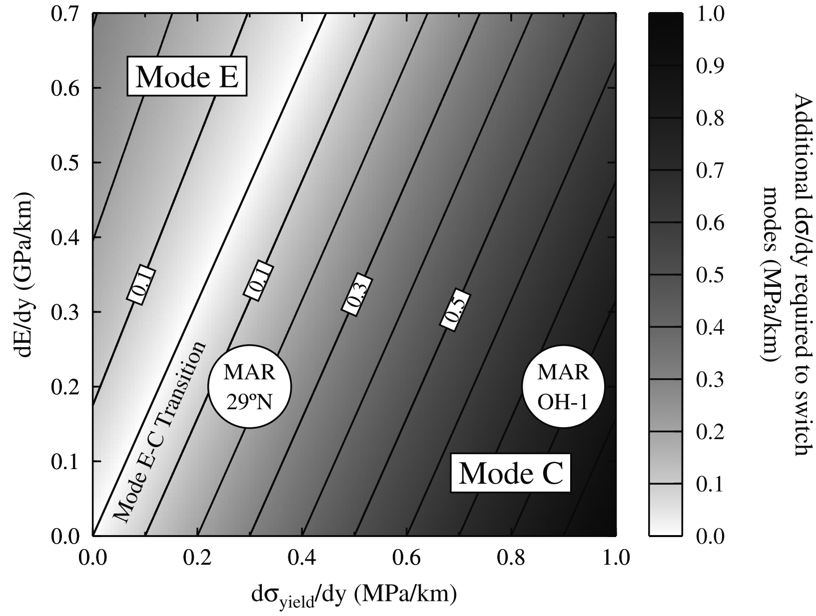


Figure 11. Contour plot of the additional gradient in σ_{eff}, after accounting for variations due to *dE*/*dy*, that is necessary to switch modes of faulting. Approximate parameter values of the OH-1 and MAR 29°N segments are shown on the basis of the values of *dE*/*dy* and $d\sigma_{yield}/dy$ calculated in Figure 1. We hypothesize that the additional gradient in σ_{eff} necessary to form the mode E faults observed at the OH-1 and MAR 29°N segments may be generated by a combination of shearing along transform faults and temporal variations in magma supply along the ridge axis.

dynamics of faulting at mid-ocean ridges. Below we discuss several mechanisms that may lead to the development of mode E faults at a ridge segment.

5.2.1. Serpentinization. [30] One hypothesis that has been proposed to explain the generation of mode E faults is that serpentinites may be sufficiently abundant toward the end of slow spreading segments to significantly reduce the strength of the lithosphere in these locations [*Escartín et al.*, 1997]. If serpentinites are present in large enough quantities to offset the gradient in lithospheric strength caused by the change in thermal and crustal structure along a segment, it could explain the formation of mode E faults at many ridge segments. At present, however, there are not sufficient observations to assess whether the effect of serpentinization alone is sufficient to offset the gradient in yield strength due to along-axis variations in thermal and crustal structure. Further, the serpentinization model also has difficulty explaining the asymmetry observed at inside and outside corners.

5.2.2. Transform fault shearing. [31] An alternative mechanism that may increase stresses toward the end of a spreading segment is the effect of shear stress resisting relative plate motion along a transform fault. *Phipps Morgan and Parmentier* [1984] and *Grindlay and Fox* [1993] modeled the stress field associated with transform offsets by applying varying ratios of the tensile stress resisting plate separation at the ridge axis, σ_R, and the shear stress resisting relative plate motion along the offset, σ_T. The tensile stresses predicted by these models are amplified at the inside corners, with their magnitude increasing with greater offset lengths and smaller σ_R/σ_T ratios. *Pollard and Aydin* [1984] predict a similar increase in stress at an inside corner without imposing any shear stress along the transform boundary by modeling the propagation of two overlapping cracks in an elastic plate.

[32] Figure 12 illustrates the effect of imposing a shear stress resisting relative plate motion along a 30-km section of the top and bottom boundaries of the model space adjacent to the ridge axis. Assuming $\sigma_R = \sigma^{\circ}_{yield}$, we vary σ_T to show the change in effective stress associated with σ_R/σ_T ratios of 2, 3, and 5 (Figures 12b, 12c, and 12d, respectively). Although for numerical simplicity we choose to vary only σ_T, we note that in reality, changes in σ_R/σ_T can be caused by variations in σ_R during waxing and waning phases of ridge axis magma supply. With the minor exception of a small region surrounding the point at which the ridge and transform meet, the inside corners are characterized by increased effective stresses relative to the outside corners. The predicted $d\sigma_{eff}/dy$ are up to $\sim$0.3 MPa km^{-1} at a distance of 15 km from the ridge axis. These values are comparable in magnitude to the predicted stress changes associated with along-axis variations in Young's modulus.

[33] On the basis of the observed rotation of normal fault scarps near nontransform offsets, *Grindlay and Fox* [1993] hypothesized that the σ_R/σ_T ratio will generally fall in the range of 3–5. However, along segments characterized by low residual gravity and shallow axial bathymetry, the observed morphology was found to be more closely matched by a σ_R/σ_T ratio of 1–3. *Grindlay and Fox* [1993] proposed that the decrease in σ_R/σ_T might be caused by a reduction in σ_R related to periods of robust magmatic activity. If correct, this could indicate a link between enhanced magmatism at the segment center and increased tectonism at the inside corners.

[34] This prediction is consistent with observations from the MAR OH-1 and OH-3 segments. Residual gravity anomalies [*Detrick et al.*, 1995] and seismic refraction profiles [*Hooft et al.*, 2000; *Canales et al.*, 2000b] show the OH-1 segment to be magmatically robust, with young, sheet-like lava flows covering the axial valley floor at the segment center [*Gràcia et al.*, 1999]. Toward the segment ends the valley floor shows extensive faulting and fissuring, and a large mode E fault is observed at the northeast inside corner (Figure 1a). In contrast, the OH-3 segment is characterized by a weaker, less stable magma source, offset to the south of the segment center [*Gràcia et al.*, 1999]. At OH-3 a series of small mode E faults is observed at the inside corners, while the zone of most intense faulting and fissuring is near the segment center (Figure 1b). Note that while the calculated asymmetry in stresses between the inside and outside corners depends on the assumed σ_R/σ_T ratio, the pre-

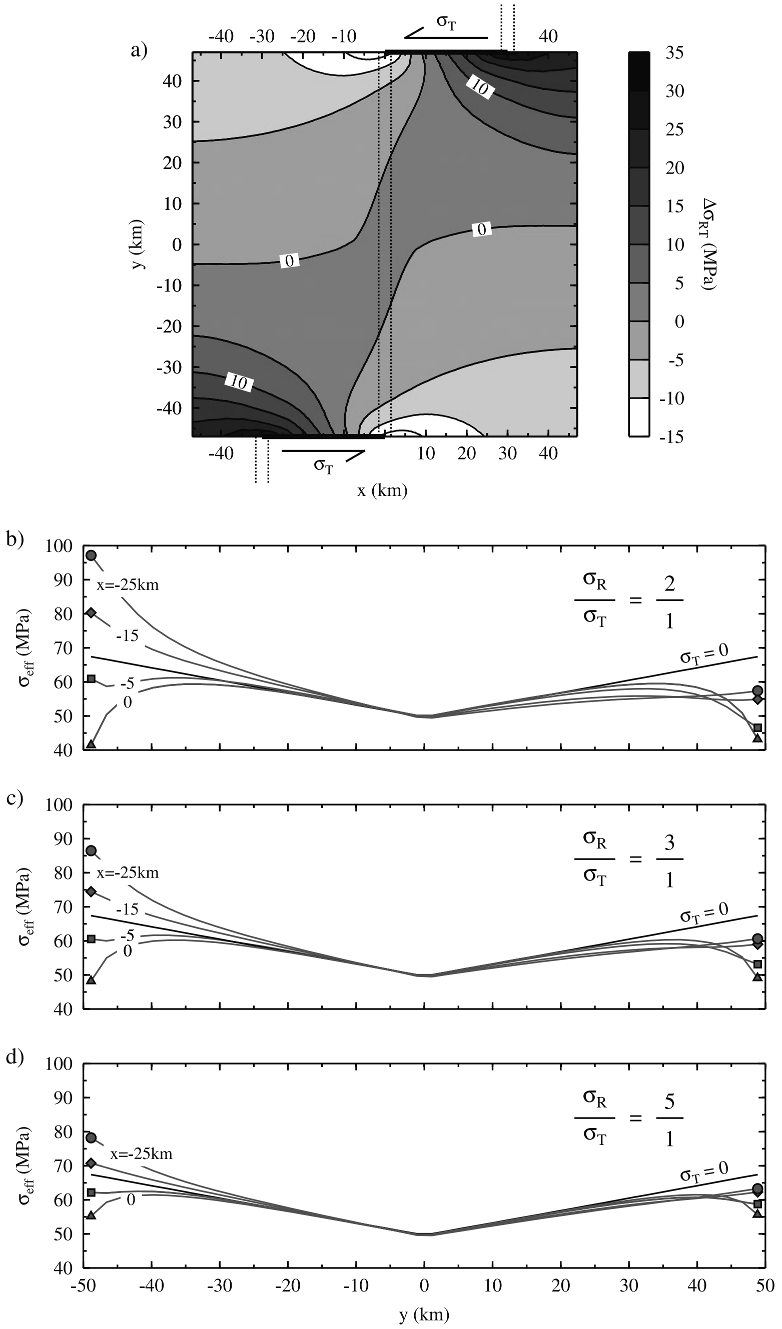


Figure 12. (a) Contour plot of the calculated change in effective stress, $\Delta\sigma_{RT}$, generated by applying a shear stress, σ_T, along two 30-km-long transform faults. We assume $\sigma_R = \sigma^{\circ}_{\text{yield}}$ and set σ_T such that the stress coupling ratio, σ_R/σ_T, is equal to 2. (b, c, and d) Along-axis variations in effective stress, with $\varepsilon_x^{ff} = 6.4 \times 10^{-4}$, for σ_R/σ_T ratios of 2, 3, and 5, respectively. Solid lines show the variation in σ_{eff} for the stress-free boundary conditions shown in Figure 6 (i.e., $\sigma_T = 0$). Shaded lines illustrate σ_{eff} at $x = 0, -5, -15$, and -25 km, respectively. Note that except for the small region surrounding the point at which the ridge and transform meet, the inside corners are characterized by increased σ_{eff} relative to the outside corners.

dicted stresses are always higher at the inside-corner crust than at the outside corner and segment center. Thus transform shearing enhances the probability of forming mode E faults on inside-corner crust.

5.2.3. Temporal variations in stresses. [35] Episodic periods of enhanced magmatic activity have been inferred from off-axis residual gravity anomalies on timescales of 2–5 Myr [*Pariso et al.*, 1995; *Tucholke et al.*, 1997]. Moreover, a recent across-axis seismic profile at the MARK area of the MAR suggested even shorter fluctuations in magma supply, with periods of 400–800 kyr [*Canales et al.*, 2000a]. Thermal and crustal structure are critical in the determination of dE/dy and $d\sigma_{\text{yield}}/dy$ and have been shown to vary as a function of magma supply [e.g., *Tucholke et al.*, 1997; *Canales et al.*, 2000a]. Thus temporal variations in magmatic accretion at slow spreading ridge axes may influence not only the ridge-transform coupling ratio

σ_R/σ_T as discussed above but also the elastic and mechanical properties of the lithosphere.

[36] In addition to variations due to magma supply, the process of faulting itself affects the local stress field. Stress drops associated with large earthquakes range from 1 to 10 MPa [*Kanamori and Anderson*, 1975]. A normal fault releases stress to either side of its center but concentrates stress at its tips [e.g., *Pollard and Aydin*, 1984; *Crider and Pollard*, 1998]. As a population of normal faults evolves, the stress fields associated with individual faults interact, leading to the coalescence of multiple small faults into a few larger structures [e.g., *Cowie et al.*, 1993; *Tuckwell et al.*, 1998]. As this process continues, extension due to the linkage of existing faults will eventually begin to dominate over the nucleation of new faults [*Spyropoulos et al.*, 1999; *Ackermann and Schlische*, 1999]. These complications are beyond the scope of this study but illustrate that the stress field at a mid-ocean ridge segment changes constantly as new faults form and deformation continues on existing fault planes.

[37] In summary, we suggest that along-axis variations in Young's modulus, shear stresses along a transform fault, and temporal variations in magma supply and fault growth can all lead to enhanced stresses toward the end of a segment. While any of these factors alone may be insufficient to generate a mode E fault, together they can produce large enough stresses at the segment ends to overcome the positive along-axis gradient in yield strength.

5.3. Fault Initiation at Fast Spreading Ridges

[38] At slow spreading MAR segments, variations in thermal and crustal structure cause dE/dy and $d\sigma_{\text{yield}}/dy$ to change significantly along axis. In contrast, at the fast spreading EPR, Young's modulus and yield strength are observed to remain relatively constant along axis (Figure 4). The lack of along-axis gradients in dE/dy and $d\sigma_{\text{yield}}/dy$ at the EPR would tend to favor uniform failure along the ridge axis, rather than the development of prominent mode C or E faults. This prediction is consistent with observations of faulting at the EPR, which show numerous small, closely spaced faults forming continuously along the entire spreading segment [e.g., *Carbotte and Macdonald*, 1994; *Alexander and Macdonald*, 1996].

6. Conclusions

[39] In this study we present a thin-plate model of a ridge segment to examine the relative importance of lateral changes in stress accumulation and the mechanical strength of the brittle lithosphere at a mid-ocean ridge spreading center. Thermal and seismic velocity models along the MAR OH-1 and MAR 29°N segments show that both Young's modulus and yield strength are expected to change considerably along a slow spreading segment, while little variation in these parameters is observed at the fast spreading EPR 9°N segment. Higher values of depth-averaged Young's modulus toward the segment ends are calculated to lead to enhanced stress accumulation in these regions. Competing with this accumulation of stress is a positive gradient in yield strength from segment center to segment ends.

[40] On the basis of this model we define two modes of fault development at slow spreading segments: mode C (center) faults, which develop at the segment center and propagate outward, and mode E (end) faults, which develop at the segment ends and propagate inward. Mode C faults are predicted to form in ridge environments where the along-axis variation in yield strength dominates the along-axis variation in stress accumulation. Conversely, mode E faults are predicted to develop in environments where enhanced stress accumulation toward the segment ends overcomes the variation in yield strength. The plastic deformation zone associate with mode E faults is predicted to be broader in across-axis extent than that of mode C faults, potentially indicating that mode E faults will initiate and remain active over a wider across-axis region.

[41] High-resolution mapping of the slow spreading Mid-Atlantic Ridge has shown both mode C and mode E faults to be prevalent features of many segments, with large mode E faults typically forming on inside-corner crust. Our calculations show that along-axis variations in Young's modulus alone do not appear to be sufficient to generate the stress gradients necessary for mode E faulting at many slow spreading segments. Therefore we propose a model in which temporal changes in magma supply affect both along-axis gradients in the stresses and mechanical properties of the lithosphere and the stress conditions along the transform fault. During periods of enhanced magmatic activity the ratio of ridge-to-transform stress, σ_R/σ_T, is predicted to decrease, generating larger stresses at inside corners and concentrating mode E faulting in these locations. The lack of strong along-axis gradients in stress and lithospheric strength at fast spreading ridges is predicted to generate a more uniform pattern of faulting as observed at the East Pacific Rise. The results of this study illustrate that the interplay between the along-axis variations in stress state and the mechanical properties of the lithosphere play an important role in controlling the style of fault development at a mid-ocean ridge spreading segment.

Appendix A: Thin-Plate Stress Solution for Linearly Varying Young's Modulus

A1. Stress and Strain Within the Plate

[42] In this section we present an analytical solution for stress and strain in a thin elastic plate with a linear gradient in Young's modulus from the center of a segment to its distal ends (see Figure 6). For a plate in plane stress the stress, σ, and strain, ε, components can be written as

$$\begin{aligned} \sigma_x &= \sigma_x(x,y), \\ \sigma_y &= \sigma_y(x,y), \\ \tau_{xy} &= \tau_{xy}(x,y), \\ \tau_{xz} &= \tau_{yz} = \sigma_z = 0. \end{aligned} \tag{A1}$$

We define a coordinate system with the x axis oriented across the ridge axis and the y axis aligned along the ridge axis. The dimensions of the model space are $2x_o$ and $2y_o$. Small displacements, Δu_x and $-\Delta u_x$, are imposed at the right- and left-hand sides of the model space, respectively. The top and bottom boundaries are assumed to be free slip

$$\tau_{xy} = 0\big|_{y=\pm yo} \tag{A2}$$

with no y displacement

$$u_y = 0\big|_{y=\pm yo}. \tag{A3}$$

The stress and strain relationships for a thin plate in plane stress [*Jaeger and Cook*, 1979] can be written as

$$\varepsilon_x = \frac{1}{E(y)}\left[\sigma_x - \nu\sigma_y\right] \tag{A4}$$

$$\varepsilon_y = \frac{1}{E(y)}\left[\sigma_y - \nu\sigma_x\right], \tag{A5}$$

where ν is Poisson's ratio and $E(y)$ is Young's modulus, which varies linearly along the y axis

$$E(y) = E^\circ + (dE/dy)\,|y|, \tag{A6}$$

where dE/dy is a constant. Note that because there is no across-axis gradient in Young's modulus, the far-field strain, $\varepsilon_x^{ff} = \Delta u_x / x_o$, is constant at all points in the model space for a given time step. Since no y displacement is allowed along the top and bottom boundaries, at any x value the integrated strain in the y direction must sum to zero

$$\int_{-y_\circ}^{y_\circ} \varepsilon_y dy = 0. \tag{A7}$$

[43] Solving (A4), (A5), and (A7) under the condition that σ_y remains constant, we arrive at the following expressions for stress and strain within the plate for any given far-field strain, ε_x^{ff}:

$$\sigma_y = \frac{\nu\varepsilon_x^{ff}(dE/dy)y_\circ}{(1-\nu^2)\ln\left[\frac{(dE/dy)y_\circ - E^\circ}{E^\circ}\right]}, \tag{A8}$$

$$\sigma_y(x) = \left[\left(dE/dy\right)|y| + E^\circ\right]\varepsilon_x^{ff} - \nu\sigma_y, \tag{A9}$$

$$\varepsilon_y(y) = \left[\frac{1-\nu^2}{(dE/dy)\,|y| + E^\circ}\right]\sigma_y - \nu\varepsilon_x^{ff}. \tag{A10}$$

We note that σ_x and ε_y are solely functions of y. Because of the stress-free boundary conditions and uniaxial extension applied to the model, the shear stresses are negligible. Numerical models show that the addition of an across-axis gradient in Young's modulus dE/dx, with

$$\frac{\int_{-x_\circ}^{x_\circ} E(x,0)dx}{2x_\circ} = E^\circ \tag{A11}$$

will generate effective stresses at the ridge axis which differ by <0.25% from the case of $dE/dx = 0$, for values of dE/dx similar to that observed at segment OH-1 (Figure 5a).

A2. Calculation of Initial Failure

[44] Perfect plasticity is characterized by a mechanical yield stress, σ_{yield}, beyond which permanent strain appears. In this study, we assume failure of a thin plate will follow the Von Mises yield criterion, defined as

$$\sigma_{\text{eff}} \geq \sigma_{\text{yield}}, \tag{A12}$$

where

$$\sigma_{\text{eff}} = \sqrt{\frac{1}{2}\left[\left(\sigma_x - \sigma_y\right)^2 + \sigma_x^2 + \sigma_y^2 + 6\tau_{xy}^2\right]}. \tag{A13}$$

At any point in the plate the yield strength is assumed to be a linear function of x and y, with

$$\sigma_{\text{yield}}(x,y) = \sigma^o_{\text{yield}} + \left(d\sigma_{\text{yield}}/dx\right)|x| + \left(d\sigma_{\text{yield}}/dy\right)|y| \tag{A14}$$

Because the across-axis gradient in yield strength, $d\sigma_{\text{yield}}/dx$, is positive and the effective stress, σ_{eff}, varies only in the y direction (see (A8) and (A9)), initial yielding must occur at the ridge axis where $x = 0$. Therefore we can solve for the value of the far-field strain when yielding occurs, $\varepsilon^{ff}_{\text{at yield}}$, which is a function of y only:

$$\varepsilon^{ff}_{\text{at yield}}(y) = \frac{\sigma_{\text{yield}}(y)}{\sqrt{A+B+C}}, \tag{A15}$$

where

$$A = \left[(dE/dy)\,|y| + E^\circ\right]^2,$$

$$B = \frac{\left[(dE/dy)\,|y| + E^\circ\right](2\nu^2 - \nu)(dE/dy)y_\circ}{(1-\nu^2)\ln\left[\frac{(dE/dy)\,|y| + E^\circ}{E^\circ}\right]},$$

$$C = \frac{(\nu^4 - \nu^3 + \nu^2)(dE/dy)^2\, y_\circ^2}{(1-\nu^2)^2\ln^2\left[\frac{(dE/dy)\,|y| + E^\circ}{E^\circ}\right]}.$$

This relationship is used to determine whether initial failure occurs at the segment center or segment ends and thus whether mode C or mode E faults are preferred.

[45] **Acknowledgments.** We are grateful to Debbie Smith for providing us with the bathymetry and TOBI data for the MAR segment at 25°10′N and for her insights in understanding mid-ocean ridge processes. Pablo Canales and Cecily Wolfe were extremely helpful in providing us with the seismic data used in this paper. This paper benefited by constructive reviews from Patience Cowie and an anonymous reviewer. We would also like to thank Greg Hirth, Brian Tucholke, Pablo Canales, Wen-lu Zhu, and Laurent Montési for helpful discussion during various stages of this research. Several figures in this paper were produced using the public domain GMT software package [*Wessel and Smith*, 1995]. This research was supported by National Science Foundation grant OCE-9811924 (J. Lin), NASA grant SENH99-0318-0160 (M. T. Zuber), and a National Defense Science and Engineering Graduate Fellowship (M. D. Behn). Contribution 10540 of Woods Hole Oceanographic Institution.

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