TECTONICS, VOL. 11, NO. 6, PAGES 1348-1356, DECEMBER 1992

HOST ROCK RHEOLOGY CONTROLS ON THE EMPLACEMENT OF TABULAR INTRUSIONS: IMPLICATIONS FOR UNDERPLATING OF EXTENDING CRUST

Tom Parsons, Norman H. Sleep, and George A. Thompson
Department of Geophysics, Stanford University, Stanford, California

Abstract. The pooling, ponding, and horizontal intrusion of basaltic magma at various depths into the crystalline crust is paradoxical because the stress conditions favoring such intrusions do not favor the opening of vertical feeder conduits necessary for their formation. The most rigid zones of the crust and upper mantle tend to behave elastically and store stress when subjected to tectonic forces, while the more ductile zones flow under stress. These rheological differences within the crust and upper mantle allow variation in the magnitude of deviatoric stress, and such variation has a profound effect on tabular intrusions. A vertical dike intruding into extending crust increases the horizontal least principal stress of the host rock when it is emplaced, and that effect is magnified in rheologically ductile zones where the pre-existing deviatoric stress has been partially relaxed. Subsequent dikes intruding into the ductile zone may encounter stress conditions that have been altered to the extent that the local least principal stress has become vertical, and horizontal intrusion initiates. Multiple geological and geophysical observations of horizontal intrusions in extending crust indicate that such principal stress interchanges occur commonly.

INTRODUCTION

One general result of the past few decades of long-offset deep seismic investigations of the crust has been the observation of a high-velocity layer at the base of the crust in many cases [e.g., Mooney and Brocher, 1987], which is usually attributed to a more mafic composition there. The Moho is an often-suggested locus of magmatic underplating [e.g., Furlong and Fountain, 1986; Matthews and Cheadle, 1986; Bohlen and Mezger, 1989; Bergantz, 1989; Wilshire, 1990] and is typically well defined in extended terranes [e.g., Klemperer et al., 1986; Smithson, 1989]. The deep crust of extending regimes is often highly reflective to vertical incidence seismic waves [e.g., Clowes et al., 1968; Fuchs, 1969; BIRPS and ECORS, 1986; Potter et al., 1987], and the origin of lower-crustal reflectors remains controversial. Subhorizontal "bright spots" imaged on Consortium for Continental Reflection Profiling (COCORP) reflection profiles recorded in the extending Basin and Range Province of the western United States have been attributed to active ponding of magma into the midcrust [Brown et al., 1987]. While sill and laccolith intrusion is well studied [e.g., Corry, 1988], the apparent paradox of horizontal magmatic intrusion into elastic crystalline rocks of extending crust is not well explained. We suggest a mechanism by which magma becomes able to fracture horizontally within extending crust at rheological contrasts such as the continental Moho and the brittle-ductile transition.

The problem of horizontal intrusion is often approached by invoking a density explanation; the magma rises until it ponds at a point of neutral buoyancy, where the melt and host rock are of equal density [e.g., Bradley, 1965; Herzberg et al., 1983; Lister and Kerr, 1991]. This is clearly the case where both melt and host rock behave as fluids, as where basalt ponds below granitic magma in caldera chambers [e.g., Hildreth, 1981]. On the other hand, where host rocks are sufficiently elastic to support differential tectonic stress, the local density is unimportant; in fact basalt dikes commonly cut low-density sedimentary and tuffaceous rocks. It is likely that in many cases it is variations in the horizontal stresses rather than host-rock density that control the behavior of tabular intrusions.

Stress and Rheology

The intrusion of vertical and horizontal dikes resembles hydraulic fracturing in that it is primarily governed by the ambient stress field in the host rock, which controls dike orientation and thickness [Anderson, 1951; Nakamura, 1977; Zoback and Zoback, 1980; Rubin and Pollard, 1988] (Figure 1). Highly fluid mafic melts are especially sensitive to the ambient stress field, tending to form tabular intrusions, while more viscous silicic melts tend to intrude as radially symmetric plugs [Emerman and Marrett, 1990]. We limit the discussion to rapidly ascending, dike-forming basaltic magmas that are not strongly contaminated by the crust as they ascend, and that tend to have chilled contacts with the host rock. Dikes exploit the weak tensional strength of crustal rocks and are observed to intrude along planes perpendicular to the least principal compressive stress, often ignoring other planes of weakness such as foliation or fault planes, unless the deviatoric stress is very small. In an extending tectonic regime dikes intrude vertically, perpendicular to the horizontal least principal stress. In a compressive regime the stress conditions favor the injection of horizontal sheets, although it is more difficult for feeder dikes to form under such conditions. When mantle plumes interact with the continental crust they locally alter the tectonic stress field and emplace large quantities of basalt into both compressional and extensional terranes [Duncan and Richards, 1991]. For example, the radial pattern of the MacKenzie dike swarm [e.g., LeCheminant and Heaman, 1989] indicates that the middle Proterozoic hotspot event that formed the dikes overwhelmed the local tectonic stresses.

Rheology variation is largely responsible for the different amounts of tectonic stress that can accumulate within the crust and mantle. Rocks generally exhibit both elastic and ductile behavior, particularly at elevated temperatures in the Earth [e.g., Kirby and Kronenberg, 1987]. Depending on the rate of strain they may respond mostly elastically (as during an earthquake or rapid dike intrusion) or in a more ductile manner (as during slow tectonic strain). Tabular dikes push out against their

Paper number 92TC01105.
0278-7407/92/92TC-01105$10.00

walls and selectively increase the least principal stress and are observed to supplant normal faulting as the primary mode of strain in extending regions [Parsons and Thompson, 1991]. Typical dike widths are comparable to the incremental horizontal components of slip along normal faults during earthquake release. The significant effect that an intruding dike has on the stress field is magnified in rheologically weaker rocks that are unable to accumulate significant tectonic stress.

The relative time scales over which crustal strain and dike injection occur are crucial to the understanding of the processes. Crustal strain rates are comparable to the rates of plate motions (millimeters to centimeters per year), while dike intrusion, like faulting, is essentially instantaneous. Basaltic melts in dikes or thin sheets chill very rapidly (in a matter of hours or days [Delaney, 1987]) implying that to reach the surface, mantle-derived melts must travel through the whole crust at rates of kilometers per day. Over the relatively very short duration of dike intrusion, ductile host rocks act elastically [Rubin, 1990], whereas over the long duration, tectonic strain is partly elastic but mostly viscous. The emplacement of a dike into the crust can have a long term effect on the stresses. If a region is extending at rates of millimeters per year, then a 10-m-thick dike accommodates thousands of years of extension in its vicinity in a matter of days or hours.

Cotrell and Rice [1980] found that a crack propagating perpendicular to the least principal stress could become unstable upon encountering an imperfection, and that the crack path could deviate as much as 90°. While such a mechanism may be a viable explanation for horizontal intrusions, the general field observation of dikes is a straight path on a regional scale, because of the extreme nonuniform stresses at their tips [Pollard, 1987; Rubin and Pollard, 1988; Moos and Zoback, 1990]. These stresses, focused at the immediate tip of the propagating dike, allow dikes to ignore structural inhomogeneities of the host rock.

Density Effects

The driving mechanism for intrusion of melts is the density instability between the melt at its source and the surrounding rocks. During incipient intergranular melting of mantle peridotite the basaltic melt is subjected to the

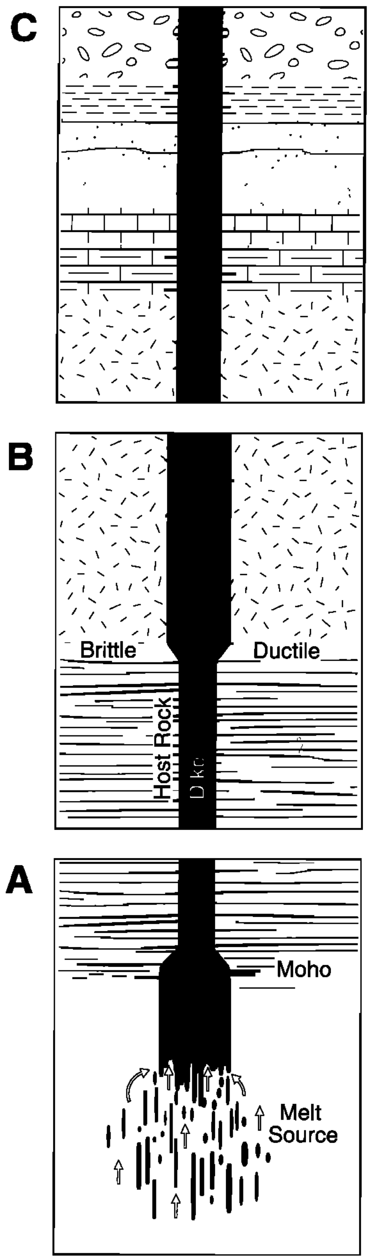

Fig. 1. Schematic diagram of a single connected vertical basaltic dike in an extending tectonic regime. (a) Partial melt collects in veins oriented perpendicular to the least principal stress in the upper mantle. The resulting density instability drives porous flow which drains the veins into a dike [Sleep, 1988]. The dike propagates upward as a magma-frac event, forcing open a conduit proportional in width to the difference between melt pressure and the horizontal least principal stress. As the dike crosses the Moho it encounters ductile lower crustal rocks which are more subject to viscous flow than are upper mantle rocks. Viscous flow tends to relax the deviatoric stress, which reduces its magnitude, and the dike thins as a result. Depending on the degree of ductile relaxation and the melt pressure, the strain imposed by the dike may quench or exceed the accumulated stress difference in the lower crust because dike widths are typically equivalent to the horizontal component of strain during large earthquakes. (b) Basaltic dikes are able to propagate through the ductile lower crust because over the short duration of the intrusion (hours to days) the host rock acts elastically. When the dike encounters the brittle-ductile transition in the midcrust, it is subject to a larger deviatoric stress because the more brittle upper-crustal rocks do not flow as readily, and the dike width increases. (c) The magnitude of deviatoric stress is reduced in the uppermost section because of jointing and fracturing in the host rocks, and the dike thins as a result. The dense basaltic melt is often able to cut vertically through less dense sediments and tuffaceous rocks because it continues to be driven upward by the deep density instability in the mantle.

same pressure as the enclosing rock. As the melt gathers into discrete bodies, the vertical gradient of pressure in the melt is less than that in the source rock because the melt is less dense than the enclosing rock at depth [Weertman, 1971; Turcotte and Schubert, 1982; Sleep, 1988]. Importantly, a dike propagates vertically not because of the density contrast between the immediate local rock and the melt at a given point along the path but because of the vertical gradient in the horizontal tectonic stress within the host rock [Rubin, 1990]. The internal melt pressure is greatest within magmas originating from sources deep in the mantle. More shallowly sourced melts are driven upward with less pressure because the integrated density contrast between the magma and host rock columns is less, and such intrusions may be stalled at a depth in the crust where the weight of the melt column counters the driving pressure [Lister and Kerr, 1991]. It is impossible for deeply sourced melts to be directly influenced by the immediate local host rock density because: (1) the host rock acts elastically over the intrusion duration, (2) the host rock does not melt and become fluid, and (3) the intrusion freezes on contact. The melt can bypass the point of neutral buoyancy with ease, provided that the internal melt pressure exceeds the least principal stress in the host rock. Observational evidence is abundant; dense basaltic melts often intrude vertically through much less dense tuffs or sediments, and these melts are able to climb to the top of high volcanoes. Thus density contrasts between the magma and local host rock are not a viable explanation for the localized intrusion of subhorizontal sheets. Instead, an alternate mechanism is required to explain how magma injects horizontally at various depths in the crust with sufficient pressure to lift the overburden. We suggest that rheological contrasts are responsible for horizontal intrusion, and we provide a simple mathematical description of the process.

MODEL FOR AN INTRUDED DIKE AT A RHEOLOGICAL CONTRAST

The Crust Mantle Boundary

Perhaps the best known and most prominent rheological boundary in the lithosphere is the crust-mantle boundary. The Moho is characterized on seismic reflection profiles by a zone of laminated reflections interpreted by many to be a region of underplating by horizontal mafic intrusions. For these reasons it is an ideal place to model the effects of rheology contrasts on the intrusion of a vertical dike crossing the crust-mantle boundary in an extending tectonic regime. We treat the rheology difference between the upper mantle and lower crust to be a variable partition between the elastic and viscous components of strain (Figure 2). For mathematical simplicity we use a Newtonian approximation for the ductile stress-strain relation in a plate, and we constrain the elastic component of the strain to be caused purely by dike intrusion. We recognize that the actual stress-strain relation is nonlinear; however, the linear case is sufficient for illustration of the process. For an extending terrane we take the greatest principal stress σ_{zz} to be the vertical lithostatic stress, σ_{xx} to be the horizontal least principal stress, and σ_{yy} to be the horizontal intermediate principal

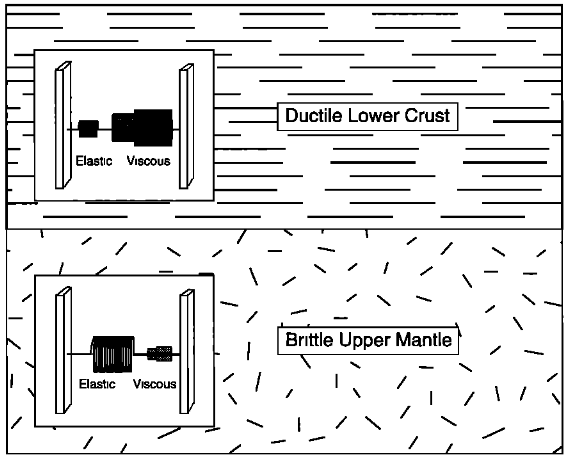

Fig. 2. Simplified view of the partition between the viscous and elastic components of strain above and below the Moho. The amount of viscous flow in the lower crust tends to be greater than in the more brittle-upper mantle. Conversely, the amount of elastic strain in the upper mantle is greater than in the lower crust. Earthquakes are rare in the upper mantle of extending regimes, which suggests that while the viscous partition of strain is less in the mantle, it is perhaps still an important mechanism. However, the common association between magmatism and extension suggests that much of the extensional strain in the upper mantle may be accomplished by dike intrusion.

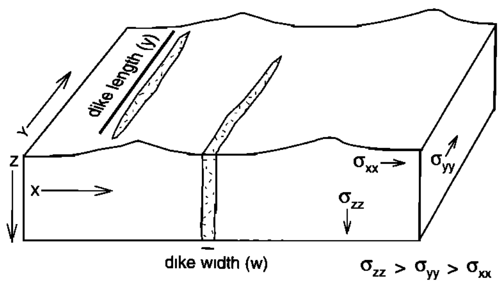

Fig. 3. Coordinate system and orientation of the principal stresses in an extending regime. Dikes tend to intrude vertically, perpendicular to the least principal stress. The greatest principal stress is oriented vertically and is equal to the lithostatic load. The contribution by the dike to the elastic strain is directly proportional to the width and the short in-plane dimension of the dike.

stress (Figure 3). In a viscous medium the equations for plane-strain rate [after Johnson, 1970] are

$$\dot{\epsilon}_{xz} = \frac{\sigma_{xz}}{\eta}$$
$$\dot{\epsilon}_{xx} = \frac{\sigma_{xx} - p}{2\eta} \qquad (1)$$
$$\dot{\epsilon}_{zz} = \frac{\sigma_{zz} - p}{2\eta}$$

where p is the mean normal stress and is expressed as

$$p = \frac{\sigma_{zz} + \sigma_{xx}}{2}.$$

The deviatoric stress is defined as

$$\sigma = \sigma_{zz} - \sigma_{xx}.$$

Thus the ductile partition of the strain rate ($\dot{\epsilon}_d$) may be expressed in terms of the deviatoric stress as

$$\dot{\epsilon}_d = \frac{\sigma}{4\eta}. \quad (2)$$

The elastic partition of the strain rate caused by dike intrusion ($\dot{\epsilon}_e$) is related directly to the aspect ratio (width-to-length) of the intruded dikes, and the intrusion rate, and can be expressed as

$$\dot{\epsilon}_e = \frac{w}{iy}, \quad (3)$$

where the dike width is w, the short in-plane dimension of the dike is y, and i is the time interval between intrusions (e.g., a large intrusion interval means few intrusions, while a small interval means continuous intrusion). Near the crust-mantle boundary the dike is presumed to be growing primarily in the vertical dimension, so that y is assumed to be the horizontal dike length (Figure 3). The total (viscous and elastic) strain rate in the more brittle upper mantle can be compared to the the ductile lower crust with the equations

$$\dot{\epsilon}_m = \frac{\sigma_m}{4\eta_m} + \frac{w_m}{iy}, \quad (4)$$

$$\dot{\epsilon}_{lc} = \frac{\sigma_{lc}}{4\eta_{lc}} + \frac{w_{lc}}{iy}$$

where the lc and m subscripts denote lower crust and mantle respectively. We treat the two layers as half-spaces of greater vertical extent than the dike length y, which are welded at their contact. The layers are assumed to be extending at the same rate but with different partition between the elastic and ductile components.

Since dike intrusion acts to accommodate accumulated (tectonic) deviatoric stress, the dike width will change with varying stress accumulation across rheologic boundaries (Figure 1). Variation in the width of vertical dikes is dependent on the difference between melt pressure and the horizontal stress (σ_{xx}). We consider as an initial case a rising melt which has an internal pressure equal to the lithostat (σ_{zz}). We can thus relate the dike width in each layer to the accumulated deviatoric stress through the expressions

$$w_{lc} = \frac{y\sigma_{lc}}{E_{lc}} \quad (5)$$

$$w_m = \frac{y\sigma_m}{E_m},$$

where E is Young's modulus. A more general case which includes the effects of varying melt pressure will be considered later. Since the more ductile lower crust develops a smaller deviatoric stress, we expect the dike width to be smaller, thinning across the crust-mantle boundary (Figure 1). During the short time span of dike intrusion, both the upper mantle and lower crust act elastically, which for the purposes of this analysis implies that Young's modulus in the two layers is approximately the same. Birch [1966] found the range of Young's modulus (corrected to 40 MPa) to be from $8.0\text{x}10^{10}\text{Nm}^{-2}$ in granite to $19.4\text{x}10^{10}\text{Nm}^{-2}$ in dunite, which is likely the largest contrast possible across the crust-mantle boundary, and is considered negligible relative to the viscosity contrast in this study.

Limit of a Large Intrusion Interval

We now look at the initial process of a single dike intruding across the boundary, so we set the intrusion interval i to ∞, which is equivalent to very slow ductile tectonic extension. Since elastic strain in this model is restricted to dike intrusion, an infinite intrusion interval implies that all strain occurs by viscous flow. The viscosity of the upper mantle is much higher than that of the lower crust, implying that a very large stress difference is expected across the Moho in this case. Taking the limit which eliminates the elastic terms, and recalling that the strain rates in both layers are set equal we have

$$\dot{\epsilon}_{lc} = \dot{\epsilon}_m = \frac{\sigma_{lc}}{4\eta_{lc}} = \frac{\sigma_m}{4\eta_m}. \quad (6)$$

Thus when the intrusion interval is large, the ratio of deviatoric stress in each layer is equal to the ratio of the layer viscosities

$$\frac{\sigma_{lc}}{\sigma_m} = \frac{\eta_{lc}}{\eta_m}. \quad (7)$$

The dike width at some point within the transition between the mantle and the crust will be the average

$$\bar{w} = \frac{w_{lc} + w_m}{2}. \quad (8)$$

The change in the deviatoric stress at the crust-mantle boundary due to dike intrusion is

$$\Delta\sigma_{lc} = \frac{\bar{w}E_{lc}}{y}, \quad (9)$$

and the new deviatoric stress in the lower crust is then

$$\sigma^{lc}_{after} = \sigma_{lc} - \frac{\bar{w}E_{lc}}{y}. \quad (10)$$

The dike width $\bar{w}$ at the interface is solved in terms of the deviatoric stresses by relating (5) and (8), which yields

$$\bar{w} = \frac{y\sigma_{lc}}{2E_{lc}} + \frac{y\sigma_m}{2E_m}. \quad (11)$$

Substituting for $\bar{w}$ in (10) and recalling from (7) that

$$\sigma_m = \frac{\sigma_{lc}\eta_m}{\eta_{lc}} \quad (12)$$

yields

$$\sigma^{lc}_{after} = \frac{\sigma_{lc}}{2}\left(1 - \frac{\eta_m}{\eta_{lc}}\right), \quad (13)$$

if the ratio E_m/E_{lc} is approximately equal to one.

Thus in this initiating process of a single (or few) dikes impinging on a rheological contrast, if η_m exceeds η_{lc}, then the sign of the new deviatoric stress (σ^{lc}_{after}) will be reversed. The physical meaning is that the orientations of the greatest and least principal stress axes are interchanged, with σ_{zz} becoming the least principal stress, which favors horizontal intrusion or ponding at the rheological contrast. In the immediate vicinity of the intruded dike, the traction along the rheologic boundary must be equal to the melt pressure in the opening dike while the dike is still molten. After the magma freezes, the resulting stress due to the dike is transmitted and is most likely to affect an immediate second dike intruding into a zone beginning a few dike widths away from the original dike, out to a horizontal distance equivalent to the dike height. Rock viscosities vary in orders of magnitude across the crust-mantle boundary [e.g., Meissner, 1986; Wilkes and Carter, 1990], which indicates that the rheological effect is significant. The process can be more realistically described if the expressions for strain rate are converted to non-Newtonian terms by defining an effective viscosity that varies with stress [Kirby and Kronenberg, 1987],

$$\eta_{effective} = \frac{\sigma^{1-n} exp(H^*/RT)}{2A}, \tag{14}$$

where T is the absolute temperature, A is a material constant, n is a dimensionless constant, and H^* is the activation enthalpy.

Limit of a Small Intrusion Interval

When the intrusion interval is very small, then dike intrusion is occurring continuously. In this case dikes will be reducing the deviatoric stresses in both layers equally, and the large stress contrast built up by flow in the more ductile layer will not occur. Thus the strain in both layers is partitioned into the elastic component. Recalling (4),

$$\dot{\epsilon}_{lc} = \dot{\epsilon}_m = \frac{\sigma_{lc}}{4\eta_{lc}} + \frac{w_{lc}}{iy} = \frac{\sigma_m}{4\eta_m} + \frac{w_m}{iy}.$$

When i approaches zero

$$\frac{w}{iy} >> \frac{\sigma}{4\eta}, \tag{15}$$

implying that when the intrusion interval is small, the viscous term of the strain rate expression is unimportant and that the deformation is primarily elastic. Neglecting the terms $\sigma/4\eta$ and substituting from (5) leads to

$$\frac{\sigma_{lc}}{\sigma_m} = \frac{E_{lc}}{E_m}. \tag{16}$$

The ratio of stresses is then directly related to the ratio of the elastic properties (Young's modulus) of the two layers. Substituting into (13) at the limit of intrusion interval i approaching zero leads to

$$\sigma^{lc}_{after} = \frac{\sigma_{lc}}{2}\left(1 - \frac{E_m}{E_{lc}}\right). \tag{17}$$

Thus the deviatoric stress after intrusion when the interval is small will be reduced by a factor equal to the ratio of the Young's moduli between the layers. If Young's modulus is approximately the same in both layers, then the deviatoric stress is completely accommodated. In other words, when the intrusion rate is high, the effect will be to accommodate extensional stress through dike intrusion, preventing the development of a large stress difference across the rheological boundary due to differential ductile strain. The dependence on intrusion interval is complicated by the possibility that the initial dikes impinging on the boundary might be reoriented horizontally. Long-term contact between host rock and a static horizontal intrusion could initiate melting of the host rock, and subsequent intrusions could be tapped into the horizontal melt body.

The Brittle-Ductile Transition

A second important rheological boundary in the lithosphere occurs at the brittle-ductile transition which is the gradational boundary between seismogenic upper crust subjected to faulting and ductile crust free of earthquakes. The deviatoric stress magnitude in the brittle crust is cyclic; tectonic stress accumulates until it is suddenly released on faults. In general, the seismogenic crust is thought to be in a higher state of stress than the ductile lower crust, which is in a more continual state of deformation. After a dike intrudes through the ductile lower crust into the brittle upper crust, the stress change caused by the dike slowly relaxes over time in the more ductile layer, while the stress change in the brittle upper crustal rocks is maintained over the same time period. The sharpness of the boundary between ductile and brittle crust depends on the temperature gradient, thus a significant effect from an intruding dike might be observed only when the temperature gradient is very strong. We investigate the effect of a dike crossing a deeply buried, sharp rheological contrast from ductile to brittle rocks.

The steady state strain rates for the two layers are set equal as before, with the assumptions that strain in the brittle layer occurs completely by elastic dike intrusion and that strain in the ductile layer occurs completely by viscous flow for simplicity; that is,

$$\dot{\epsilon}_{bc} = \dot{\epsilon}_{dc} = \frac{w_{bc}}{iy} = \frac{\sigma_{dc}}{4\eta_{dc}}. \tag{18}$$

The bc and dc subscripts denote brittle and ductile crust respectively. Recalling from (5) that

$$w_{bc} = \frac{y\sigma_{bc}}{E_{bc}},$$

$$w_{dc} = \frac{y\sigma_{dc}}{E_{dc}},$$

then the ratio of deviatoric stresses across the transition becomes

$$\frac{\sigma_{bc}}{\sigma_{dc}} = \frac{iE_{bc}}{4\eta_{dc}}. \tag{19}$$

Substituting into (10) and (11) yields

$$\sigma^{bc}_{after} = \frac{\sigma_{bc}}{2}\left(1 - \frac{4\eta_{dc}}{iE_{bc}}\right). \tag{20}$$

While we have assumed for convenience that extension in the brittle crust is accommodated by dike intrusion, it is clear that the most common strain mechanism in the brittle crust is normal faulting. Equation (20) does, however, isolate the effects of magmatism on the deviatoric stress near the brittle-ductile transition. The stress after intrusion is related to the ratio of the viscosity of the ductile lower layer and Young's modulus of the brittle upper layer. However, the relationship is also dependent on the intrusion interval (i). When the intrusion interval is intermediate, then the ductile lower crust has time to relax the compressional stress caused by the dike, while the brittle upper crust stores the compressional stress. Subsequent intrusions might encounter locally more compressive stresses in the brittle layer as compared with the ductile layer, and be induced to intrude horizontally. An intermediate intrusion interval is the most likely to lead to horizontal intrusion, particularly in a weakly extending terrane such that continued remote extension does not relieve the dike-induced compression in the brittle layer. If intrusion is more continuous, then dikes suppress faulting and accommodate most of the extensional strain. Suppression of normal faulting by dike intrusion into the brittle upper crust occurs at various localities across the Basin and Range Province of the western United States, in the East African Rift, and at the mid-ocean ridges [Parsons and Thompson, 1991]. A very large intrusion interval would tend to have little effect on the stresses at the brittle-ductile transition, and extensional strain in the brittle crust would most likely occur as normal faulting.

Effects of Varying Melt Pressure

The analysis so far has assumed that the melt pressure (P_{melt}) equals the vertical principal stress (σ_{zz}). That assumption is based on a melt pressure that allows an intruding dike to exactly accommodate the deviatoric stress. A spectrum of conditions can exist, ranging from a limited magma supply pressured less than the vertical stress, to an effectively unlimited supply of overpressured magma injected at pressures far exceeding the vertical greatest principal stress. We examine a dike crossing from the upper mantle into the lower crust, with the dike width (w) specified directly as a function of melt pressure;

$$w = \frac{y\sigma_{eff}}{E} \tag{21}$$

$$\sigma_{eff} = P_{melt} - \sigma_{xx},$$

where w is defined as zero when $\sigma_{xx} > P_{melt}$. Substitution into (10) yields

$$\sigma^{lc}_{after} = \sigma_{lc} - \frac{1}{2}\left(\sigma^{lc}_{eff} + \sigma^{m}_{eff}\right), \tag{22}$$

which expressed in terms of the deviatoric stress (σ) and viscosity (η) becomes a modified version of (13)

$$\sigma^{lc}_{after} = \frac{\sigma_{lc}}{2}\left(1 - \frac{\eta_m}{\eta_{lc}}\right) - (P_{melt} - \sigma_{zz}), \tag{23}$$

assuming that at the crust-mantle interface $\sigma^{lc}_{zz} = \sigma^{m}_{zz}$ and $P^{lc}_{melt} = P^{m}_{melt}$. The additional term implies that when the melt pressure is less than the vertical principal stress (σ_{zz}), the new deviatoric stress is not as affected as when the melt pressure is equal to σ_{zz}. When the melt is overpressured ($P_{melt} > \sigma_{zz}$), the effect of the intruding dike on the deviatoric stress is enhanced. A highly overpressured melt could increase the horizontal stress to the extent that horizontal intrusions are favored even in the absence of a rheological contrast [e.g., McCarthy and Thompson, 1988].

DISCUSSION AND EXAMPLES

The rheologic boundaries of the lithosphere can be thought of as traps where basaltic magma is more likely to orient horizontally. An interesting example of the process might be found by examining the Skaergaard intrusion of east Greenland. The Skaergaard magma chamber formed about 55 m.y. ago during the rifting of the North American and European continents, and it intruded horizontally near a contact between Precambrian basement gneiss and a 7- to 9-km-thick section of basalts and sediments [Norton et al., 1984] (Figure 4). It is clear that the intrusion did not pond at a depth of neutral buoyancy, because basalt roof rocks sank into the intrusion [Taylor, 1983], while blocks of basement gneiss floated up toward the top of the magma chamber [Norton et al., 1984]. At full extent the Skaergaard magma warped the 7- to 9-km-thick overburden nearly 2 km upward [Norton et al., 1984], which suggests that the melt was highly pressured and that it was not stalled because of low driving pressure. The layered basaltic roof rocks were only slightly older than the Skaergaard intrusion when it was emplaced [Wager and Brown, 1967; Brooks and Gleadow, 1977] and may have been rheologically weaker than the Precambrian gneissic basement rocks. Nearby vertical dike swarms [Bird et al., 1986] may have increased the horizontal stress within the basalt overburden to the extent that the Skaergaard magma was induced to intrude horizontally.

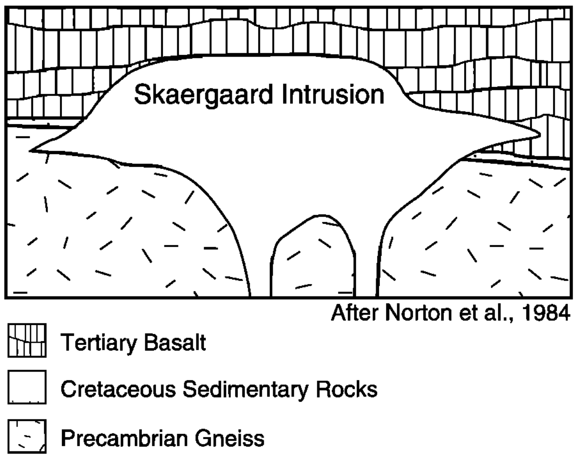

Fig. 4. Simplified north-south reconstructed cross section of the Skaergaard intrusion. Magma fractured horizontally near the contact between a 7-to 9-km-thick section of Tertiary basalts and Precambrian gneiss. The melt at the time of emplacement was denser than the basement gneiss and less dense than the basaltic roof rocks. The overlying basalt was quite young when the Skaergaard intrusion formed, and we suggest that there may have been a rheologic contrast between the layered basalts and the Precambrian basement rocks, which may have focussed horizontal intrusion there.

A similar process may occur at the base of the crust in extending terranes. While the upper mantle is likely more rigid than the lower crust, it is seldom seismogenic in extending regimes. The commonly observed association of extension with magmatism and high heat flow is perhaps an indication that dike intrusion along with some amount of ductile deformation is the means by which upper mantle extensional strain occurs. The ductile lower crust develops less deviatoric stress and may become overinflated by dike intrusion (Figure 5). Subsequent dikes in the mantle reach the ductile lower crust in which the horizontal stress exceeds the lithostatic load, and the magma is hence forced to to intrude horizontally, underplating the Moho. Multiple occurrences of this cycle may be important in the evolution of the lower crust and Moho in extending terranes. For example, Gans [1987] suggested that a 5-km layer of basalt was added to the Basin and Range crust in

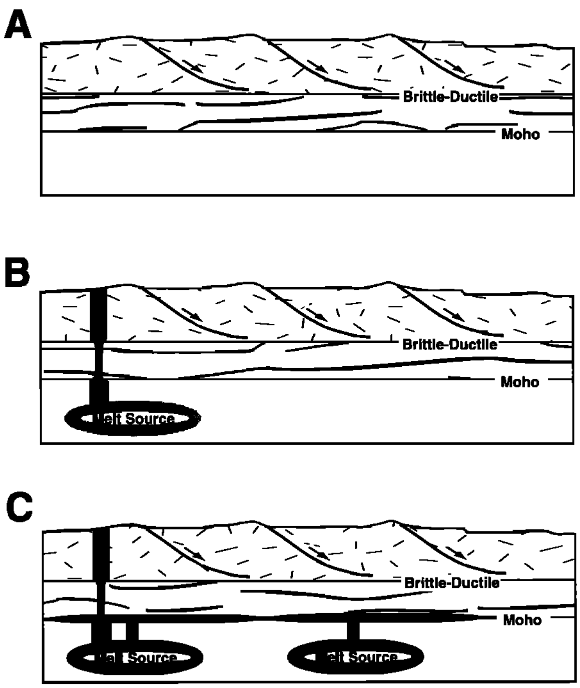

Fig. 5. Sequence of events leading to horizontal intrusion and underplating at the crust-mantle boundary. (a) In an extending regime the deviatoric stress (σ, difference of maximum vertical and least horizontal) accumulates in the more brittle upper crust and upper mantle. The more ductile lower crust tends to flow and relax the deviatoric stress before much can accumulate there. (b) A vertical dike initiates and then thins as it crosses the Moho, because of the smaller deviatoric stress. The strain caused by the dike in this case imposes a stress which exceeds the residual deviatoric stress in the lower crust. The dike continues into the brittle upper crust where it widens and combines with normal faulting to accommodate the deviatoric stress there. (c) A second pulse of dike intrusions form in the mantle and propagate upward, but the dikes encounter a compressive regime in the lower crust. The melt is induced to intrude horizontally at the crust-mantle boundary because of the new stress conditions there. The second set of dikes accommodates the remaining deviatoric stress in the mantle, which may begin accumulating again with continued extension; the whole cycle may repeat many times. Multiple cycles of this process would cause the lower crust to become more mafic, would help extending crust maintain its thickness, and would influence the character of the Moho.

order for the highly extended terrane to have achieved its current thickness of 30 to 35 km.

Deep seismic reflection imaging has located multiple occurrences of what is inferred to be magma ponding at midcrustal and Moho depths within extending terranes, as well as through the upper crust. We suggest that many of these intrusions have been trapped at rheological boundaries in the crust, particularly those in the mid and lower crust. Horizontally injected basaltic intrusions into crystalline rock of the upper crust appear as bright continuous events on seismic reflection sections because they contrast sharply in velocity with more silicic rocks. Seismic reflection profiles recorded in the Southern Basin and Range Province have identified a widespread (100 by 100 km area) series of reflections in the upper crust, known as the Bagdad Reflection sequence [Hauser et al., 1987; Goodwin et al., 1989; Howie et al., 1991]. Waveform modeling has identified the Bagdad reflectors as consistent with a large complex of horizontally intruded mafic sheets [Goodwin et al., 1989]. A series of bright, continuous reflectors were drilled at Siljan, Sweden, and were found to be horizontal diabase intrusions [Juhlin, 1988]. Initially horizontal diabase intrusions of middle Proterozoic age outcrop in tilted basement blocks throughout the southern Basin and Range Province of the western United States and were intruded from near-surface depths down to at least 13 km [Howard, 1991]. Pratt et al. [1991] found the reflection polarity of the Surrency bright spot beneath southeastern Georgia to be positive and suggested that the midcrustal event is most likely a mafic intrusion. Warner [1990] concluded that horizontal basaltic intrusions are the most viable cause of mid and lower crustal reflectivity observed on deep seismic reflection profiles, because of the unrealistic amounts of strain required to generate high-impedance shear zones. Waveform modeling of lower crustal reflection events from beneath the extending margin of the Colorado Plateau identifies the reflectors as thin, high-velocity layers, which based on xenolith data and magmatic patterns are likely recently intruded basaltic sheets [Parsons et al., 1992].

Although comparatively rare, still molten intrusions are distinctive in the mid and lower crust and often have a pronounced shear wave response. Reflections of microearthquakes indicate that a 2-km-thick active magma body is being intruded into the Rio Grande Rift near Socorro, New Mexico, at or deeper than the brittle-ductile transition (18-20 km) [Sanford et al., 1977]. Deep seismic reflection profiles recorded in northern Nevada show a very high amplitude Moho reflection beneath Buena Vista Valley. Converted P to S wave reflections from the Moho were observed at wide angles, and the Pn phase was attenuated; both are characteristic of a fluid interface, which was interpreted as magmatic underplating at the Moho [Jarchow, 1991].

CONCLUSIONS

1. In an extending terrane, intruding basaltic dikes affect the stress field of the crust they intrude because they push out against their walls in opposition to the least principal stress. Dike intrusion is thus an effective means of accommodating extension, as individual dike widths are equivalent to the horizontal slip component of a normal fault during a large earthquake. Overpressured magma imposes a still greater effect on the host rocks because in

some cases the high magma pressure may exceed the magnitude of the greatest principal stress.

2. The process by which magma injects horizontally into the crust is related to the horizontally stratified stress field produced by rheology variations. When a region is subjected to long-term tectonic stress, rheologically weak layers accumulate less stress than do stronger layers. Following a long interval of no intrusions, the ratio of deviatoric stress between two layers is proportional to the layer viscosities. An intruding dike will impose a greater compressive stress on the weak layer to the extent that the local greatest and least principal stress axes are interchanged, and subsequent dikes intrude horizontally.

3. In an extending terrane, when the intrusion time interval is large, the magnified effect of a single or few dikes in a weak layer is much enhanced, and such a case is most likely to cause horizontal intrusion. When the intrusion time interval is small, then extension in all layers is accommodated by dike intrusion, and stress differences do not develop across rheological boundaries.

4. The Moho and brittle-ductile transitions are found to be possible rheological contrasts that trap magma. Horizontal intrusions of basaltic magma have been inferred from geophysical remote sensing methods in extended terranes at the Moho and at midcrustal levels. Upper crustal basement-intruded mafic sills are commonly imaged on seismic reflection profiles and are observed in outcrops of tilted basement blocks. We suggest that the varying depths that such intrusions intrude is controlled in part by the varying rheological strength of the crust.

Acknowledgments. The authors are indebted to Allan Rubin, Mary Lou Zoback, and Jill McCarthy for extremely helpful reviews. This work was supported by National Science Foundation grants EAR 8915570, and EAR 9017667.

REFERENCES

Anderson, E. M., The Dynamics of Faulting and Dyke Formation, 206 pp., Oliver and Boyd, Edinburgh, 1951.

Bergantz, G. W., Underplating and partial melting: Implications for melt generation and extraction, *Science, 245*, 1093–1095, 1989.

Birch, F, Compressibility; elastic constants, *Mem. Geol. Soc. Am., 97*, 97–173, 1966.

Bird, D. K., R. D. Rogers, and C. E. Manning, Mineralized fracture systems of the Skaergard intrusion, *Medd. Grn. Geosci., 16*, 68 pp., 1986.

BIRPS and ECORS, Deep seismic reflection profiling between England, France and Ireland, *J. Geol. Soc. London, 143*, 45–52, 1986.

Bohlen, S. R., and K. Mezger, Origin of granulite terranes and the formation of the lowermost continental crust, *Science, 244*, 326–329, 1989.

Bradley, J., Intrusion of major dolorite sills, *Trans. R. Soc. N. Z. Geol., 3*, 27–55, 1965.

Brooks, C. K., and A. J. W. Gleadow, A fission-track age for the Skaergaard intrusion and the age of East Greenland basalts, *Geology, 5*, 357–374, 1977.

Brown, L. D., C. E. Wille, L. Zheng, B. de Voogd, J. Mayer, T. Hearn, W. Sanford, C. Caruso, T. F. Zhu, D. Nelson, C. Potter, E. Hauser, S. Klemperer, S. Kaufman, and J. Oliver, COCORP: new perspectives on the deep crust, *Geophys. J. R. Astron. Soc., 89*, 47–54, 1987.

Clowes, R. M., E. R. Kanasewitch, and G. L. Cumming, Deep crustal seismic reflections at near-vertical incidence, *Geophysics, 33*, 441–451, 1968.

Corry, C. E., Lacoliths; mechanics of emplacement and growth, *Geol. Soc. Am. Spec. Pap., 220*, 110 pp., 1988.

Cottrell, B., and J. R. Rice, Slightly curved or kinked cracks, *Int. J. Fract., 16*, 155–169, 1980.

Delaney, P. T., Heat transfer during emplacement and cooling of mafic dykes, *Geol. Assoc. Can. Spec. Pap., 34*, 31–46, 1987.

Duncan, R. A., and M. A. Richards, Hotspots, mantle plumes, flood basalts, and true polar wander, *Rev. Geophys., 29*, 31–50, 1991.

Emerman, S. H., and R. Marrett, Why dikes? *Geology, 18*, 231–237, 1990.

Fuchs, K., On the properties of deep crustal reflectors, *J. Geophys., 35*, 133–149, 1969.

Furlong, K. P., and D. M. Fountain, Continental crustal underplating: Thermal considerations and seismic-petrologic consequences, *J. Geophys. Res., 91*, 8285–8294, 1986.

Gans, P. B., An open-system, two-layer crustal stretching model for the eastern Great Basin, *Tectonics, 6*, 1–12, 1987.

Goodwin, E., G.A. Thompson, and D.A. Okaya, Seismic identification of basement reflectors: The Bagdad reflection sequence in the Basin and Range Province-Colorado Plateau Transition Zone, Arizona, *Tectonics, 8*, 821–832, 1989.

Hauser, E. C., J. Gephart, T. Latham, L. Brown, S. Kaufman, J. Oliver, and I. Lucchitta, COCORP Arizona Transect: Strong crustal reflections and offset Moho beneath the transition zone, *Geology, 15*, 1103–1106, 1987.

Herzberg, C. T., W. F. Fyfe, and M. J. Carr, Density constraints on the formation of the continental Moho and crust, *Contrib. Mineral. Petrol., 84*, 1–5, 1983.

Hildreth, W., Gradients in silicic magma chambers: Implications for lithospheric magmatism, *J. Geophys. Res., 86*, 10153–10192, 1981.

Howard, K. A., Intrusion of horizontal dikes: Tectonic significance of middle Proterozoic diabase sheets widespread in the upper crust of the southwestern United States, *J. Geophys. Res., 96*, 12461–12478, 1991.

Howie, J. M., T. Parsons, and G. A. Thompson, High-resolution P- and S-wave deep crustal imaging across the edge of the Colorado Plateau, USA: Increased reflectivity caused by initiating extension, in *Continental Lithosphere: Deep Seismic Reflections, Geodyn. Ser., vol. 22*, edited by R. Meissner, L. Brown, H. Dürbaum, W. Franke, K. Fuchs, and F. Seifert, pp. 21–29, AGU, Washington, D. C.,1991.

Jarchow, C. M., Investigations of magmatic underplating beneath the northwestern Basin and Range Province, Nevada, seismic data acquisition and tectonic problems of the Columbia Plateau, Washington, and the nature of the Mohorovičić discontinuity worldwide, Ph.D. thesis, Stanford Univ., Stanford, Calif., 1991.

Johnson, A., Physical Processes in Geology, 576 pp., Freeman, Cooper and Co., San Francisco, 1970.

Juhlin, C., Interpretation of seismic reflectors in the Gravberg-1 well, in *Deep Drilling in Crystalline Bedrock*, edited by A. Bodén and K. G. Eriksson, pp. 113–121, Springer-Verlag, New York, 1988.

Kirby, S. H., and A. K. Kronenberg, Rheology of the lithosphere: Selected topics, *Rev. Geophys., 25*, 1219–1244, 1987.

Klemperer, S. L., T. A. Hauge, E. C. Hauser, J. E. Oliver, and C. J. Potter, The Moho in the northern Basin and Range province, Nevada, along the COCORP 40°N seismic-reflection transect, *Geol. Soc. Am. Bull., 97*, 603–618, 1986.

LeCheminant, A. N., and L. M. Heaman, Mac Kenzie igneous events, Canada: Middle Proterozoic hotspot magmatism associated with ocean opening, *Earth Planet. Sci. Lett., 96*, 38–48, 1989.

Lister, J. R., and R. C. Kerr, Fluid-mechanical models of crack propagation and their application to magma transport in dykes, *J. Geophys. Res., 96*, 10049–10077, 1991.

McCarthy, J., and G. A. Thompson, Seismic imaging of extended crust with emphasis on the western United States, *Geol. Soc. Am. Bull., 100*, 1361–1374, 1988.

Matthews, D., and M. Cheadle, Deep reflections from the Caledonides and Variscides west of Britain, and comparisons with the Hymalayas, in *Reflection Seismology: A Global Perspective, Geodyn. Ser., vol. 13*, edited by M. Barazangi and L. Brown, pp. 5–19, AGU, Washington, D. C., 1986.

Meissner, R., The Continental Crust: A Geophysical Approach, 426 pp., Academic, San Diego, Calif., 1986.

Mooney, W. D., and T. M. Brocher, Coincident seismic reflection/refraction studies of the continental lithosphere; A global review, *Rev. Geophys., 25*, 723–742, 1987.

Moos, D., and M. D. Zoback, Utilization of observations of well bore failures to constrain the orientation and magnitude of crustal stresses: Application to continental, deep sea drilling project, and ocean drilling program boreholes, *J. Geophys. Res., 95*, 9305–9325, 1990.

Nakamura, K., Volcanoes as possible stress indicators of tectonic stress orientation - principle and proposal, *J. Volcanol. Geotherm. Res., 2*, 1–16, 1977.

Norton, D., H. P. Taylor, and D. K. Bird, The geometry and high-temperature brittle deformation of the Skaergaard intrusion, *J. Geophys. Res., 89*, 10178–10192, 1984.

Parsons, T., and G. A. Thompson, The role of magma overpressure in suppressing earthquakes and topography: World-wide examples, *Science, 253*, 1399–1402, 1991.

Parsons, T., J. M. Howie, and G. A. Thompson, Seismic constraints on the nature of lower crustal reflectors beneath the extending southern transition zone of the Colorado Plateau, Arizona, *J. Geophys. Res.*, in press, 1992.

Pollard, D. D., Elementary fracture mechanics applied to the structural interpretation of dykes, *Geol. Assoc. Can. Spec. Pap., 34*, 31–46, 1987.

Potter, C. J., C. -S. Liu, J. Huang, L. Zheng, T. A. Hauge, E. C. Hauser, R. W. Allmendinger, J. E. Oliver, S. Kaufman, and L. Brown, Crustal structure of north-central Nevada: results from COCORP deep seismic profiling, *Geol. Soc. Am. Bull., 98*, 330–337, 1987.

Pratt, T. L., E. C. Hauser, T. M. Hearn, and T., J. Reston, Reflection polarity of the midcrustal Surrency bright spot beneath southeastern Georgia: Testing the fluid hypothesis, *J. Geophys. Res., 96*, 10145–10158, 1991.

Rubin, A. M., A comparison of rift-zone tectonics in Iceland and Hawaii, *Bull. Volcanol., 52*, 302–319, 1990.

Rubin, A. M., and D. D. Pollard, Dike-induced faulting in rift zones of Iceland and Afar, *Geology, 16*, 413–417, 1988.

Sanford, A. R., R. P. Mott, Jr., P. J. Shuleski, E. J. Rhinehart, F. J. Caravella, R. M. Ward, and T. C. Wallace, Geophysical evidence for a magma body in the crust in the vicinity of Socorro, New Mexico, in *The Earth's Crust, Its Nature and Physical Properties, Geophys. Monogr. Ser., vol. 20*, edited by J. G. Heathcock, G. V. Keller, J. E. Oliver, and G. Simmons, pp. 385–403, AGU, Washington, D. C., 1977.

Sleep, N. H., Tapping of melt by veins and dikes, *J. Geophys. Res., 93*, 10,225–10,272, 1988.

Smithson, S. B., Contrasting types of lower crust, in *Properties and Processes of Earth's Lower Crust, Geophys. Monogr. Ser.* vol. 51, edited by R. F. Mereu, S. Mueller, and D. M. Fountain, pp. 53–63, 1989.

Taylor, H. P., Oxygen and hydrogen isotope studies of hydrothermal interactions at submarine and subaerial spreading centers, in *Hydrothermal Processes at Seafloor Spreading Centers, NATO Conf. Ser. IV: Mar. Sci.*, vol. 12, edited by P. Rona, K. Bostrom, L. Laubier, and K. Smith, pp. 83–139, Plenum, New York, 1983.

Turcotte, D. L., and G. Schubert, Geodynamics - Applications of Continuum Physics to Geological Problems, 450 pp., John Wiley, New York, 1982.

Wager, L. R., and G. M. Brown, Layered Igneous Rocks, 588 pp., Freeman, Cooper, San Francisco, Calif., 1967.

Warner, M., Basalts, water, or shear zones in the lower continental crust?, *Tectonophysics, 173*, 163–174, 1990.

Weertman, J., Theory of water-filled crevasses in glaciers applied to vertical magma transport beneath oceanic ridges, *J. Geophys. Res., 76*, 1171–1183, 1971.

Wilkes, K. R., and N. L. Carter, Rheology of some continental lower crustal rocks, *Tectonophysics, 182*, 57–77, 1990.

Wilshire, H. G., Lithology and evolution of the crust-mantle boundary region in the southwestern Basin and Range province, *J. Geophys. Res., 95*, 649–665, 1990.

Zoback, M. L., and M. D. Zoback, State of stress in the coterminous United States, *J. Geophys. Res., 76*, 1171–1183, 1980.

T. Parsons, N. H. Sleep, and G. A. Thompson, Department of Geophysics , Stanford University, Stanford, CA 94305.

(Received January 23, 1992;
revised May 4, 1992;
accepted May 11, 1992.)