Tectonic stresses in the African plate: Constraints on the ambient lithospheric stress state

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ABSTRACT

An elastic finite-element analysis of the African intraplate stress field is used to determine constraints on the stress state resulting from variations in the gravitational potential energy of the lithosphere (U_l) produced by lateral density variations. The modeling is constrained by 150 stress indicators extracted from the World Stress Map Project data set. Lateral variations in U_l are calculated by using a simple lithospheric density model that is consistent with observed geoid anomalies across mid-ocean ridges and continental margins. Predicted tectonic stresses in the oceanic regions of the African plate range from tension along the mid-ocean ridges (9 MPa) to compression in the ocean basins (10 MPa). Continental regions near sea level are in a near-neutral state of stress. There are large extensional stresses present in the Ethiopian highlands (15 MPa), the East African rift (9 MPa), and southern Africa (8 MPa). The general agreement between the predicted and the observed stress fields suggests that the principal long-wavelength features of the intraplate stress field, including the observed extension in eastern and southern Africa, can be explained in terms of stresses arising from lithospheric density variations without appeal to poorly determined sublithospheric processes. The state of stress in continental regions with elevations greater than 70 m is predicted to be extensional, providing an alternative source of continental tension that has important implications for the dynamics of continental breakup.

INTRODUCTION

The ambient lithospheric stress state (ALSS) is the state of stress that exists in the absence of tractions acting along the plate boundaries or along the base of the plate (Dahlen, 1981). In this case, the intraplate stress field is governed solely by lateral density variations in the lithosphere. Because these variations produce corresponding variations in the gravitational potential-energy distribution, a reference tectonic stress state can be defined in terms of the plate-scale mean gravitational potential energy $\bar{U}_l$. The difference $\Delta \bar{U} U_l$ between the potential energy of a lithospheric column and the plate-scale mean ($U_l - \bar{U}_l$) determines the state of stress of the column: extensional if $\Delta \bar{U}_l$ is positive, neutral if $\Delta \bar{U}_l$ is negligible, and compressional if $\Delta \bar{U}_l$ is negative. Thus, information about $\bar{U}_l$ and the ALSS has important implications for understanding the source of tectonic stresses responsible for sedimentary basin development, mountain-building processes, and continental deformation. In most plates it is difficult to isolate the ambient state of stress. The major continental plates, including North America, South America, and Indo-Australia, are fast moving (suggesting the possibility of a large amount of drag along the base of the plate) and have long segments of convergent or transcurrent plate boundary (Forsyth and Uyeda, 1975). The African and Antarctic plates are unique in that both are slow moving (producing negligible drag tractions along the bases of the plates) and are predominantly surrounded by mid-ocean ridges. Thus, of Earth's tectonic plates, these two plates can be expected to best approximate the ALSS (Crough, 1983).

In this study we evaluate the ALSS with a finite-element analysis of the African intraplate stress field. The goal of this study is twofold: to estimate the magnitude of the ambient tectonic stresses and to evaluate what part of the observed African intraplate stress field is explicable in terms of lateral density variations. We hope to clarify the significance of other postulated sources of intraplate stress such as shear tractions acting along the base of the lithosphere and to evaluate the role the predicted stresses may play in continental rifting.

LITHOSPHERIC GRAVITATIONAL POTENTIAL ENERGY

The gravitational potential energy per unit area of a column of material U above a given depth z is given by the integral of the vertical stress σ_{zz} from z to the surface h (e.g., Molnar and Lyon-Caen, 1988),

$$U_l = \int_z^h \sigma_{zz}(\tau)\, d\tau = g \int_z^h \int_t^h \rho(\tau')\, d\tau'\, d\tau, \qquad (1)$$

where $\rho(\tau')$ is the density, z is equipotential depth, h is the surface elevation, g is the gravitational acceleration, and τ' and τ are integration variables. In the ALSS, the intraplate stress field can be predicted from knowledge of the plate-scale potential-energy distribution (Coblentz et al., 1994; Sandiford and Coblentz, 1994).

For the assumed lithospheric density structure, the mean potential energy per unit area of the African plate ($\bar{U}_l = 2.378 \times 10^{14}$ N·m^{-1}) is equal to the potential energy of cooling oceanic lithosphere at a depth of ~4.3 km and to continental lithosphere with ~70 m elevation. Thus, the mid-ocean ridges and continental regions with elevations greater than 650 m have potential energies significantly greater than the plate mean (Fig. 1, Table 1).

AFRICAN INTRAPLATE STRESS FIELD

The present-day intraplate stress field in the African plate is well documented by 150 stress indicators with quality rankings of A–C (Zoback, 1992). A majority of the stress indicators are located on the continent, providing an excellent basis for evaluating the predicted lithospheric stresses within the continent regions. The lo-
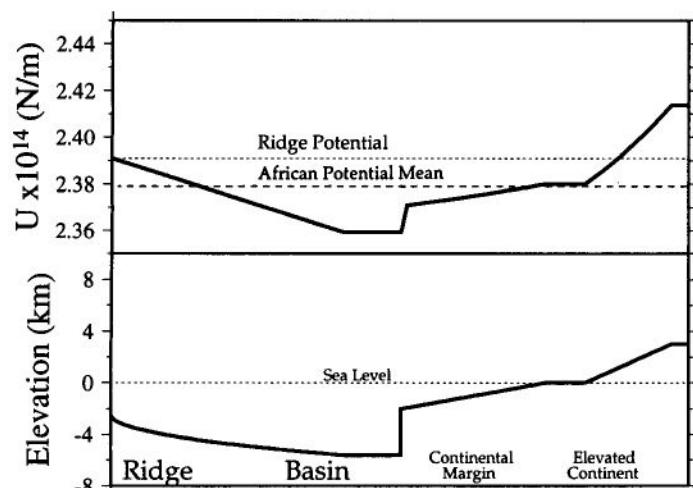
Figure 1. Calculated potential energy, U, across topographic cross section representing mid-ocean ridge, oceanic basin, passive (Atlantic-type) continental margin, and elevated continental lithosphere. Global topographic mean is -2880 m, mid-ocean ridge potential is 2.391×10^{14} $N \cdot m^{-1}$, and mean potential energy of African plate is 2.378×10^{14} $N \cdot m^{-1}$ (calculated with $\rho_c = 2750$ $kg \cdot m^{-3}$).

TABLE 1. POTENTIAL-ENERGY MEANS, DIFFERENCES, AND CORRESPONDING HORIZONTAL STRESSES DUE TO VARIOUS LITHOSPHERIC DENSITY VARIATIONS IN THE AFRICAN PLATE

Source	Potential energy ($\times 10^{14}$ $N \cdot m^{-1}$)	Potential difference* ($\times 10^{12}$ $N \cdot m^{-1}$)	Cumulative force[†]
Plate mean	2.378	0.0	0.0
Ridge crest	2.391	1.4	0.7
Old ocean basin	2.365	-1.2	-0.6
Mean continental elevation (650 m)	2.386	0.9	0.4
Elevated continent (1500 m)	2.394	1.6	0.8

* Between the calculated potential energy of the lithospheric column and the plate mean.

[†] The cumulative force α required to deform the lithosphere in regions of high heat flow (> 60 mW·m⁻¹), assumed to be 2 ×10¹² N·m⁻¹ (Zoback et al., 1993).

cation, type, and orientation of the maximum horizontal stress, S_{Hmax}, for the indicators are plotted in Figure 2. In northernmost Africa, S_{Hmax} is oriented north-south, and the stress regime is strike slip to compressional. In the midplate regions, S_{Hmax} is oriented east-west, and the stress regime is strike slip (Suleiman et al., 1993). In the East African rift region, S_{Hmax} is oriented roughly N20°E (Bosworth et al., 1992), and the stress regime is dominantly extensional. The magnitude of ($S_{Hmax} - S_{hmin}$) in eastern Africa has been estimated from the rotations of the principal stresses in the East African rift at ~14 MPa (Zoback, 1992).

MODELING METHOD

We have used a linear finite-element method to calculate the magnitude and orientation of the tectonic stresses resulting from lateral variations in potential energy across the African plate. In this study, tectonic stress refers to the horizontal stress component minus the reference state (Engelder, 1993). The lithosphere is represented by a spherical elastic shell composed of 1762 nodes in a network of 3348 constant-strain triangular elements. The spatial resolution of the finite-element grid is ~2° in both latitude and longitude. Thus, the sensitivity of the modeled stresses is limited to large-scale tectonic features with wavelengths of a few hundred ki-
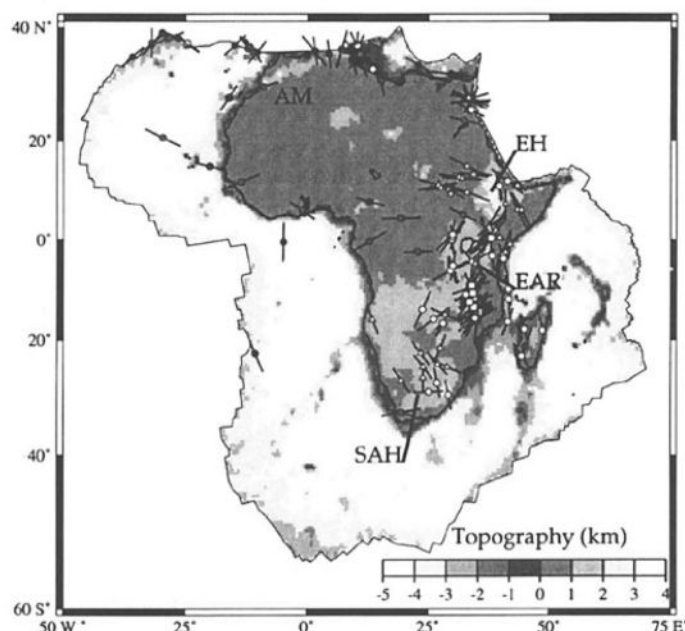

Figure 2. African plate with boundaries as defined by DeMets et al. (1990). Also shown are the 150 stress indicators with quality rankings of A–C from *World Stress Map* database (Zoback, 1992). Circles represent focal mechanisms, squares represent geologic indicators, and triangles represent borehole data. Solid, open, and gray-shaded stress-indicator symbols represent compressional, extensional, and strike-slip deformational styles, respectively. Orientation of maximum horizontal compressive stress (S_{Hmax}) is also shown. Orientations without symbols designate volcanic vent alignments. Lengths of vectors representing S_{Hmax} have been weighted by indicator quality (A–C, after Zoback et al., 1992). Major topographic features of continental Africa are labeled. Abbreviations are AM—Atlas Mountains, EH—Ethiopian highlands, EAR—East African rift, and SAH—South African highlands.

lometres. The stress magnitudes are presented as averages over a lithosphere of constant thickness, assumed to be 125 km. Substantial stress focusing may occur where there are variations in the thickness of the elastic lithosphere such as beneath the East African rift where the lithosphere is thought to be as thin as 30 km (e.g., Brown and Girdler, 1980). Horizontal stresses due to lateral potential-energy variations were incorporated in the modeling through the use of a horizontal volume force, proportional to the horizontal gradient of the density moment (Fleitout, 1991; Richardson and Reding, 1991). For the purpose of this study, the plate was assumed to be stationary, and no tractions due to drag forces were applied along the base of the plate. We assume a condition of static equilibrium that requires the sum of the torques acting on the plates to be zero. In the case of the African plate, the zero net-torque condition is readily achieved by fixing the plate boundaries.

MODELING RESULTS

The tectonic stresses predicted by our modeling correlate well with the observed distribution of extensional and compressional stress regimes in the African continent (cf. Figs. 2 and 3). The mid-ocean ridges and much of the ridge flanks are in tension (up to 9 MPa); S_{Hmax} is oriented parallel to the ridge axis. In the older, deeper parts of the oceanic basins, the predicted state of stress is compressional; the maximum compressive stress is ~10 MPa. At a depth of ~4 km along the ridge flanks, the state of stress is neutral. Continental regions near sea level are in a near-neutral state of stress; large extensional stresses exist in the Ethiopian highlands (15 MPa), the East African rift (9 MPa), and southern Africa (8 MPa) and are in agreement with stress magnitudes predicted by previous modeling studies of the stresses associated with the combined effect
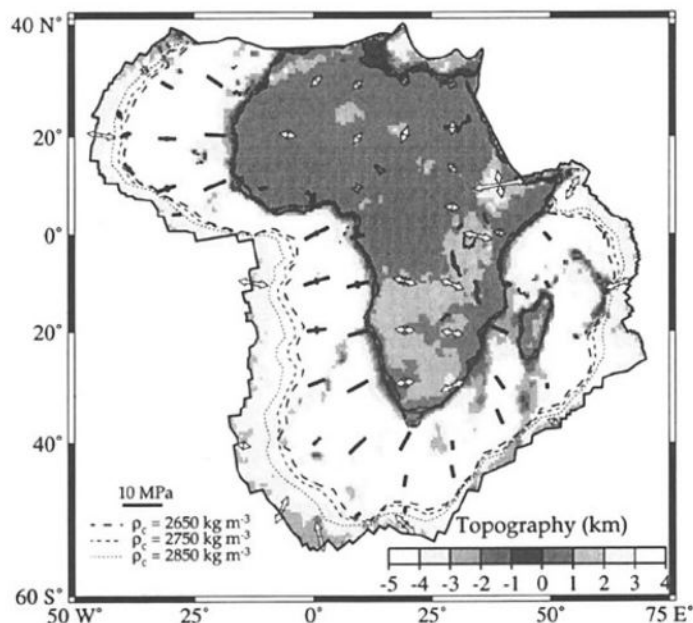
Figure 3. Predicted tectonic stresses for African plate at selected element locations. Solid bars indicate compression; open arrows indicate tension. Maximum extension in Ethiopian highlands is 17 MPa (averaged over a 125-km-thick lithosphere); maximum compression in oceanic basins is 10 MPa. Dashed lines show locations where ΔU_l (= $U_l - \bar{U}_l$) is zero for three continental crustal density (ρ_c) values as indicated. Mid-ocean ridges and continental regions have potential energy in excess of plate mean for ρ_c in this range.

TABLE 2. RELATIVE TORQUE CONTRIBUTIONS

Source	Magnitude ($\times 10^{25}$ N $\cdot$ m)	Latitude (°N)	Longitude (°E)
Whole plate	1.81	20.3	-67.0
Young oceanic lithosphere	3.21	57.9	-34.4
Old oceanic lithosphere	1.97	-63.6	-159.7
Continental margin	0.32	-25.4	106.6
Elevated continental lithosphere	0.77	-16.8	-74.2

of the excess topography and upthrust of the underlying low-density region in East Africa (Bott and Kusznir, 1979). Furthermore, the prediction of extensional stresses in continental Africa is consistent with the observation that most West African earthquakes are strike-slip events (Suleiman et al., 1993). In addition, the orientation of P axes for the West African events shows a large degree of variability, suggesting that local sources of stress and not ridge-push forces dominate the stress field in this region. In the East African rift region, S_{Hmax} is oriented roughly north-south, which compares well with the observed orientation of about N20°E (Bosworth et al., 1992). We conclude that since most long-wavelength features in the observed stress field are explicable in terms of intralithospheric sources of stress, there may be no need to appeal to poorly determined sublithospheric processes such as viscous drag (i.e., Pavoni, 1992; Westaway, 1993) to explain the African intraplate stress field. We note that the state of stress in the African plate is in sharp contrast to that in eastern North America and South America where most earthquakes are thrust events and the orientation of P axes correlates well with the ridge-push torque direction (Zoback and Magee, 1991; Richardson, 1992; Zoback, 1992; Suleiman et al., 1993) where other sources of tectonic stress (i.e., plate-boundary forces) exert a strong influence on the intraplate stress field.

In plates that approximate the ALSS, the net torque resulting from the potential-energy distribution should be zero. For the density model assumed here, the net torque acting on the African plate is 1.8×10^{25} N $\cdot$ m about a pole at lat 20°N, long 67°W (Table 2), and is due primarily to the absence of a mid-ocean ridge along the northern margin. This torque acts to drive the plate northward. The resistance of this motion by collisional processes acting along the northern boundary can be expected to result in some north-south compression along the northern part of the plate, as observed in the Atlas Mountains (Fig. 2).

The results of the modeling provide an important constraint on

the ridge-push contribution to the intraplate stress field. The magnitude of the ridge forces is generally accepted to be 2–3 × 10¹² N per metre of ridge length (e.g., Lister, 1975; Parsons and Richter, 1980). Although the ridges have an excess potential energy per unit area over the old ocean basins of about 2.6×10^{12} N $\cdot$ m^{-1}, the actual force contribution from the ridges to the intraplate stress field will be less than this value, because the stress magnitude is governed by the difference in potential energy $\Delta \bar{U}_l$ between the mean potential energy $\bar{U}_l$ and the potential energy of the ridge crest. In the case of the African plate, $\Delta \bar{U}_l$ is $\sim 1.4 \times 10^{12}$ N $\cdot$ m^{-1}, which corresponds to a compressive horizontal stress of ~ 11 MPa (averaged over a 125-km-thick lithosphere), rather than the value of 21 MPa predicted by the $\Delta \bar{U}_l$ between the ridge crest and the old ocean basin.

The greatest uncertainty in lithospheric potential energy relates to the density structure of the continental lithosphere, and the predicted stress regimes may be strongly dependent on the reference density of the continent, ρ_c. $\bar{U}_l$ is dependent on ρ_c, increasing 6 × 10¹¹ N $\cdot$ m^{-1} (from 2.375 to 2.381 × 10¹⁴ N $\cdot$ m^{-1}) as ρ_c varies from 2650 to 2850 kg $\cdot$ m^{-3}, a range that is consistent with predicted mean crustal-density values for African continental crust (Brown and Girdler, 1980). We have evaluated the sensitivity of the modeling results ρ_c in this range. The depth along the oceanic ridge corresponding to the plate-scale potential mean (dashed lines in Fig. 3) is a strong function of ρ_c. We note, however, that the continental regions remain in an excess potential state for all values of ρ_c in this range.

DISCUSSION AND CONCLUSIONS

The origin of the stresses that drive continental extension remains controversial. Much current debate exists about the relative contribution of tractions exerted at distant plate boundaries, viscous forces applied at the base of the plate, and buoyancy forces arising from lithospheric density distributions (e.g., Bott, 1982; Houseman and England, 1986; Gurnis, 1988; Bott, 1992; Pavoni, 1992; Westaway, 1993; Duncan and Turcotte, 1994). The importance of lateral density variations in the lithosphere has long been recognized as an important source of intraplate stress and associated deformation (e.g., Evison, 1960; Frank, 1972; Artyushkov, 1973; Lister, 1975; Molnar and Tapponier, 1978; Houseman et al., 1981; Bott, 1982; England and McKenzie, 1982; Fleitout and Froidevaux, 1982, 1983; Turcotte, 1983; England, 1987; Molnar and Lyon-Caen, 1988; Bott, 1992; Zhou and Sandiford, 1992). Under certain conditions, the magnitudes of the tectonic forces within the African lithosphere are large enough to play an important role in the active deformation observed in East Africa. The extensional strength of the lithosphere at the limit of geologically significant strain rates has been predicted to be in the range of 3–4 × 10¹² N $\cdot$ m^{-1} (Houseman and England, 1986; Kusznir and Park, 1987). Estimates of the upper-crustal strength inferred from stress measurements in the KTB (Continental Deep-bore Drilling Program) well hole in Germany show that α, the cumulative force needed to deform crustal material, is in the same range (Zoback et al., 1993). If it is assumed that α is as small as 2 × 10¹² N $\cdot$ m^{-1} in the tectonically active regions of continental Africa

where the high heat flow is in excess of $60 \, \text{mW} \cdot \text{m}^{-2}$ (Nyblade et al., 1990), the excess potential energy of the elevated continental regions is a significant fraction of α (Table 2). In regions where the elevation is equal to the continental mean (650 m), the excess potential energy is 0.4α, and in eastern and southern Africa where the mean elevation approaches 1500 m, the excess potential energy may be as much as 0.8α. These results highlight the importance of intralithospheric forces for understanding the forces responsible for continental deformation.

Our prediction that the ambient state of stress in the continental lithosphere is extensional has important implications for understanding the sources of intraplate tension that is responsible for continental breakup. This prediction differs significantly from other investigators' assumptions that the state of stress within the continents is dominated by stresses transmitted from the mid-ocean ridges and is therefore compressional (e.g., Crough, 1983; Houseman and England, 1986; Zoback, 1992). Our prediction of an extensional state of stress for continental regions provides an additional source of intraplate tension that may help contribute to the rifting on continents. An important implication of this additional source of tension is that it may be possible to explain the breakup of predominately continental plates such as Pangea without appealing to poorly determined subduction pull forces (Bott, 1982, 1992).

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