New seismic model of the upper mantle beneath Africa

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ABSTRACT

We present a seismic model of the upper 400 km of the mantle beneath Africa and surrounding regions. This model is constructed by inverse modeling of fundamental mode Rayleigh wave phase velocities (40–200 s) for about 8000 propagation paths. Among the most pronounced anomalies are high shear velocity structures (as much as 6% higher than in the Preliminary Reference Earth model) beneath the West African, Congo, and Kalahari cratons that extend to about 250 km depth. These structures have near-vertical margins across which the shear velocity changes by as much as 6% over 500 km distance. Anomalous low shear velocities (3%–4% lower than in the Preliminary Reference Earth Model) structures are observed beneath the East African, Red Sea, and Gulf of Aden rifts, and beneath the northwestern Indian Ocean. These structures extend to a depth of at least 250 km. Our model cannot be reconciled with models that invoke a large number of plumes that have impinged on the base of the lithosphere, nor does our seismic model indicate that high-temperature, low-density material beneath the lithosphere is responsible for the uplift of southern Africa.

Keywords: Africa, cratonic structure, East African Rift, seismic tomography, Rayleigh waves, shear wave velocity.

INTRODUCTION

The deployment of new seismic stations in and around Africa in the past decade has resulted in a substantial increase of high-quality recordings of seismic wave propagation through the mantle beneath Africa. These new seismic data enable us to improve models of seismic structure beneath Africa. In this paper we present a new three-dimensional model of seismic shear velocity in the upper mantle beneath Africa and surrounding regions that has been constructed by tomographic inversion of Rayleigh wave phase velocity data. Because our model area is only one-ninth of the Earth's surface area, we can afford to use a significantly denser model parameterization than global tomographic inversions (e.g., Li and Romanowicz, 1996; Masters et al., 1996). Hence, we resolve shear velocity variations in the mantle beneath Africa with unprecedented lateral resolution.

Although our model is extremely valuable to relate diverse geologic terrains and tectonic processes with seismic structures in the deep mantle, we limit our interpretation of the model with the following points in mind: (1) the extent to which Mesozoic and Cenozoic rifting processes in central and eastern Africa (Fairhead, 1992; Prodehl et al., 1994) affected Archean and Proterozoic terrains that occupy large regions of western and southern Africa (Fig. 1); (2) the thickness of cratons; and (3) whether anomalous thinning of the cratonic lithosphere is a viable explanation for the uplift of southern Africa (e.g., Brown and Girdler, 1980; Nyblade and Robinson, 1994).

SEISMIC SHEAR VELOCITY MODEL FOR THE AFRICAN UPPER MANTLE

Rayleigh waves are often used to determine seismic structure in the upper mantle (e.g., Cichowicz and Green, 1992; Van der Lee and Nolet, 1997; Ekström and Dziewonski, 1998; Vdovin et al., 1999) because they propagate entirely within the crust and upper mantle, have large amplitudes compared to body waves (Fig. 2), and are generally well recorded at teleseismic distances (>3000 km) even when they are generated by moderate-size earthquakes. Moreover,

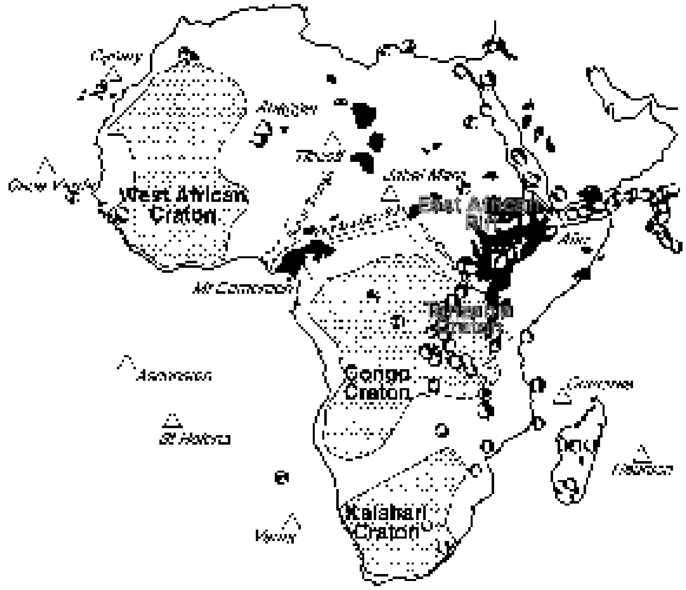

Figure 1. Tectonic map of Africa. Cratonic provinces are shaded light gray; dark shaded regions outline volcanic regions. Dashed lines indicate location of rifts, triangles are hotspot locations, and focal mechanisms are plotted at epicenters of African earthquakes that occurred in past 20 yr.

Figure 2. Vertical component recordings of July 23, 1983, South Shetland Islands earthquake at station SLR in South Africa. Recording is lowpass filtered so that only signals with seismic periods longer than 30 s are retained. Seismic phases P, PP, and S are body wave phases. Rayleigh waves are large-amplitude surface waves that propagate along Earth's surface and are recorded well after body wave signals. Long-period Rayleigh wave signals propagate faster than shorter period signals, causing dispersion of Rayleigh waves into relatively long wave train.

the dispersion of Rayleigh waves, caused by the fact that Rayleigh waves with different frequencies propagate with different speeds, provides excellent constraints on the variation of seismic velocity with depth.

We analyze fundamental mode Rayleigh wave data for periods ranging from 40 to 200 s. Rayleigh wave data for this period range constrain seismic velocity structures to a depth of about 400 km. We measure Rayleigh waves phase velocities with the mode-branch stripping method of Van Heijst and Woodhouse (1997). In this procedure, frequency-dependent phase velocities are measured by cross-correlating vertical component long-period seismograms with synthetic seismograms. These recordings are from digital broadband seismic instruments in Africa, Europe, and the Middle East. In order to maximize the sampling of the upper mantle beneath Africa, we have analyzed recordings of earthquakes as small as $M_w = 5.2$. Data for these relatively low magnitude earthquakes are often very useful and have been carefully processed to ensure that only reliable phase velocity measurements are retained. Furthermore, we have collected all available data from global networks (Global Seismic Network, GEOSCOPE), regional networks (MedNet, German Regional Seismic network), and temporary seismic deployments in Tanzania and Saudi Arabia. We obtain the largest number of phase velocity measurements for the shortest seismic periods (40–62 s) when the signal-to-noise ratio of Rayleigh waves generated by small, shallow earthquakes is best. Nonetheless, even for the relatively long period of 150 s, we obtain more than 3600 high-quality measurements for source-receiver paths that are well distributed over Africa (Fig. 3).

The Earth's crust has a strong influence on Rayleigh wave propagation even at relatively long periods. We account for the effects of surface topography, ocean bathymetry, and lateral variations of crustal thickness using the global crustal model CRUST5.1 derived by Mooney et al. (1998). Corrections for the crust are important to account for the large variation in crustal thickness between oceans and continents. Uncertainty in the crustal thickness of as much as 10 km, as expected for Africa, does not significantly affect the modeling of Rayleigh waves in terms of seismic velocity structure (Van Heijst, 1997). We invert the crust-corrected Rayleigh wave phase velocity data for a three-dimensional model of shear velocity following a regionalized version of the global inversion procedure developed by Van Heijst (1997). In this procedure, we assume that Rayleigh waves propagate along the great-circle path between source and receiver, and that shear velocity variations are two times stronger than P wave velocity variations. The variation of shear velocity with depth is parameterized by 10 overlapping spline functions that extend to a depth of 400 km, and lateral shear velocity variations are parameterized by surface harmonic functions that span a model region between 60°S and 65°N and between 35°W and 75°E. The seismic model presents shear velocity variations with a lateral resolution of about 500 km. Depth resolution in the upper 250 km is on the order of 50 km, but it is considerably lower at larger depths.

Figure 4 shows horizontal and vertical cross sections through the shear velocity model that is obtained after inversion. At 100 km depth, the model most clearly reveals the major geologic provinces. Prominent high-velocity velocity structures are resolved beneath the West African, Congo, and Kalahari cratons in Africa, and the Baltic shield in northern Europe. Maximum

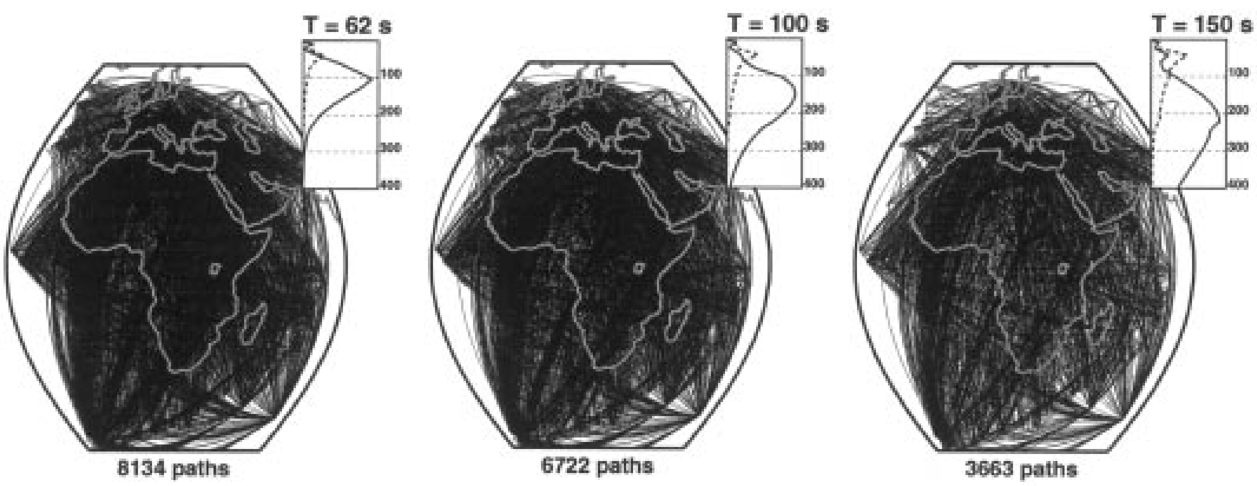

Figure 3. Path distribution of Rayleigh waves for which phase velocity measurements at seismic periods of 62, 100, and 150 s have been made. Superposed kernels indicate Rayleigh wave sensitivity to shear velocity (thick line) and P wave velocity (dashed line) in upper mantle. Rayleigh waves with periods shorter than 62 s are primarily sensitive to seismic structure shallower than 250 km depth, whereas Rayleigh waves with periods longer than 150 s are sensitive to seismic structure well below 300 km depth.

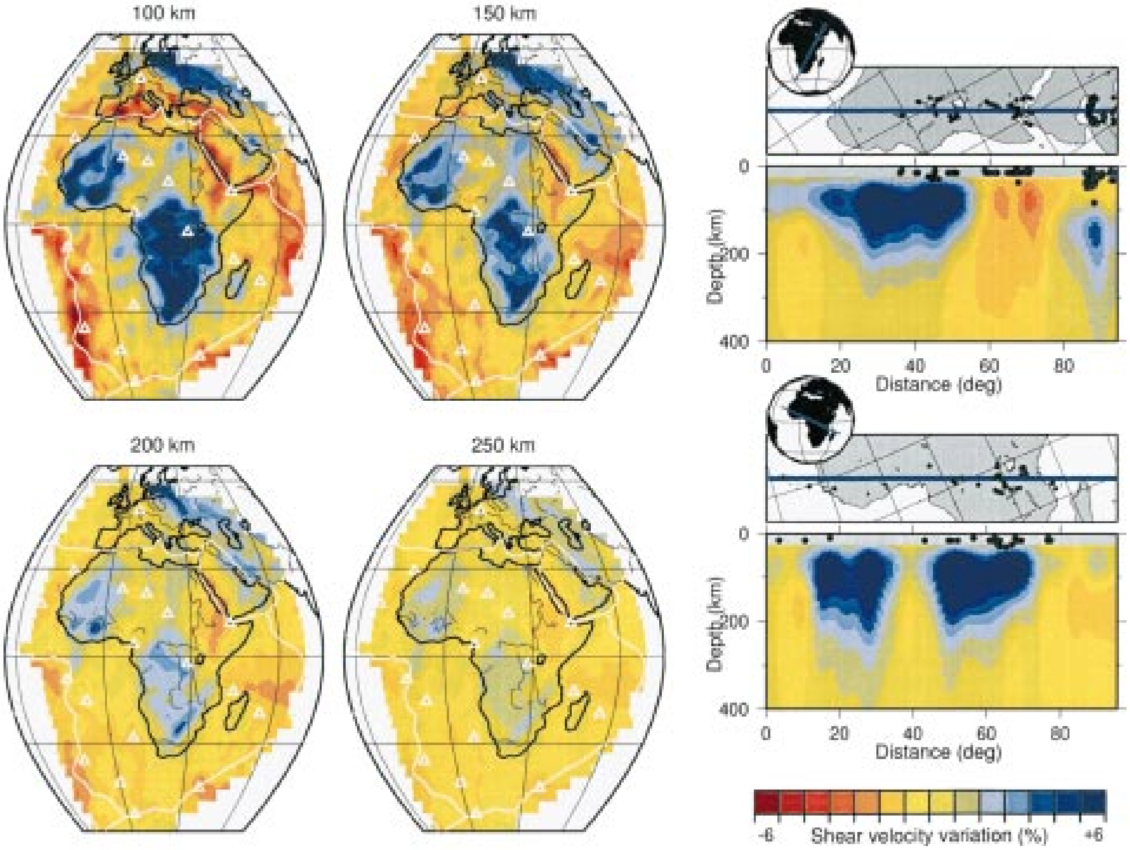

Figure 4. Left: Horizontal cross sections through shear velocity model at 100 km, 150 km, 200 km, and 250 km depth. Thin lines represent plate boundaries and white triangles are hotspot locations. Right: Vertical cross sections across great circle paths from southwestern Atlantic Ocean to southern Iran and from central Atlantic Ocean to central Indian Ocean. Scale of seismic velocity perturbation from Preliminary Reference Earth Model ranges from −6% to +6%. Dark circles are plotted at earthquake hypocenters provided in Harvard Centroid Moment Tensor catalog.

shear velocity perturbations from the Preliminary Reference Earth Model (Dziewonski and Anderson, 1981) in these structures are about 6%. Low shear velocity structures (3%–4% lower than in the Preliminary Reference Earth Model) are associated with mid-ocean ridges, the Afar triple junction of the East African, Red Sea, and Gulf of Aden rifts, and backarc volcanism in the Mediterranean. With increasing depth, the amplitudes of these anomalies diminish quickly. At a depth of 250 km, shear velocity perturbations from the Preliminary Reference Earth Model are <1%–2%.

Smaller scale and lower amplitude seismic anomalies include the relatively high shear velocity structures beneath Egypt and beneath Somalia adjacent to the rift regions of northeastern Africa. The progressively increasing shear velocity from the southwest to the northeast beneath Saudi Arabia follows the decreasing elevation of the Arabian plate. High shear velocity structure beneath the Zagros orogenic belt in Iran is probably related to subduction of oceanic lithosphere during the convergence between the Afro-Arabian and Eurasian plates (Takin, 1972). High shear velocity structure is also evident beneath Italy and Greece associated with subduction of Africa under Eurasia (Spakman, 1991). Relatively low shear velocity structures coincide with Cretaceous rifts along the Benue Trough that extend into Niger and Chad (e.g., Binks and Fairhead, 1992), marking a clear separation between the West African and Congo cratons. At a depth greater than 100 km, low shear velocity structure beneath the northwestern Indian Ocean extends far from the mid-ocean ridge and possibly connects with low-velocity structure beneath the East African rift and the Red Sea rift.

Vertical cross sections demonstrate that the margins of the high shear velocity structures beneath cratons are steep and that the shear velocity changes across these margins are at least 6% over 500 km distance. The Tanzania craton is about 50–80 km thinner than the Congo and Kalahari cratons. Low shear velocity material from the East African rift may have penetrated beneath the base of the lithosphere under the Tanzania craton. However, complete erosion of the keel of Tanzania craton by the East African rift can be ruled out, in accord with the study by Ritsema et al. (1998).

DISCUSSION

The presence of high velocities beneath cratons in our surface wave model is consistent with regional body wave modeling results (e.g., Zhao et al., 1999) and with results from the study of mantle xenoliths (Rudnick et al., 1998), diamondiferous kimberlites (e.g., Boyd et al., 1985), and surface heat flow (Nyblade et al., 1990) that suggest that cratonic mantle temperatures are anomalously low. We estimate that the thickness of the West African, Congo, and Kalahari cratons is about 250 km, similar to the thickness of cratons in other regions of the world (e.g., Van Heijst, 1997; Ekström and Dziewonski, 1998). This indicates that the African lithosphere has not been significantly eroded by rifting processes during the past 200 m.y. Furthermore, we conclude that the elevation of southern Africa (Nyblade and Robinson, 1994) is not supported by warm and low-density material in the upper mantle beneath the craton. Our data cannot address whether the uplift is caused by a broad thermal anomaly in the lower mantle (e.g., Lithgow-Bertelloni and Silver, 1998).

Except for the active rift regions in northeastern Africa, we do not resolve anomalous low-velocity structures beneath the lithosphere. It is therefore unlikely that spreading plume heads at the base of the lithosphere are responsible for plate-wide hotspot volcanism in Africa (Burke, 1996). The only significant broad low-velocity structures in the upper mantle are located beneath the Afar region and the East African rift, which extend into the northwestern Indian Ocean. This observation is consistent with the modeling results of Ebinger and Sleep (1998), who suggested that hot material originating from a single plume beneath Africa flows along the stiff African cratonic boundaries into the Indian Ocean and into the African continent. This material reaches the Earth's surface by propagating through the lithosphere along weak (rifted) zones.

CONCLUSIONS

From more than 8000 surface wave phase velocity measurements using stations in Africa, Europe, and the Middle East, we constructed a shear velocity model of the upper 400 km of the mantle beneath Africa and surrounding regions. High-velocity structures (as much as 6% higher than in the Preliminary Reference Earth Model) beneath the cratons and low-velocity structure beneath mid-ocean ridges, southern Europe, the Red Sea rift, and the Afar region (3%–4% lower than in the Preliminary Reference Earth Model) are the most anomalous features of the model. The cratons are ~250 km thick. Significant low-velocity structures at depths greater than 100 km are present only beneath northeastern Africa and the northwestern Indian Ocean.

ACKNOWLEDGMENTS

MedNet and the Tanzania and Saudi Arabia PASSCAL data were provided by the IRIS and GEOSCOPE data management centers. All figures were generated with the GMT software. This research is funded by National Science Foundation grant EAR-98-96210. Software written by John Woodhouse helped us with the data processing. We thank the reviewers for helpful comments. This is contribution 8673 of the Division of Geological and Planetary Sciences, California Institute of Technology.

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Manuscript received July 1, 1999
Revised manuscript received September 22, 1999
Manuscript accepted September 28, 1999