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One-dimensional Shear Velocity Structure of Northern Africa from Rayleigh Wave Group Velocity Dispersion

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Abstract—Rayleigh wave group velocity dispersion measurements from 10 s to 160 s periods have been made for paths traversing Northern Africa. Data were accumulated from the IRIS DMC, GEOSCOPE, and MEDNET seismic networks covering the years 1991–1997. The group velocity measurements are made including the effects of debiasing for instantaneous period and a single-iteration, mode-isolation (phase match) filter. The curves are grouped by tectonic province and compared to tomographic model-based curves in an effort to test and validate the tomographic models. Within each tectonic category (rift, orogenic zone, or craton) group velocity curves from various provinces are similar. Between tectonic categories, however, there are marked differences. The rift related paths exhibit the lowest group velocities observed, and cratonic paths the fastest. One-dimensional shear velocity inversions are performed, and while highly nonunique, the ranges of models show significant differences in upper mantle velocities between the tectonic provinces.

This work is part of a larger project to determine group velocity maps for North Africa and the Middle East. The work presented here provides important tools for the validation of tomographic group velocity models. This is accomplished by comparing group velocity curves calculated from the tomographic models with carefully selected high-quality group velocity measurements. The final group velocity models will be used in M_s measurements, which will contribute to the m_b:M_s discriminant important to the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The improved shear wave velocity models provided by this study also contribute to the detection, location, and identification of seismic sources.

Key words: Seismology, surface waves, Africa, mantle, crust, lithosphere.

Introduction

North Africa has been only sparsely sampled both geologically and seismically; yet knowledge of regions such as this is critical for CTBT monitoring purposes. In an effort to fill in the gaps present in our knowledge of the seismic structure of Northern Africa, a comprehensive study of the shear wave velocity structure beneath this

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region has been undertaken (HAZLER, 1998; PASYANOS *et al.*, 2001). North Africa includes a number of interesting tectonic provinces (Fig. 1), and the work presented here seeks to seismically characterize these provinces through a surface wave regionalization approach (Fig. 2). Orogenic domains are grouped together into larger regions where the tectonics of mountain building dominate. Similarly shield bodies have been grouped into larger cratonic bodies. Regions of recent tectonic activity have also been grouped together. Should these regions show a distinct seismic signal, an important step toward the seismic characterization of North Africa will have been made.

Most previous seismic studies concerning Africa were small in scale (LAST *et al.*, 1997; NYBLADE *et al.*, 1996; ACHAUER, 1992; CLOUSER and LANGSTON, 1990; BERKHEMER *et al.*, 1975; LONG *et al.*, 1972; KNOPOFF and SCHULE, 1972), and while providing important constraints on particular regions, do not address the large-scale structure of North Africa specifically. These regional studies contrast with global velocity models in which Africa plays only a small part (e.g. EKSTRÖM *et al.*, 1997; MASTERS *et al.*, 1996; ZHANG and LAY, 1996; SU *et al.*, 1994). In these global studies,

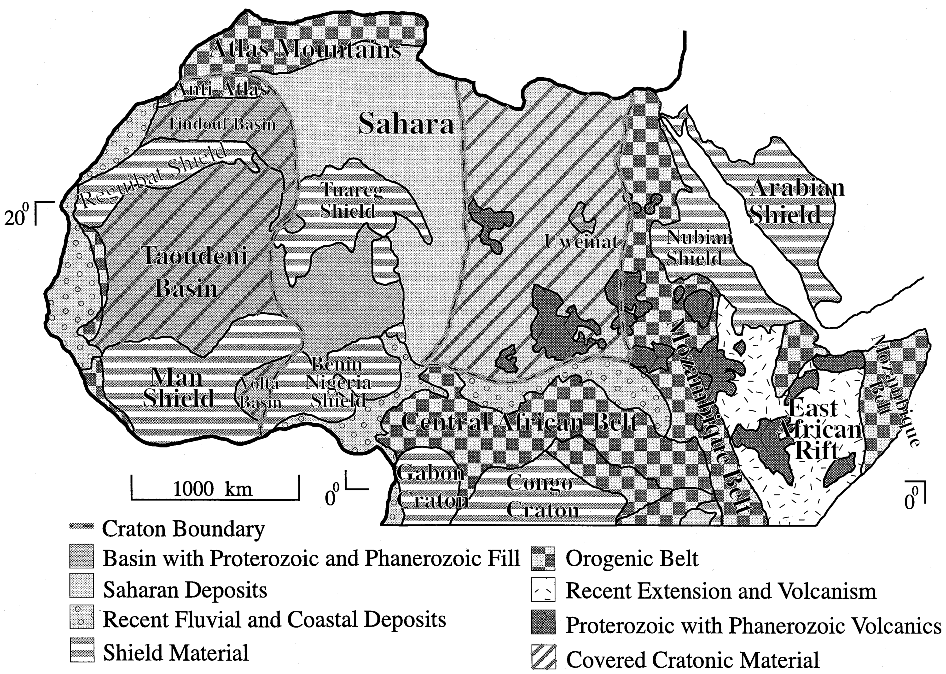

Figure 1

Generalized geologic divisions of North Africa. Major divisions include shield material, covered cratonic material, basins filled with Proterozoic and Phanerozoic sediment, Saharan deposits, recent fluvial and coastal deposits, orogenic belts, regions of recent extension, and Proterozoic regions with Phanerozoic volcanics. After GOODWIN (1996).

resolution constraints due to path coverage and wavelengths used limit the ability to distinguish the properties and interrelations between the various tectonic provinces of Africa. In an attempt to link seismic data with geologic information, CHRISTENSEN and MOONEY (1995) inferred global crustal composition and structure on the basis of seismic refraction profiles and high pressure laboratory studies of common crustal rocks. Their inferences are applied to all continents although data points for Africa were only taken in Morocco, in Southern Africa, and along the East African Rift. The recent crustal model CRUST 5.1 (MOONEY *et al.*, 1998) also lacks sufficient coverage in Africa. Some work has also been done on a regional level in Africa (HADIOUCHE and ZÜRN, 1992; TANAKA and HAMAGUCHI, 1992; HADIOUCHE and JOBERT, 1988b; HADIOUCHE *et al.*, 1986; GUMPER and POMEROY, 1970); but these regional studies often fail to link results to regional geology. Further, considerably more data are available now to augment this work.

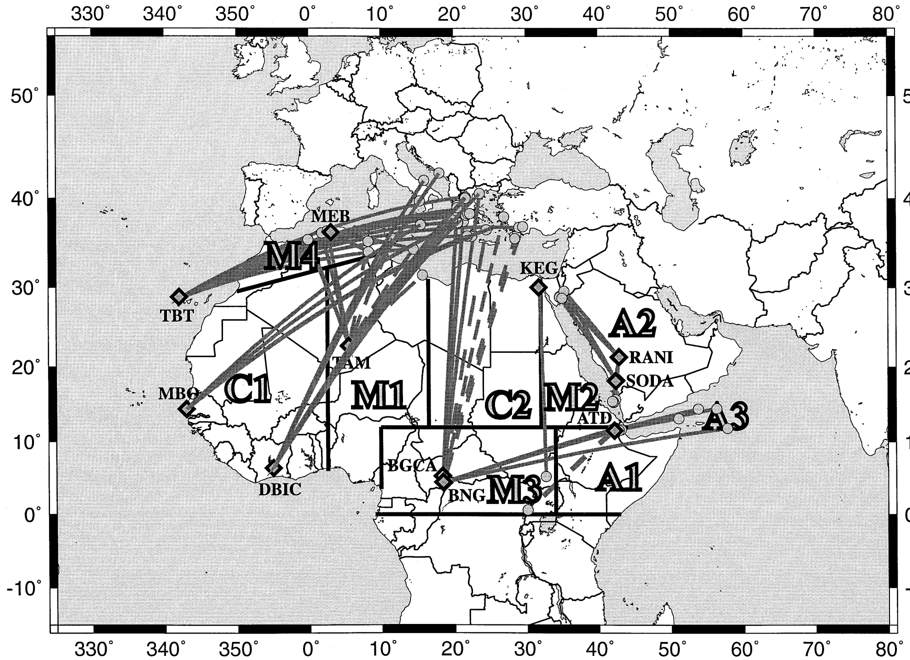

Figure 2

Tectonic provinces used in regionalization. The numbers correspond to the following regions: C1) the West African Cratonic Block, C2) the East African Cratonic Block, M1) the North-Central Pan-African Orogenic Block, M2) the Eastern Pan-African Block, M3) the Central Pan-African Block, M4) the Atlas Mountains, A1) the East African Rift Block, A2) the Arabian Shield, and A3) the Gulf of Aden Spreading Center. The tectonic regions were chosen on the basis of basement geology and current active tectonic processes (see text). Also labeled are the great circle paths, the broadband seismic stations (diamonds), and the earthquakes (circles) used in this study.

Continental scale studies are an important complement to global studies and allow us to concentrate on specific regions and processes in more detail. To do this, we make use of Rayleigh wave group velocity dispersion, and concentrate on the crust and upper mantle beneath North Africa. By examining group velocities which describe a single path, certain ambiguities found in global group velocity models such as those related to poor crossing paths can be eliminated. In this study, group velocities of regional and teleseismic Rayleigh waves in the period range of 10 to 160 s are measured from seismograms which have been recorded on broadband seismic stations. The group velocity curves are grouped according to the tectonic region they traverse. The clustered group velocity curves are averaged; and the averaged curves are inverted for one-dimensional shear velocity structure. Increased understanding of the regional tectonic setting and shear velocity structure will better define the seismic characteristics need to properly monitor the Comprehensive Test-Ban Treaty (CTBT). In particular, increased knowledge of seismic shear wave structure will lead to improved detection, location, identification capabilities in the region. Our high-quality path measurements will be used to validate 3-D models currently under development (e.g., PASYANOS *et al.*, 2001).

Data Selection

Regionalization

The North African study area is divided into tectonic provinces on the basis of basement geology and currently active tectonic processes (HAZLER, 1998). A generalized map of the basement geology of North Africa is depicted in Fig. 1 (after GOODWIN, 1996). Given the complex geology of Northern Africa and the sparse earthquake/station coverage, it is difficult to perform a 'pure-path' surface wave regionalization where a given path traverses only a single geologic province. Instead, nine broad regions are selected for this study (Fig. 2). These regions are described as follows: C1) the West African Cratonic Block which consists of two Precambrian shield bodies, three basins containing mainly lithified sediments, and four orogenic belts reactivated in the earliest Paleozoic, C2) the East African Cratonic Block which is largely covered by Saharan sediments but also displays scattered Archean and Proterozoic outcrops, M1) the North-Central Pan-African Orogenic Mobile Belt which also contains a large portion of recent sediments as well as the massively deformed Benin-Nigeria Shield and the Tuareg Shield, M2) the Eastern Pan-African Mobile Belt which splits its area between the Mozambique Orogenic Belt and the Nubian Shield (an amalgam of island arc material), M3) the Central Pan-African Mobile Belt and Pan-African Orogenic Belt, M4) the Atlas Mountains, A1) the East African Rift Block; an area affected by recent rifting and magmatism, A2) the Arabian Shield Block which consists of former island arc material once contiguous with the Nubian Shield, and A3) the Gulf of Aden Spreading Center. Figure 2 depicts these nine regions as well as the Rayleigh wave paths used to study them.

Paths Chosen

Once these boundaries were established, a search was made for earthquake/station pairs whose connecting paths could provide insight into the chosen tectonic regions. Broadband three-component stations from the IRIS/GSN, MEDNET, and GEOSCOPE networks were included in the search. Seismograms from all earthquakes from the years 1991–1997 of magnitude 4.0 and greater located between 15°W to 65°E longitude and 5°S to 50°N latitude with paths crossing North Africa or the Middle East were examined. The bulk of the earthquakes used in this study surround the Mediterranean Sea. In addition to the Mediterranean events, several sources were located in the Gulf of Aden, several more were found in the Sinai Peninsula region, several more were centered in the southern Red Sea, and two earthquakes were located in the interior of the African continent (Fig. 2). Chosen paths are not intended to represent pure path propagation within a given tectonic block. Event/station locations in the region often preclude such pure path geometries. Thus, paths chosen in this study provide a broad comparison between chosen geologic blocks.

Analysis

Measurement Technique

Before undergoing the group velocity measurement procedure, the data were demeaned and detrended, and the instrument response was removed from all seismograms. The remainder of the measurement process follows the procedure outlined in AMMON (1998). The Rayleigh waves present in the chosen broadband records were examined using a narrow band filter centered on a suite of different periods (HERRMANN, 1973) referred to as filter periods. Measurements were made for filter periods ranging from 7 to 200 s. Typical measurements in this study range from 15 to 120 s. The peak amplitude of each energy packet is determined using an envelope function. The arrival time of the peak amplitude is recorded and converted to a velocity value assuming a known location and origin time of the source. These velocity values were then compiled into a group velocity dispersion curve for each station/event pair. Group velocity errors for each period were estimated by measuring the width of the group velocity peak.

In an effort to resolve the most accurate group velocity dispersion curve, the instantaneous period is used for the final group velocity dispersion curve rather than the filter period. The instantaneous period refers to that period which is most closely associated with the peak amplitude of the energy packet (CLAERBOUT, 1992). The filter period is often very close to the instantaneous period in cases where a good signal-to-noise ratio is present for the energy packet under examination. However, in cases where a spectral hole is present or where amplitudes are diminishing, the variation between instantaneous period and filter period can be significant.

Curve Averaging

Dispersion curves obtained from the narrow band-filtering method were averaged in an effort to minimize errors due to noise endemic to any particular path. Paths that contributed to the averaged curve satisfied the following criteria: a) the paths must be used to examine the same geologic block; and b) paths must have backazimuths which diverge by three degrees or less. The dispersion curves satisfying these criteria were collected and averaged. A total of 2529 Rayleigh wave group velocity dispersion curves were measured for the entire project, which includes the larger scale tomography work of PASYANOS *et al.* (2001). Of these 2529 curves, a subset (69 before averaging and 16 after averaging) was selected for our regionalized one-dimensional inversions. Tectonic regions are sampled by anywhere from a single dispersion curve in the case of the East African Rift to fifteen dispersion curves in the case of the Arabian Shield.

Inversion Technique

A maximum likelihood technique was used to invert the group velocity dispersion curves for earth shear velocity structure (e.g., WIGGINS, 1972; TAYLOR, 1980). Input for this process consists of an initial velocity model and the measured group velocities as well as their corresponding periods and the errors associated with each data point. A linearized system of equations is obtained by performing a Taylor series expansion to first order about the initial model, and the system of equations is solved using damped least squares. In the inversion, only shear velocity is adjusted, i.e., compressional velocity, density, and layer thicknesses remain fixed. Since errors in group velocity measurements vary with period and partial derivatives are a function of layer thickness, the solution is weighted in both model and data space. The inversion is terminated when the misfit to the observed data drops below a preset minimum; or after 40 iterations. If convergence is not achieved in 40 iterations, the final model is discarded. The partial derivatives that make up the Rayleigh wave sensitivity kernels are recalculated for each iteration. Final output consists of a final velocity model, the model resolution matrix, covariance information, and error propagation information.

The original starting model for the inversion was developed by forward modeling (MCNAMARA and WALTER, 1995; HAZLER, 1998). This model consists of four crustal layers over the mantle part of the radial earth model PREM (DZIEWONSKI and ANDERSON, 1981). In an attempt to obtain the best possible fit to the input data, velocity and thickness values in the original starting model were varied randomly by ±1% in velocity and ±2.5 km in thickness. This variation process was used to produce a suite of one hundred different starting models. Each of these different starting models was employed in the inversion process to produce a large suite of inverted models. The various models indicate the large range of possible solutions that can equally or nearly equally fit the data, illustrating the nonuniqueness of group velocity inversion. Despite the nonuniqueness, the models for each tectonic grouping do display common features, which will be discussed further in the following sections.

Error Sources

Scattering and inaccurate source information are two of the factors that contribute error or uncertainty to the group velocity curves. Scattering occurs when an incoming seismic ray encounters a geologic feature which changes the ray's path so that it deviates from the path predicted by the ray-tracing method employed in a given study (e.g., WANG and DAHLEN, 1995). The errors associated with this scattering effect are due to the observer's choice of an assumed path which deviates from the true path of the seismic wave. Errors can also appear due to the interaction of several different raypaths.

Two values that are paramount in measuring group velocity are the arrival time of the wave packet and the distance the wave packet traveled from source to receiver. These values are extremely sensitive to the reported event locations and the assigned origin time. A study of the deviation between teleseismically determined epicentral locations and locally determined epicentral locations in the Middle East and Northern Africa was developed in SWEENEY (1996). A maximum of 15 km mislocation in ISC (International Seismic Center) source locations and less than 2.5 s in origin time was found. For path lengths relevant to this study, we find that the potential errors associated with the longest path are ±0.02 km/s; while the errors associated with the shortest path are ±0.12 km/s. As a result of this work, the value of ±0.2 km/s has been assigned as a conservative error estimate for each group velocity measurement. Comparison of group velocity curves with nearly identical paths (same station, earthquakes within 10 km) has been performed, and the resulting group velocity curves are nearly identical (HAZLER, 1998).

Discussion

Since seismicity and seismic stations are sparse in North Africa, we choose to look at first order differences between regions of North Africa by grouping dispersions curves which sample regions with similar geology, and solving for one-dimensional shear velocity structure in these regions. We have identified nine different regions on the basis of their geology and surface wave path coverage. We examine the tectonic regions by comparing them in three similar groups: active, orogenic, and cratonic. The active tectonic grouping includes the East Africa Rift, Arabian Shield/Red Sea Rift, and Gulf of Aden regions (regions A1, A2, and A3 of Fig. 2, respectively). The orogenic grouping includes the North-Central Pan-African Belt, Mozambique Belt/Eastern Pan-African Block, Central Pan-African Belt, and the Atlas Mountains (regions M1, M2, M3, and M4 of Fig. 2). The cratonic grouping includes the West African Craton and East African Craton (regions C1 and C2 of Fig. 2). The chosen paths do not represent pure path propagation within a given tectonic block but rather provide a rough comparison between chosen geologic blocks. The model validation aspects of this study are not affected by the degree to which a given path is contained within a particular tectonic region, because model curves can be generated for any given path.

Tectonically Active Paths

The top-left panel in Figure 3 depicts group velocity dispersion curves belonging to paths from tectonically active rift or rift-like settings including the East African Rift, Gulf of Aden, and the Arabian Shield region. A cursory inspection of these curves reveals that the greatest degree of heterogeneity can be found in the period range from 10 to 55 s. This heterogeneity in large part reflects the differing crustal structure of the three paths.

The East African Rift path (A1) samples faulted material belonging to the Mozambique Orogenic Belt. At the uppermost crustal level, this material is interfingered with largely alkaline volcanics implaced during the rifting process (Sandvol *et al.*, 1998; Cahen and Snelling, 1984; Tesha *et al.*, 1997). These extrusive volcanics are believed to be underlain by magmatic intrusions at the middle and lower crustal level (Petters, 1991). Like most of East Africa, this region is covered by unlithified sediments. At short periods (10–30 s) the East African Rift dispersion curve velocities are comparable to those from non-rift related regions (Fig. 3d). This is likely due to the combination of the mix of crustal components including orogenic material, rift related volcanics, and sediment cover.

The Arabian Shield/Red Sea Rift path (A2) samples a region composed of accreted island arcs and is analogous to the Nubian Shield on the western side of the Red Sea. The Nubian Shield comprises the bulk of the Eastern Pan-African Mobile Belt (Figs. 1 and 2). The metavolcanics and younger igneous bodies of the Arabian Shield should provide a fast crustal path for the Rayleigh waves examined, as was observed by Rodgers *et al.* (1999) for paths just east of those examined here. Measurements along the Arabian Shield do indeed reveal this fast crustal structure. The Arabian Shield path records nearly the highest group velocities examined in this study, slower only than the Gulf of Aden curve, between the periods of 10 and 35 s. The Gulf of Aden path is essentially an oceanic path connecting earthquakes in the Gulf of Aden to the ATD broadband station in Djibouti. This path passes along the

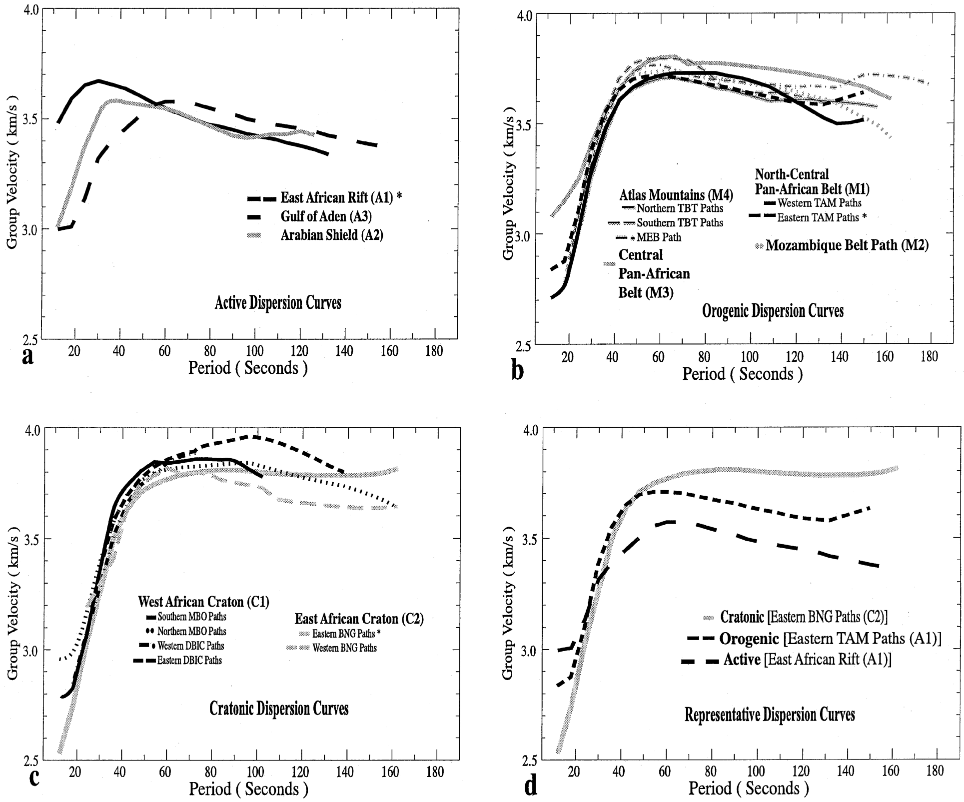

Figure 3
Rayleigh wave group velocity dispersion curves for North Africa grouped by tectonic type, including active tectonic regions (a), orogenic regions (b), and cratonic regions (c). Curves used in inversions (Figs. 4–8) denoted by *. (d) Comparison between respresentative (*) curves from (a–c).

axis of the rift which is currently expanding the Gulf of Aden. The group velocity curve corresponding to this path contains high velocities at short period (10–40 s) reflecting the volcanic material extruded from the active rift.

At periods greater than 40 s, the three group velocity curves corresponding to tectonically active are markedly slower (3–9%) than those for the orogenic or cratonic regions considered in this study (Figs. 3a, 3d), suggesting lower velocities in the upper mantle. At a period of approximately 60 s, the three curves in the tectonically active grouping converge at around 3.5 km/s. These low velocities appear to indicate the presence of high temperatures and partial melt in the upper mantle which might correspond to the presence of a plume head (EBINGER and SLEEP, 1998).

Due to the large number of paths examined in this study, inversion results for only one path from each major grouping (active tectonic, orogenic, cratonic) are presented in detail. Figure 4 presents results from the East African Rift. Figure 4a depicts the measured group velocity curve compared to one calculated from the 3-D tomographic group velocity model of PAYANOS *et al.* (this issue) for the same path. The model-based curve is faster than the measured curve at all periods >20 s, and this plot highlights the potential deviations that a single measured path can make from a larger 3-D tomographic model. The measured path is strictly continental whereas the majority of the paths which contribute to this part of the tomographic model have both continental and oceanic components. This oceanic contribution may be the cause of the higher group velocities found in the 3-D model.

Figure 4b depicts group velocity curves calculated from the suite of final inversion models as well as the original measured dispersion curve. The close fit of all

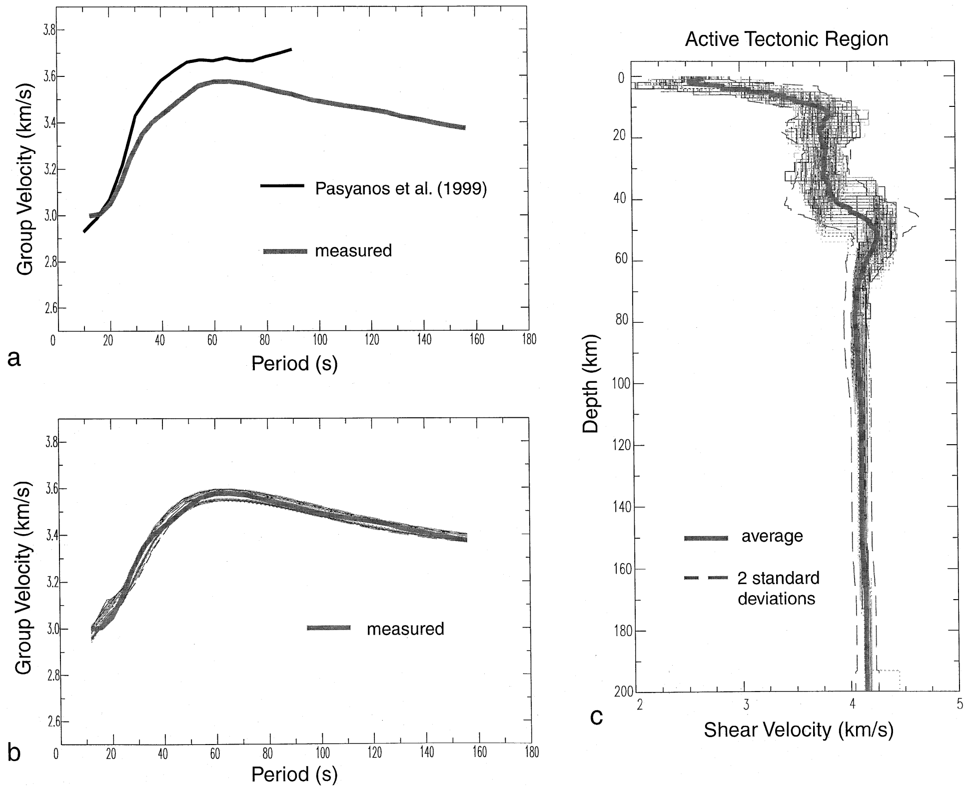

Figure 4
Inversion and forward modeling results for the East African Rift path (A1): (a) measured group velocity curve from this study compared to one calculated from a regional 3-D tomographic velocity model (PASYANOS *et al.*, this issue) for the same path; (b) observed group velocity curve versus group velocity curves calculated from inversion results (shear velocity models) in panel (c); (c) inversion results for the East African Rift path. Average of the models shown as thick solid grey line, with standard deviation (dashed).

the calculated group velocity curves to the measured data points out the non-uniqueness of this inversion, i.e., many different models can fit the data equally well. The shear velocity structures which produced the calculated group velocity curves are displayed in Figure 4c. The inversion results are presented with their average as well as two standard deviations from that average. It is important to note that averaging shear velocity versus depth models tends to smooth out the sharp transitions likely present in the earth. Thus examining the range of inversion results is more representative of possible earth structure than merely referring to the average. Not surprisingly the shear velocity structure for this tectonically active path is uniformly lower than those reported in global radial reference earth models (e.g., PREM, DZIEWONSKI and ANDERSON, 1981). The inversion results show maximal variation in the top 60 km of the model with a Moho depth of 43 ± 5 km. These results concur with the crustal thickness values for rift regimes found by CHRISTENSEN and MOONEY (1995). CHRISTENSEN and MOONEY report crustal thicknesses of 36 ± 8 km in rifts. The Moho range found in the current study reflects the higher end of Christensen and Mooney's crustal thickness range perhaps because the path in question (region A1) samples the rift axis obliquely. A path which followed the rift axis more directly would be more likely to reflect a thinner crust. Other techniques, such as teleseismic receiver functions and regional waveform modeling, would be required to better constrain the crustal thickness.

Depending upon the velocity-temperature scaling relation used (e.g., BASS, 1995; SHEEHAN and SOLOMON, 1991; KARATO, 1993), the low shear wave velocities for the active tectonic paths suggest upper mantle temperature anomalies over 240 K and perhaps up to 1700 K. The high end of these temperatures is thought to be unreasonably large, as this is nearly four times the thermal variation predicted between oceans and continents, and would also elevate the temperature of the mantle rocks above their solidus and cause massive melting. The presence of high attenuation can moderate the temperature variation required (KARATO, 1993), and represents our low temperature estimate. The maximum temperature variation associated with a mantle plume is approximately 300 K (MCKENZIE and BICKLE, 1988; SCHILLING, 1991), and our models cannot be used to reject a plume hypothesis for the region (KNOX *et al.*, 1998).

Orogenic Belts

Figure 3b depicts group velocity dispersion curves that have traveled through orogenic belts. The group velocity dispersion curves displayed in this panel show a tight grouping overall with the greatest heterogeneity at short periods, 10 to 30 s (Fig. 3). The fastest curve at these short periods corresponds to the averaged path passing through the Central Pan-African Belt. This region describes the suture zone between North Africa and the Congo Craton of Central Africa. More importantly, this region has little to no sediment cover as compared to the three other orogenic belts examined. This lack of sedimentary cover results in a faster crustal segment which in turn explains the higher velocities displayed at short periods. Longer period measurements for these four regions indicate lower group velocities than those found at similar periods in cratonic regions (Fig. 3).

Figure 5 depicts the inversion results from the eastern TAM grouping in the North-Central Pan-African Block, M1. Figure 5a displays the measured results versus those taken from the 3-D tomographic group velocity model of PASYANOS *et al.* (this issue). This plot shows a much closer fit than that in Figure 4a, indicating that the tomographic velocity model better describes orogenic belts than the actively deforming regions in this study. Figure 5b displays the group velocity

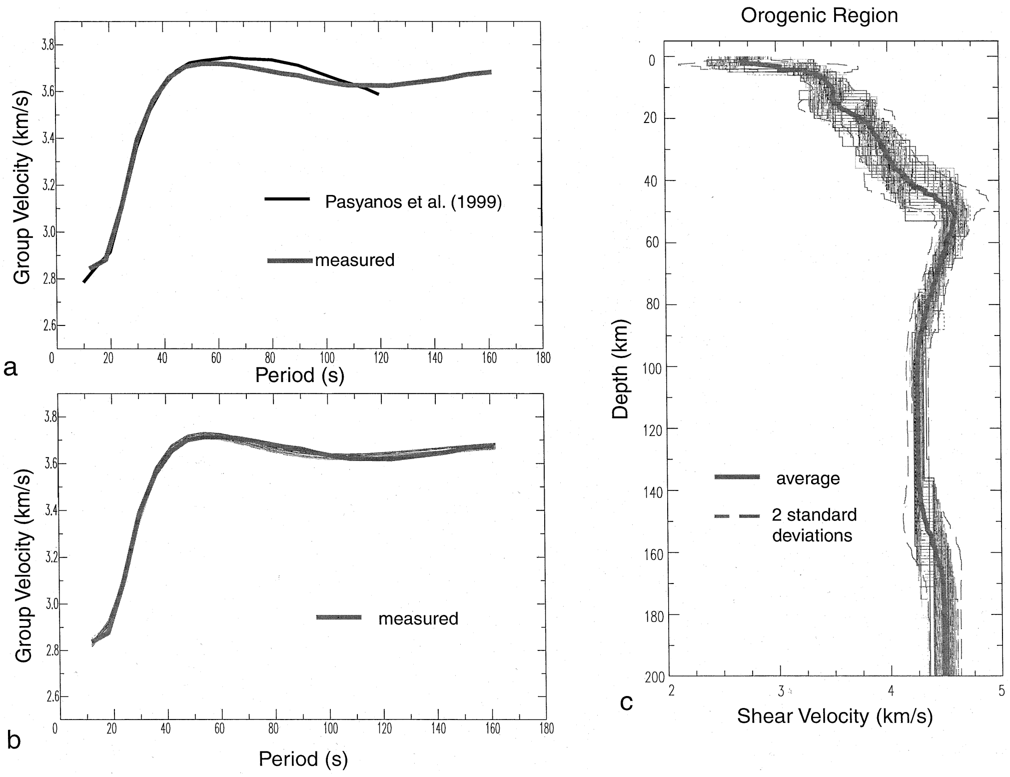

Figure 5
Inversion and forward modeling results for a sample orogenic path (the eastern TAM path of the orogenic block, M1): (a) average measured group velocity curve from this study (thick grey line) compared to one calculated from a regional 3-D tomographic velocity model (PASYANOS *et al.*, this issue) for the same path (black line); (b) average measured group velocity curve (thick grey line) compared to group velocity curves calculated from shear velocity models in panel c (thin grey lines) (c) inversion results for the eastern TAM path and the average (thick grey line) and standard deviation (dashed) of the models.

curves that have been calculated from the velocity models resulting from the suite of one hundred different starting models, in comparison to the measured dispersion curve. The close fit to the observed data highlights the non-uniqueness of the individual velocity models depicted in Figure 5c. These inversion results show maximal variation in the top 50 km of the model with Moho depths of 43 ± 5 km. Crustal thicknesses for orogenic regions as reported by CHRISTENSEN and MOONEY (1995) are found to average 46 ± 10 km. Since the orogenic belts of Northern Africa have been largely eroded and no longer show significant relief, it is not unexpected that our results reflect the thinner end of the Christensen and Mooney range. Below crustal depths, the sample orogenic shear velocity model is slightly slower than the shear velocities predicted by the PREM global model (DZIEWONSKI and ANDERSON, 1981). However, the PREM curve at these depths does fall within the region encompassed by two standard deviations from the averaged model.

Cratonic Regions

Figure 3c presents the group velocity dispersion results for the two large-scale cratonic bodies present in Northern Africa, the West African Craton and the East African Craton (Figs. 1 and 2). The West African Craton contains two major shield bodies and three major basin structures (PETTERS, 1991). The paths that represent the West African Craton are not well bounded by our generalized geologic boundaries, with just half to two-thirds of their path length within shield material. However, these paths were included in this study in the hope that they might reveal significant difference from or similarity to other paths within this study.

The extent of the East African Craton is not well defined as the bulk of the hypothesized cratonic body lies beneath a thick layer of Phanerozoic sediment, the Sahara desert. The existence of a cratonic body beneath the Sahara is proposed on the basis of scattered Precambrian outcrops in the region (CONDIE, 1982). The oldest of these outcrops is the Archean aged Uweinat Inlier. Other outcrops such as Tibesti, Kordofan, and Darfour display Proterozoic basement material mingled with Phanerozoic volcanics (GOODWIN, 1996; CAHEN and SNELLING, 1984; VINCENT, 1970) (see Fig. 1).

Despite these uncertainties, the group velocity curves corresponding to cratonic paths indicate a tight grouping between the periods of 20 s and 80 s (Fig. 3c). The divergence between the group velocity curves from 10 s to 20 s can be ascribed to differences in sedimentary thicknesses sampled by the different paths. For example, the northern MBO (a broadband station in M'bour, Senegal) paths pass through exposed basement and lithified, Paleozoic, basin material; however, the southern MBO paths cross twice the distance through thick unlithified sediments that the northern MBO paths cross. This difference is demonstrated in the short-period segments of the two averaged group velocity curves. Between 10 s and 20 s we can easily see the faster group velocities of the northern MBO path, less sampling of unlithified sediments, and the slower group velocities of the southern MBO path, greater sampling of unlithified sediments.

Overall, the group velocity curves belonging to the East African Craton record slower group velocities at the same periods than the group velocity curves belonging to the West African Cratonic Block. This west to east velocity gradient (faster in west, slower in east) is also present in the African portion of global velocity models (e.g., EKSTRÖM *et al.*, 1997; MASTERS *et al.*, 1996). This velocity gradient might be the result of the proposed plume head beneath Eastern Africa (e.g., KNOX *et al.*, 1998; LITHGOW-BERTELLONI and SILVER, 1998; NYBLADE and ROBINSON, 1994; HADIOUCHE, 1990; HADIOUCHE and JOBERT, 1988a).

As with the tectonically active regions and the orogenic regions, a sample path has been chosen to represent the cratonic group. Figure 6 depicts the inversion results from the eastern BNG grouping in the East African Craton. Figure 6a demonstrates the very close fit of the measured data to the dispersion curve taken from the 3-D tomographic group velocity model (Pasyanos *et al.*, this issue), indicating that this region is well resolved by the 3-D velocity model. Figure 6b shows the measured group velocity dispersion curve and the group velocity curves calculated using the suite of velocity models resulting from the inversion process. These velocity models are displayed in Figure 6c. These inversion results show maximal variation in the top 50 km of the model with Moho 43 $\pm$ 5 km which compares to the global average of crustal thickness for shields and platforms of 41.5 $\pm$ 6 km (CHRISTENSEN and MOONEY, 1995). Below the crust, shear velocities reflected in this averaged model are slightly faster than those found in PREM (DZIEWONSKI and ANDERSON, 1981). However, the PREM curve at these depths does fall within the region encompassed by two standard deviations from the averaged model.

Comparison Between Regions

Figure 3d shows observed group velocity curves for the different tectonic regions, and Figure 7 depicts the corresponding velocity inversion results. The hashed regions in Figure 7 represent the area encompassed by two standard deviations from the mean value at each depth. All curves overlap at the 2 sigma level from 0 to 50 km depth. Below 50 km, the active curve is markedly slower and completely separated from the cratonic path. The active curve is also slower than the orogenic curve below 50 km and indicates minimal overlap within two standard deviations of the average. The cratonic curve displays the fastest shear velocities below 60 km. These results are not particularly surprising, but are useful tectonic constraints in this region of sparse seismic coverage. Given the range of acceptable values for cratonic mantle velocities, we cannot establish the degree to which North African cratonic bodies do or do not differ from other cratonic bodies.

Summary

In this study we have measured Rayleigh wave group velocity dispersion across nine regions based upon tectonics and geology. We have performed inversion tests for three representative tectonic regions. Groupings of active tectonic regions, orogenic regions, and cratons reflect mantle velocity structures comparable to those from similar tectonic regions elsewhere in the world. Shallow crustal velocities are strongly controlled by the presence or absence of sedimentary basins. Our results from active tectonic paths suggest the presence of a large low velocity body apparently centered on the Afar triple junction. This region has been subject to significant volcanic activity in the recent geologic past, and it is likely that the low

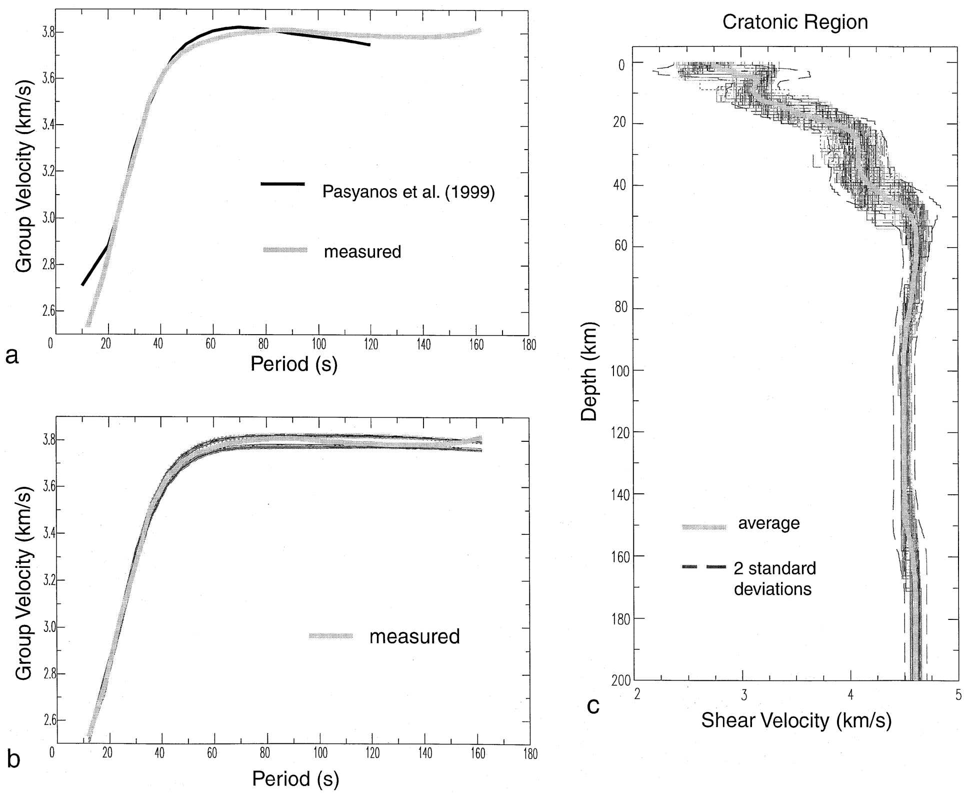

Figure 6
Inversion and forward modeling results for a sample cratonic path (the eastern BNG path of the cratonic block, C2): (a) average measured group velocity curve from this study (thick grey line) compared to one calculated from a regional 3-D tomographic velocity model (PASYANOS *et al.*, this issue) for the same path (black line); (b) average measured group velocity curve (thick grey line) versus group velocity curves (thin grey lines) calculated from shear velocity models (inversion results) in panel c; (c) inversion results for the eastern BNG path and the average (thick grey line) and standard deviation (dashed) of the shear velocity models.

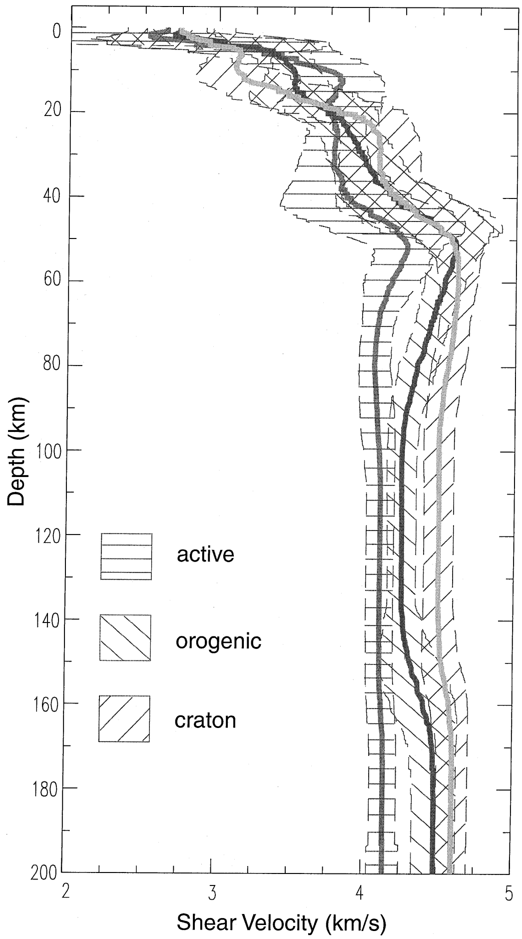

Figure 7
Inversion results (shear velocity models) from the East African Rift, the M1 orogenic block, and the C2 cratonic block. The average (thick solid line) as well as the area encompassed by two standard deviations (dashed) are shown for each region.

velocities we see in the upper mantle are due to both thermal variations and partial melt. In order to produce such a large region of partial melt, one might well appeal to the action of a plume. However, the one-dimensional nature of the inversions produced in this study as well as the depth penetration limitations imposed by the Rayleigh wave sensitivity kernels preclude any definitive imaging of a plume structure.

Group velocity curves are influenced by crust and upper mantle velocities and the thickness of unlithified sediments through which the surface wave passes. In terms of CTBT monitoring objectives, variations in crustal and upper mantle structure affect event locations; while the amount of unlithified sediment through which a surface wave passes affects M_s values. On the basis of these observations, a good regionalization scheme of Northern Africa for CTBT monitoring purposes should rely primarily on sediment thickness for shallow structure and on the basement geology (orogenic, cratonic, or rift regions) for the upper mantle velocities. The very low velocities associated with the broad Afar/Djibouti plume need to be better mapped and paths which traverse the region identified as potentially anomalously slow. By comparing direct group velocity measurements and/or averaged group velocity measurements to those generated from tomographic models, important insight can be gained into the accuracy of 3-D tomographic studies which will be vital in the CTBT monitoring effort. These observed curves serve as a 'ground truth' by which to validate the tomographic models. Such tomographic models used in conjunction with look-up tables of observed group velocity curves could allow for rapid, and potentially automate, comparison of a suspect waveform with the waveform one would expect from an earthquake of similar magnitude occurring within the region.

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References

Achauer, U. (1992), *A Study of the Kenya Rift Using Delay-time Tomography Analysis and Gravity Modeling*, Tectonophysics *209*, 197–207.

Ammon, C. J., Notes on Surface-wave Tomography. Part I - Surface-wave Processing, unpublished notes, 44 pages, 1998.

Bass, J. D., *Elasticity of minerals, glasses, and melts*. In *Mineral Physics and Crystallography* (ed. Ahrens, T. J.), Am. Geophys. Union (Washington, D.C., 1995), pp. 45–63.

Berkhemer, H., Baier, B., Bartelsen, H., Behle, A., Burkhardt, H., Gerbrande, H., Makris, J., Menzel, H., Miller, H., and Vees, R., *Deep seismic soundings in the Afar region and on the highland of Ethiopia*. In *Afar Depression of Ethiopia* (eds. Pilger, A., and Rösler, A.) (Stuttgart, Germany: E. Schweizerbart'sche Verlagsbuchhandlung, 1976), pp. 89–106.

Cahen, L., and Snelling, N. J., *The Geochronology and Evolution of Africa* (Clarendon Press, Oxford 1984).

Christensen, N. I., and Mooney, W. D. (1995), *Seismic Velocity Structure and Composition of the Continental Crust: A Global View*, J. Geophys. Res. *100*, 9761–9788.

CLAERBOUT, J. F., *Earth Soundings Analysis: Processing versus Inversion* (Blackwell Scientific Publications, Boston, MA, 1992) 304 pp.

CLOUSER, R. H., and LANGSTON, C. A. (1990), *Upper Mantle Structure of Southern Africa from P_{nl} Waves*, J. Geophys. Res. *95*, 17,403–17,415.

CONDIE, K. C., *Plate Tectonics and Crustal Evolution* (Pergamon Press, New York 1982).

DZIEWONSKI, A. M., and ANDERSON, D. L. (1981), *Preliminary Reference Earth Model*, Phys. Earth and Planet. Inter. *25*, 297–356.

EBINGER, C. J., and SLEEP, N. H. (1998), *Cenozoic Magmatism Throughout East Africa Resulting from Impact of a Single Plume*, Nature *395*, 788–791.

EKSTRÖM, G., TROMP, J., and LARSON, E. (1997), *Measurements and Global Models of Surface Wave Propagation*, J. Geophys. Res. *102*, 8137–8157.

GOODWIN, A. M., *Principles of Precambrian Geology* (Academic Press Limited, Great Britain 1996).

GUMPER, F., and POMEROY, P. W. (1970), *Seismic Wave Velocities and Earth Structure on the African Continent*, Bull. Seismol. Soc. Am. *60*, 651–668.

HADIOUCHE, O. (1990), *First Evidence for High Anelastic Attenuation Beneath the Red Sea from Love Wave Analysis*, Geophys. Res. Lett. *17*, 1973–1976.

HADIOUCHE, O., and JOBERT, N. (1988a), *Geographical Distribution of Surface-wave Velocities and 3-D Upper-mantle Structure in Africa*, Geophys. J. *95*, 87–109.

HADIOUCHE, O., and JOBERT, N. (1988b), *Evidence for Anisotropy in Northeast Africa, from Geographical and Azimuthal Distribution of Rayleigh Wave Velocities, and Average Upper-mantle Structure*, Geophys. Res. Lett. *15*, 365–368.

HADIOUCHE, O., and ZÜRN, W. (1992), *On the Structure of the Crust and Upper Mantle Beneath the Afro-Arabian Region from Surface Wave Dispersion*, Tectonophysics *209*, 179–196.

HADIOUCHE, O., JOBERT, N., and RAMANOWICZ, B. (1986), *First Two-station Results from Long-period Surface Waves Velocity from the GEOSCOPE Stations in Africa*, Geophys. Res. Lett. *13*, 547–550.

HAZLER, S. E. (1998), *One-dimensional Velocity Structure of Northern Africa as Determined by Rayleigh Wave Group Velocity Dispersion*, Masters Thesis, University of Colorado, Boulder, Colorado.

HERRMANN, R. B. (1973), *Some Aspects of Surface Waves*, Bull. Seismol. Soc. Am. *63*, 663–671.

KARATO, S. (1993), *The Importance of Anelasticity in the Interpretation of Seismic Tomography*, Geophys. Res. Lett. *20*, 1623–1626.

KNOPOFF, L., and SCHLUE, J. W. (1972), *Rayleigh Wave Phase Velocities for the Path Addis Ababa-Nairobi*, Tectonophysics *15*, 157–163.

KNOX, R. P., NYBLADE, A. A., and LANGSTON, C. A. (1998), *Upper Mantle S Velocities Beneath Afar and Western Saudi Arabia*, Geophys. Res. Lett. *25*, 4233–4236.

LAST, R. J., NYBLADE, A. A., LANGSTON, C. A., and OWENS, T. J. (1997), *Crustal Structure of the East African Plateau from Receiver Functions and Rayleigh Wave Phase Velocities*, J. Geophys. Res. *102*, 24,469–24,483.

LITHGOW-BERTELLONI, C., and SILVER, P. G. (1998), *Dynamic Topography, Plate Driving Forces and the African Superswell*, Nature *395*, 269–272.

LONG, R. E., BACKHOUSE, R. W., MAGUIRE, P. K. H., and SUNDARLINGHAM, K. (1972), *The Structure of East Africa Using Surface Wave Dispersion and Durham Seismic Array Data*, Tectonophysics *15*, 165–178.

MASTERS, G., JOHNSON, S., LASKE, G., and BOLTON, H. (1996), *A Shear-velocity Model of the Mantle*, Philosoph. Transact. Royal Soc. London *354*, 1385–1411.

MCKENZIE, D., and BICKLE, M. J. (1988), *The Volume and Composition of Melt Generated by Extension of the Lithosphere*, J. Petrol. *29*, 625–679.

MCNAMARA, D. E., and WALTER, W. R. (1995), *Regional Waveform Modeling and Phase Propagation in Northern Africa*, EOS, Transact. Am. Geophys. Union *76*, 428.

MOONEY, W. D., LASKE, G., and MASTERS, T. G. (1998), *CRUST 5.1:A Global Crustal Model at* $5^\circ \times 5^\circ$, J. Geophys. Res. *103*, 727–747.

NYBLADE, A. A., VOGFJORD, K. S., and LANGSTON, C. A. (1996), *P-wave Velocity of the Proterozoic Upper Mantle Beneath Central and Southern Africa*, J. Geophys. Res. *101*, 11,159–11,171.

NYBLADE, A. A., and ROBINSON, S. W. (1994), *The African Superswell*, Geophys. Res. Lett. *21*, 765–768.

PASYANOS, M. E., WALTER, W. R., and HAZLER, S. E. (2001), *A Surface Wave Dispersion Study of the Middle East and North Africa for Monitoring the Comprehensive Nuclear-Test-Ban Treaty*, Pure appl. geophys., this issue.

PETTERS, S. W., *Regional Geology of Africa* (Springer-Verlag, Germany 1991).

RODGERS, A. J., WALTER, W. R., MELLORS, R. J., AL-AMRI, A. M. S., and ZHANG, Y. S. (1999), *Lithospheric Structure of the Arabian Shield and Platform from Complete Regional Waveform Modelling and Surface Wave Group Velocities*, Geophys. J. Int. *138*, 871–878.

SANDVOL, E., SERBER, D., CALVERT, A., and BARAZANGI, M. (1998), *Grid Search Modeling of Receiver Functions: Implications for Crustal Structure in the Middle East and North Africa*, J. Geophys. Res. *103*, 26,899–26,917.

SCHILLING, J-G. (1991), *Fluxes and Excess Temperatures of Mantle Plumes Inferred from their Interaction with Migrating Ocean Ridges*, Nature *352*, 397–403.

SHEEHAN, A. F., and SOLOMON, S. C. (1991), *Joint Inversion of Shear Wave Travel Time Residuals and Geoid and Depth Anomalies for Long-wavelength Variations in Upper Mantle Temperature and Composition along the Mid-Atlantic Ridge*, J. Geophys. Res. *96*, 19,981–20,009.

SU, W., WOODWARD, R., and DZIEWONSKI, A. (1994), *Degree 12 Model of Shear Velocity Heterogeneity in the Mantle*, J. Geophys. Res. *99*, 6945–6980.

SWEENEY, J. J. (1996), *Accuracy of Teleseismic Event Location in the Middle East and North Africa*, Lawrence Livermore National Laboratory, UCRL-ID-125868.

TANAKA, S., and HAMAGUCHI, H. (1992), *Heterogeneity in the Lower Mantle Beneath Africa, as Revealed from S and ScS Phases*, Tectonophysics *209*, 213–222.

TAYLOR, S. R. (1980), *Crust and Upper Mantle Structure of the Northeastern United States*, Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts.

TESHA, A. L., NYBLADE, A. A., KELLER, G. R., and DOSER, D. I. (1997), *Rift Localization in Suture-thickened Crust: Evidence from Bouguer Gravity Anomalies in Northeastern Tanzania, East Africa*, Tectonophysics *278*, 315–328.

VINCENT, P. M. (1970), *The evolution of the Tibesti Volcanic Province, eastern Sahara*. In *African Magmatism and Tectonics* (eds. CLIFFORD, T. N., and GASS, I. G.) (Hafner Publishing Co., Darien, Conn., 1970), pp. 301–319.

WANG, Z., and DAHLEN, F. A. (1995), *Validity of a Surface-wave Ray Theory on a Laterally Heterogeneous Earth*, Geophys. J. Int. *123*, 757–773.

WIGGINS, R. A. (1972), *The General Linear Inverse Problem: Implication of Surface Waves and Free Oscillations for Earth Structure*, Rev. Geophys. Space Phys. *10*, 251–285.

ZHANG, Y., and LAY, T. (1996), *Global Surface Wave Phase Velocity Variations*, J. Geophys. Res. *101*, 8415–8436.

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