# ONE-DIMENSIONAL SHEAR VELOCITY STRUCTURE OF NORTHERN FROM RAYLEIGH WAVE GROUP VELOCITY DISPERSION

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ABSTRACT
Provide a concise summary of the whole paper. You can draw from your fall 1998 AGU abstract in part. Here's some text you can use if you wish.

Rayleigh wave group velocity dispersion measurements from 7s to 200s period 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 affects of debiasing for instantaneous period and a single-iteration, mode-isolation (phase match) filter. The curves are grouped by tectonic province and inverted for one-dimensional shear wave velocity structure. Within each tectonic category (rift, orogenic zone, or craton) curves from various provinces are remarkably similar. The slowest velocities are observed for rifts and the fastest for cratons. The deep structures beneath orogenic zones and cratons appear to be similar.

This work is part of a larger project to determine group velocity maps for North Africa and the Middle East. The group velocity maps will be used in Ms measurements, which will contribute to the mb:Ms discriminant important to the Comprehensive 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.

## INTRODUCTION

The continent of Africa lies largely unexplored seismically and provides a myriad of geologic puzzles. Most continents have an Archean core around which are arranged mobile belts and other recent additions to the landmass. Africa, on the other hand, lays claim to four separate large scale cratonic bodies which have been sutured together by Proterozoic mobile belts. The bulk of the African landmass is surprisingly uniform in its relief; and yet these uniform plains lie at higher elevation than most comparable plains regions in the world. The continental shelf of Africa is also markedly narrower than that of most continents.

Beyond these geologic and geographic distinctions, Africa also presents the largest ratio of exposed Precambrian material to exposed Phanerozoic material of any continent. Its late Proterozoic to early Phanerozoic mountain ranges, the Mauritanides, Basserides, and Rokelides, which developed roughly concurrent with the Appalachian mountains of eastern North America, have been eroded to a base level similar to that of the plains (Culver et al. 1991, Lécorché et al. 1991, Pique et al. 1991, and Ponsard et al. 1988); while the Appalachians of North America remain a distinct topographic feature. The continent has two regional scale domal structures, collectively referred to as the African superswell (Nyblade and Robinson, 1994). Africa is also the home of the largest number of proposed continental hotspots in the world. These proposed hotspots such as Hoggar, Kordofan, Darfur, Afar, and Tibesti dot Northern Africa and provide most of the relief in this region. Finally, Africa has remained one of the least mobile continents since the break up of Pangea. Since that time it has drifted slowly northward and rotated counterclockwise slightly, essentially remaining over the same region of upper mantle for the last 200 million years (DeMets et al., 1990).

Most previous seismic studies concerning Africa are 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 Schlue 1972], and while providing important constraints on particular regions, do not address the African landmass as a whole. These regional studies contrast with global velocity models in which Africa plays only a small part [Ekström et al. 1997, Masters et al. 1996, Zhang and Lay 1996, Christensen and Mooney 1995, Grand 1994, Pollitz 1994, Su et al. 1994, Montager and Tanimoto 1991, Woodward and Masters 1991, Anderson 1987]. In these global studies, resolution constraints limit our ability to distinguish the properties and interrelations between the various tectonic provinces of Africa. For example, 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. Some work has also been done on a regional level in Africa [Hadiouche and Zürn 1992, Tanaka and Hamaguchi 1992, Hadiouche and Jobert 1988 b, Hadiouche et al. 1986, Gumper and Pomeroy 1970]; but these regional studies often rely on surface wave dispersion along a single path [Hadiouche and Zürn 1992, Hadiouche et al 1986] making it difficult to make statements about the continent's seismic behavior as a whole.

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. The study area is divided into discrete regions on the basis of basement geology and group velocities of regional and teleseismic Rayleigh waves are measured from seismograms which have been recorded on broadband seismic stations. The group velocity curves are grouped according to the tectonic region they traversed. The clustered group velocity curves are averaged; and the averaged curves are inverted for 1D 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, and identification capabilities in the region.

## DATA SELECTION

### *Regionalization*

The North African study area is divided into tectonic provinces on the basis of basement geology and currently active tectonic processes. A generalized map of the basement geology of North Africa is depicted in Figure 1. From this map nine regions are selected for this study. These regions are described as follows: 1) the West African Cratonic Block which consists of two Precambrian shield bodies, three basins containing mainly lithified sediments, and four orogenic belts linked to the formation of Pangea, 2) the East African Cratonic Block which is largely covered by Saharan sediments but also displays scattered Archean and Proterozoic outcrops, 3) the North-Central Pan-African Mobile Belt which also contains a large portion of recent sediments as well as the massively deformed Benin-Nigeria Shield and the Tuareg Shield, 4) 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), 5) the Central Pan-African Mobile Belt and Pan-African Orogenic Belt, 6) the Arabian Shield Block which consists of former island arc material once contiguous with the Nubian Shield, 7) the Atlas Mountains, 8) the East African Rift Block an area affected recent rifting and magmatism, and 9) 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 best conformed to 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 345˚E to 65˚E longitude and 50˚N to 5˚S latitude were examined. The bulk of the earthquakes used in this study surround the Mediterranean. 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.

## ANALYSIS

### *Measurement Technique*

Before undergoing the group velocity measurement procedure, the data were demeaned and detrended, the horizontal components were rotated to radial and transverse, and the instrument response was removed from all seismograms. The Rayleigh waves present in the chosen broadband records are examined using a narrow band filter centered on a suite of different periods (Herrmann, 1973); these periods shall be referred to as filter periods. 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. Further details of the measurement procedure are outlined in Ammon (1998).

In an effort to resolve the most accurate group velocity dispersion curve, the instantaneous period is used for 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 contained within the same geologic block; and b) the paths must diverge by three degrees or less. The dispersion curves satisfying these criteria were collected and averaged, for results see figure 3. In an effort to preserve as much information as possible, portions of contributing curves containing periods which were not reflected in the other curves within the grouping were retained. Thus the beginnings and ends of some of the averaged curves represent information from only one seismic record. 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. (this issue). Of these 2529 curves, a subset of 69 were selected for our regionalized one-dimensional inversions. Each tectonic region was sampled by approximately 7 dispersion curves.

*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. Since the inversion problem is nonlinear, an iterative process is necessary. The inversion routine goes through a maximum of five iterations and is terminated when the misfit to the observed data drops below a preset minimum. 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). 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, the invariant layer thicknesses of the input model were manipulated and another inversion performed. This process was repeated until the rms misfit between the calculated curve and the observed input data was optimized. After the fit of the calculated dispersion curve to the observed data was optimized, the data resolution matrix was examined. The input model was truncated such that only the layers which the data could resolve remained. This truncated model was then used as the starting point for the final inversion.

*Error Sources*

The two factors which have most contributed to the errors inherent in this study are scattering and inaccurate source information. Scattering occurs when an incoming seismic ray encounters a geologic feature, most often crustal, which changes the ray's path so that it deviates from the path predicted by the ray tracing method employed in a given study. 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 ray paths.

As previously discussed, two values are paramount in measuring group velocity. These are the arrival time of the wave packet and the distance that 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). Sweeney found that, in the study area, events with body wave magnitudes larger than approximately 4.4 to 4.5 have ISC (International Seismic Center) locations accurate to about 15 km or less. For this same group of events, errors in origin time reports were generally found to be less than 2.5 s. Applying a 15 km mislocation as well as a 2.5 s error in the reported origin time to the longest path examined in this study, 4790 km path length recorded at station MBO, and the shortest path examined in this study, 670 km path length recorded at station RANI, we find that the errors associated with the longest path are ± .02 km/s; while the errors associated with the shortest path are ± .12 km/s. As a result of this work, the value of ±.2 km/s has been assigned as a conservative error estimate for each group velocity measurement.

## 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 nine 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 8, 6, and 9 of Figure 2, respectively). The orogenic grouping includes the Atlas Mountains, North-Central Pan-African Belt, Central Pan-African Belt, and Mozambique Belt/Eastern Pan-African Block paths (regions 7, 3, 5, and 4 of Figure 2). The cratonic grouping includes the West African Craton and East African Craton (regions 1 and 2 of Figure 2).

*Tectonically Active Paths*

The left-hand 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 seconds. This heterogeneity in large part reflects the differing crustal structure of the three paths.

The East African Rift path samples faulted material belonging to the Mozambique Orogenic Belt which dates to the Proterozoic. At the uppermost crustal level, this material is interfingered with largely alkaline volcanics implaced during the rifting process beginning in the mid-Tertiary [Sandoval 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 Phanerozoic sediments. At short periods (10 – 30 s) the East African Rift dispersion curve velocities are comparable to those from non-rift related regions (Figure 3). This is likely due to the combination of the mix of crustal components including Proterozoic orogenic material, Tertiary to Quaternary rift related volcanics, and Phanerozoic cover.

The Arabian Shield/Red Sea Rift path samples a region composed of accreted island arcs and is analogous to the Nubian Shield on the eastern side of the Red Sea. The Nubian Shield comprises the bulk of the Eastern Pan-African Mobile Belt, region four in this study (Figures 1 and 2). The metavolcanics and younger igneous bodies of the Arabian Shield should provide a fast crustal path for the Rayleigh waves examined. Measurements along the Arabian Shield do indeed reveal a fast crustal structure. The Arabian Shield path records nearly the highest group velocities of any region examined in this study, slower only than the Gulf of Aden curve, between the periods of 10 and 35 seconds. The Gulf of Aden path passes along the 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). These high velocities at short periods are typical of oceanic crust.

At periods greater than 40 seconds, 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 (Figure 3), suggesting lower velocities in the upper mantle. At a period of approximately 60 seconds, 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 [Knox et al, 1998; Lithgow-Bertelloni and Silver, 1998; Simiyu and Keller, 1997; Zeyen et al, 1997; Tanaka and Hamaguchi, 1992; Ebinger et al, 1989].

The inversion results corresponding to the rift related paths (Figure 4) tell much the same story as the group velocity curves. The Gulf of Aden structural profile depicts a thin region with relatively typical crustal velocities followed by higher velocities representative of the uppermost mantle. The Arabian Shield profile describes a thicker region with typical crustal velocities , approximately 20 km, which is again followed by higher velocities representative of the uppermost mantle. The upper 40 km of the East African Rift profile displays crustal velocities similar to those found in the non-rift related inversion results. From 50 km to 130 km, the three rift-related velocity profiles display velocities which under-shoot the results found in the other profiles examined in this study.

The inversion results for the tectonically active paths developed here display shear velocities which are not surprisingly uniformly lower than those reported in global radial reference Earth models (e.g. PREM, Dziewonski and Andreson, 1981). The shear velocity vs. depth profiles developed by Priestley and Brune (1978) in their work on the Basin and Range province in the Western United States closely mirror the shear velocities found in this study within the depth range of 60 to 200 km. At 40 – 60 km depth, the Basin and Range model (Priestley and Brune, 1978) has a faster velocity lid than we have found for the African rift regions (Figure 4) suggesting that the lithosphere is thinner beneath the African rift regions (Red Sea, Gulf of Aden, and East African Rift) than beneath the Basin and Range.

Following the example set forth by Knox et al (1998), the maximum shear wave velocity anomaly with respect to PREM was calculated. For the East African Rift path, that anomaly is .24 km/s; the anomaly for the Arabian Shield is .44 km/s; and the anomaly for the Gulf of Aden is .52 km/s. Given these values and assuming $\partial V_s/\partial T = 3.1\text{x}10^{-4}$km/sK (Bass, 1995), we obtain $\partial T$ values ranging from 770 K for the East African Rift path to 1680 K for the Gulf of Aden path. Assuming $\partial V_s/\partial T = 6.0\text{x}10^{-4}$km/sK (Sheehan and Solomon, 1991), we obtain $\partial T$ values ranging from 400 K for the East African Rift path to 870 K for the Gulf of Aden path. Assuming the relation set forth in Karato (1993), we obtain $\partial T$ values of 240 K for the East African Rift path, 450 K for the Arabian Shield, path and 540 K for the Gulf of Aden path. Since a maximum temperature anomaly of 300K can be associated with a mantle plume (Schilling, 1991), we see that in only one of the cases examined can the low velocities associated with the tectonically active regions be reasonably attributed to a temperature anomaly alone. Hence, it is necessary to appeal to some other mechanism such as the presence of partial melt to explain the low velocities we see surrounding the Afar region.

*Orogenic Belts*

The center panel of figure 3 depicts group velocity dispersion curves which have traveled through orogenic belts of various ages. The North-Central Pan- African Belt, the Central Pan-African Belt, and the Mozambique Belt date to the formation of Pangea in the late Proterozoic and earliest Paleozoic [Goodwin, 1996; Affaton et al, 1991; Boullier, 1991]; while the Atlas Mountains were sculpted by more recent orogenic events in the mid-Devonian and the Mesozoic-Cenozoic transition [Pique et al, 1991; Serber et al 1996].

The group velocity dispersion curves displayed in this panel show a tight grouping overall with the greatest heterogeneity at short periods, 10 to 30 seconds (Figure 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 display lower group velocities than those found at similar periods in cratonic regions (Figure 3).

The inversion results which correspond to these orogenic paths display greatest heterogeneity at crustal depths, 0 km to ~40 km (Figure 4). Here we see that the shear velocity profile for the Central Pan-African path does indeed show higher shear velocities at shallow depths, 0 km to 20 km, that one would expect of a region with significantly reduced sediment cover, ie. increased basement exposure. At depths greater than 40 km, the inversion results are tightly grouped and are slightly slower than the PREM global model (Dziewonski and Andreson, 1981) and the EU2 shield model (Lerner-Lam and Jordan, 1987).

*Cratonic Regions*

The right hand panel of figure 3 depicts 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 (Figure 1 and 2). The West African Craton contains to major shield bodies, the Reguibat Shield and the Man Shield. Approximately half of the Reguibat Shield presents Archean material; the remainder of the exposed Reguibat dates to the Proterozoic. The Man Shield reveals approximately one third of its extent to be Archean; the remainder, again, dates to the Proterozoic [Rocci et al. ,1991; Clifford, 1970]. The West African Craton also contains three major basin structures, the Taoudeni Basin, the Tindouf Basin and the Volta Basin. Sedimentation in these basins begins in the Late Proterozoic and continues well into the Phanerozoic [Bertrand-Safati et al, 1991; Petters, 1991]. The paths which represent the West African Craton are not well bounded by our generalized geologic boundaries. However these paths were included in this study in the hope that they might reveal some 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, Darfour etc. display Proterozoic basement material mingled with Phanerozoic volcanics [Goodwin, 1996; Cahen and Snelling, 1984; Vincent, 1970] (see Figure 1).

Despite these uncertainties, the group velocity curves corresponding to cratonic paths display a tight grouping between the periods of 20 seconds and 80 seconds. The divergence between the group velocity curves from 10 seconds to 20 seconds 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 seconds and 20 seconds 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 [Ekström et al. 1997, Masters et al. 1996, Zhang and Lay 1996, Christensen and Mooney 1995, Grand 1994, Pollitz 1994, Su et al. 1994, Montanger and Tanimoto 1991, Woodward and Masters 1991, Anderson 1987]. 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, 1988 a].

As with the tectonically active grouping and the orogenic grouping, the inversion results for the cratonic paths display the greatest heterogeneity at crustal depths, 0 km to 40 km. At depths greater than 40 km, this variation is greatly reduced. When the inversion results for the cratonic paths are compared to previously published studies such as the Eurasian Shield Model EU2 (Lerner-Lam and Jordan, 1987) and the global reference Earth model PREM (Dziewonski and Andreson, 1981), we see that the cratonic inversion results developed in this study are, for the most part, slightly faster than our two reference models at depths of 40km and greater. We find that our results for the craton paths are significantly slower than the North American Shield model SNA of Grand and Helmberger (1984). However, SNA is an SH model, and our model (as is EU2) is an SV model, so the differences could be due to transverse anisotropy rather than due to a fundamental difference between African cratons and the North American Craton. Thus, from this limited study we do not see strong evidence for a 'superplume' eroding the African cratonic tectosphere at depth.

## CONCLUSIONS

In this study we have performed regionalized inversions of nine regions in Northern Africa based upon tectonics and geologic structure. 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 region of Eastern Africa. This region has been subject to significant volcanic activity in the recent geologic past, and it is believed that the low 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. Resolution constraints prevent us from making any conclusions about the upper mantle structure of other more localized regions where recent volcanic activity has taken place such as Tibesti, Darfour, and Kordofan.

The results of this study indicate that the two greatest factors which influence group velocity curves in Northern Africa are differences in upper mantle structure (affects event location) ,in this case the presence the eastern African low velocity zone, and the thickness of unlithified sediments through which the surface wave passes (affects Ms). On the basis of these observations, the best 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 mantle velocity. A function representing distance to the Afar/Djibouti “plume” would also provide an appropriate regionalization. An optimized regionalization scheme in conjunction with accurate one-dimensional shear velocity profiles will allow for a 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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