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Surface Wave Dispersion Tomography in Libya

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Abstract: ***The Mediterranean region has evolved into a geologically complex area due to its geodynamic evolution and its position near the boundary between the Eurasian and African plates. To better determine the Earth structure in Northern Libya and the southern - eastern Mediterranean Sea, we analyze regional seismograms (< 30° from an earthquake) recorded by the Libyan National Seismic Network (LNSN) and compute Rayleigh wave group velocity dispersion curves over periods of 20 - 80 s, individually measuring over 640 waveforms from 67 earthquakes covering the Northern Libya to southern - eastern Mediterranean regions. To process this data, each waveform is: 1) updated with the epicentral parameters, 2) rotated (N - E to R - T), 2) the instrument response removed, and 3) reviewed manually for stability by ensuring that only data with clear surface wave arrivals will be included. The data is then processed for group velocity, and again quality controlled for stability based on visually inspection of each dispersion curve. We then performed a tomographic inversion of Rayleigh group velocities to obtain 2 - D tomographic maps group velocities variations at each period on a grid of 2.0° x 2.0° assuming a constant isotropic velocity model. Although the data are limited and not optimal, we were able to extract reasonable Rayleigh dispersion group velocity curves from the tomographic maps. We present maps that show the region complexity and will be using this data to generate 1 - D shear wave velocity models in a separate study with additional data (specifically receiver functions and gravity measurements).***

Keywords: Rayleigh wave**,** Group velocity, Surface wave tomography, Northern Libya, East central Mediterranean

1. Introduction

The crustal thickness and velocity variations in the region around Libya have been targets for many studies (e. g., Pasyanos, 2010; Roure et al., 2012), including many surface wave tomography studies in the central - eastern Mediterranean e. g. (Lucio and Pasyanos 2007; Schivardi and Morelli, 2009). Despite these studies, the crustal thickness (Moho depth) and velocity in the Libyan region has still to be fully defined (e. g., Sandvol et al., 1998; Roure 2012). For example, there is depth uncertainty of the African continental crust in the eastern Libyan margin (Casten et al., 2006) and possible crustal thinning (< 15 km) beneath the Sirt basin (Tedla et al., 2011). The thinnest crust (24 - 30 km) lies in the northern Libya and possibly thickens to 32 to 36 km in southern Libya (Leminifi et al., 2017). Analysis of surface wave group velocity variations through use of seismic tomography canresolve changes in crustal thickness and composition present in the area (e. g., Schivardi & Morelli, 2009). Using available data from the Libya National Seismic Network (LNSN), we determine Rayleigh wave group velocity dispersion curves and use this data to invert for 2 - D tomographic maps for group velocity variations. The results of this study allow us to investigate crustal thickness through joint inversion of Rayleigh wave dispersion curves and receiver functions (RFs). Here, we present our initial result for Rayleigh wave dispersion curves that show variations of crustal and upper mantle structure across the region around Libya.

2. Data

In this study, we utilize data (regional 2008–2010) collected from LNSN. The sampling rate of the stations is 40 - 100 samples/s, with an operating bandwidth of 0.1 Hz to 85.5 Hz. The raw seismic data were received in SEISAN (seismic analysis system) format (Ottemoller et al., 2013). We converted the data into SAC (Seismic Analysis Code) format, updating their information (event location, depth, etc.).

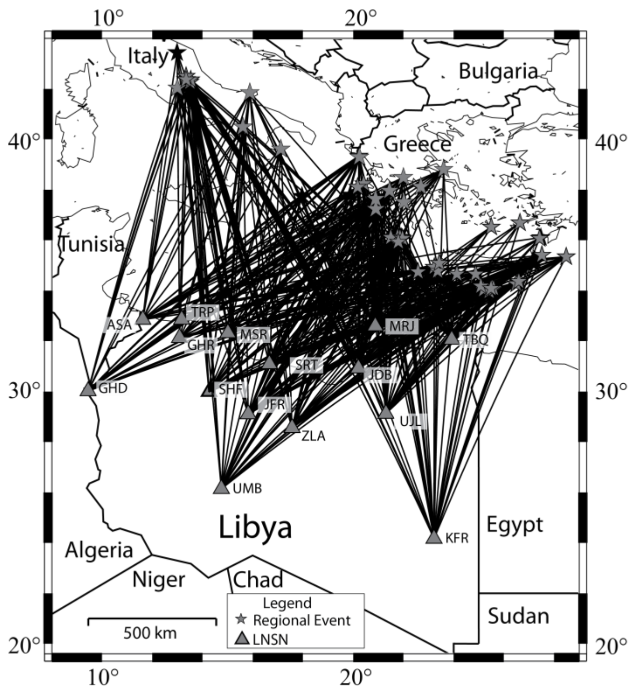

Figure 1: Ray coverage map for regional events used to compute Rayleigh wave dispersion curves from the Libyan National Seismological Network (LNSN). Each line represents a path between an earthquake and a seismic station.

The events' locations, magnitudes, and depths were taken from the reviewed Bulletin of the International Seismological Centre (ISC). In addition, SAC instrument response files were created for each station using PDCC (Portable Data Collection Center) software. A total number of 71 regional events were used in this study with magnitudes (m_b) between 3.2 to 5.5 (Figure 1). Figure 1 illustrates the location of the study along with station to event ray paths showing the coverage of our dataset in Libya. Note our coverage is limited in the south, mainly due to the lack of regional earthquakes in the region. To measure surface wave dispersion, we removed the instrument response using the response files we created for the network, and then used the displacement data. We then measured velocity dispersion using the PGSWMFA (PGplot Surface Wave Multiple Filter Analysis) code Ammon (2001). Afterwards, we picked the maximum amplitude of the envelope function along the computed group velocity curve, and selected periods in which there was a continuous dispersion curve. The arrival time of the amplitude was then used to calculate the group velocity Herrmann, (1973). We measured the group velocity between 2.5 - 4.75 km/s for periods between 15 - 80s. Figure 2 shows an example of group velocity for three of our stations. We take the velocity at a period for all stations, and invert for group velocity as a function of position in Libya (see next section).

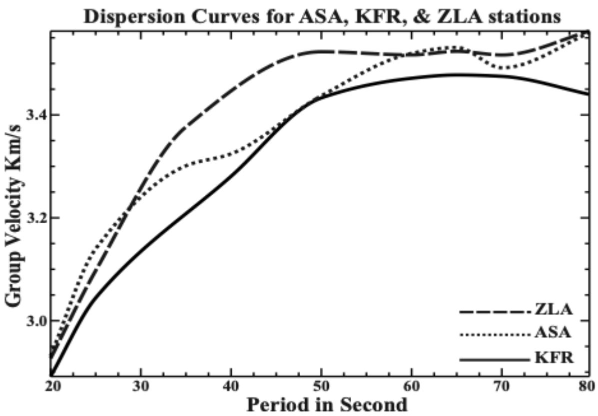

Figure 2: Examples of group velocity dispersion curves constructed from the tomographic maps for seismic stations ASA, KFR, and ZLA.

3. Inversion Method

We applied the tomographic method of Barmin et al. (2001), which uses the Gaussian beam method, to obtain 2-D tomographic maps for group velocity variations assuming a constant isotropic velocity model.The tomographic maps were constructed on a grid of 2.0° x 2.0° for a variety of periods. According to Barmin et al. (2001), the inverse problem is based on estimating a vector function $m(r) = [m_0(r), \ldots, m_n(r)]$ which minimizes the travel time residuals d with respect to a reference model $C_0(r)$, where $r = [\theta, \phi]$ is a surface vector with respect to latitude and longitude. To estimate the penalty function$m(r)$, which relates the data misfit between the model and a reference model, we assumed the isotropic model can be minimized:

$$(G(m) - d)^T C^{-1}(G(m) - d) + \sum_{k=0}^{n} \alpha_k^2 \|F_k(m)\|^2 + \sum_{k=0}^{n} \beta_k^2 \|H_k(m)\|^2$$

where $\beta_k$and α_k are regularization constants that can be defined by the user, G is the operator for calculating travel times $G_i(m) = \sum_{k=0}^{n} \int_{P_i} \left(\gamma_k(\varphi(r)) C_0^{-1}(r)\right) m_k(r) ds$, d is the data vector for travel time residuals, C is the data covariance matrix, and H is an operator for penalizing the norm in the model. For calculating travel times, $P_i$is the wave path, while γ_k and $m_k$are defined parameters.

The penalty function that represents both the data misfit and the spatial smoothing kernel is the spatial smoothing operator:

$$F_k(m) = m_k(r) - \int_s S_k(r, r') m_k(r') dr'$$

where $S_k$is the smoothing kernel $S_k(r, r') = K_{0_k} \exp\left(-\frac{|r - r'|^2}{2\sigma_k^2}\right)$, and $\sigma_k$is the spatial smoothing for width/length.

Uncertainties in group velocity measurements were also considered. Here, we implemented the method shown by Schivardi and Morelli (2009) to estimate data errors to verify our Rayleigh waves dispersion measurements. This method assumes that the measured group velocity in a cluster of events (group of events within < 5 km) should be theoretically equal. Six clusters were selected to be examined, each with two to six events. We estimated the error by finding the average travel times for each cluster for different periods. The error is represented by the standard deviation plotted for each period.

Tomographic inversion results were also tested, to determine the stability of our inversion and examine the uncertainty using Doser et al. (1998). We added random noise of up to 10% to our group velocity data and then we inverted the data. The results obtained showed a very similar result to those from free noise data. Adding noise above ~17% results in the inversion code failing to converge.

4. Results

We measured velocity dispersion curves from computed displacement seismograms for regional events and the group velocity between 2.5 - 4.75 km/s for periods between 15 - 80. Group velocity maps over a range of periods for Rayleigh waves were constructed on a 2.0° x 2.0° grid (Figure 3). Figure 3 illustrates the complexity of the crust and upper mantle structure. In the Mediterranean Sea, oceanic crust appears to be much faster than the continental structure in the Libyan crust and upper mantle. Surface wave dispersion reflects these overall structures, but future work will have to be conducted in order to relate these results to crust and upper mantle structure.

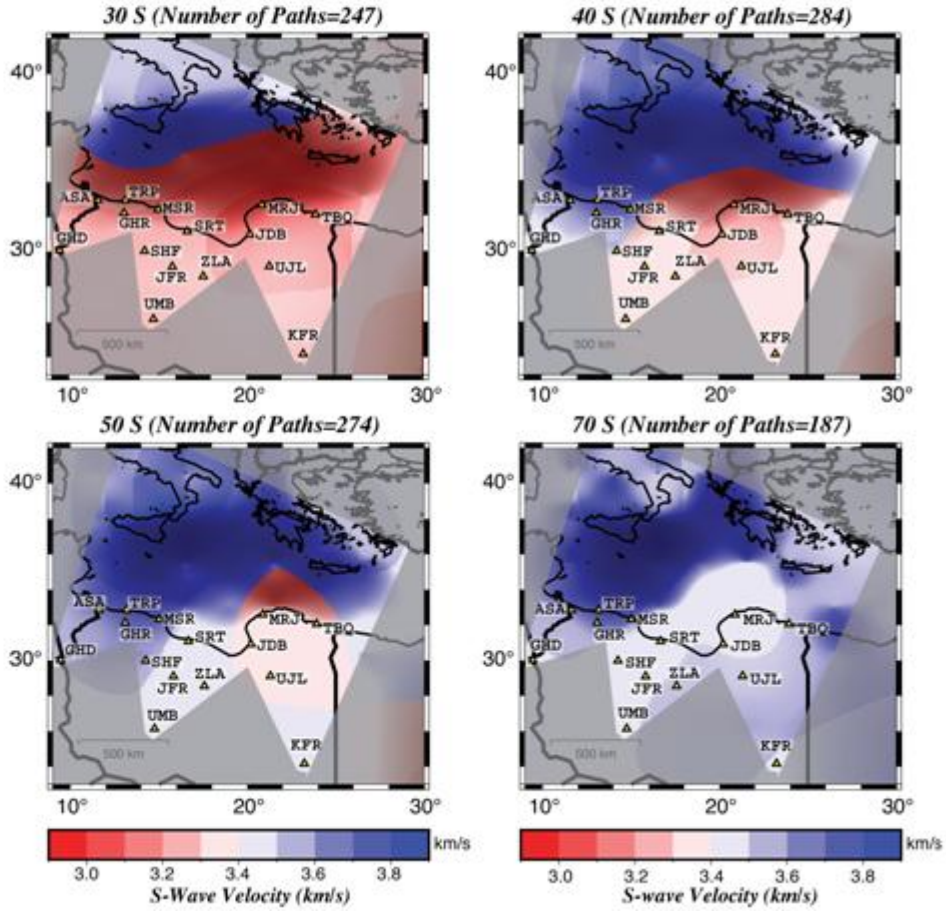

Figure 3: Examples of some tomographic inversion maps for Rayleigh wave group velocities for periods 25, 30, 35, and 40 sec. The number of paths is also included for each map. These maps were computed using the approach of Barmin et al.(2001) over a grid of 2.0° x 2.0°, for constricting tomographic maps. No raypaths were available in the shaded regions.

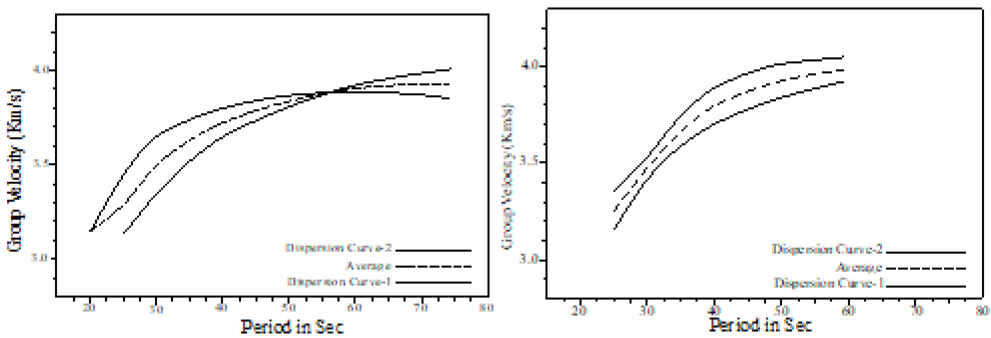

Figure 4: Dispersion curves for some selected clustered events to display the error in the group velocity measurements. This plot shows the variation of different dispersion curves for one (cluster-6) (left) station-JDB and (right) station-MRJ. The two black lines represent the dispersion curves for two different events in one cluster for the two stations JDB and MRJ. The dashed line shows the mean of the dispersion curves. The clustered events (2-6 events) are located within < 5 km of each other.

Uncertainties in group velocity measurements can arise from different sources. Some errors may not only result from uneven path distributions that cause uneven sampling of velocity variations, but also from assumptions made about the input parameters inthe inversion processes. Here, we implemented the method used by Schivardi and Morelli (2009) to estimate data errors to verify our Rayleigh waves dispersion measurements. This method assumes that the measured group velocity in a cluster (group of events within < 5 km) of events should be theoretically equal. We selected six clusters to examine, each with two to six events and estimated the error by finding the average travel times for each cluster for different periods. The error is represented by standard deviation plotted for each period. Some measured group velocities have higher values than expected (UMB station). We believe that these high error values may be due to wrong events selected for the time window. These values are not representative of all the measured clusters. Earthquake mislocation may also contribute to these errors but are not explored further. We plot the dispersion curves for some selected clustered events (Figure 4); the dashed curve shows the mean of the dispersion curves for Rayleigh. The plotted dispersion curves should show a very low deviation error on the graph. In some cases, the shifted dispersion curves that show a higher standard deviation error, reflect the error in the measured group velocity.

The dispersion group velocity curves of Rayleigh (Figure 2) were extracted from the tomographic maps that can be used for 1 - D velocity inversions for future work. The velocity variation in percentage shows that the largest variation occurs at 20s for Rayleigh waves. The lowest velocity variation can be found in between periods of 40 - 60s. The maximum number of group velocities obtained is within the period of 40 - 60s. The resulting inversion curves were then used in the joint inversion along with the RFs to create 1 - D shear wave velocity models for the Libyan region. We present here new results for the study area, which we believe can be a basis for 3 - D velocity models in the area (Figure 2).

5. Discussion

Surface waves, although limited in their ability to produce high resolution images because of their longer wavelengths compared to body wave, are sensitive to average earth structure, making them ideal to study average Earth structure in this region (Ammon et al., 2020). Furthermore, the results also illustrate the nature of surface wave dispersion, where the longer periods penetrate deeper than shorter periods thus are generally faster than shorter periods. In this paper, we utilized data regional events collected from the LNSN network to compute Rayleigh wave dispersion measurements. Using our dispersion measurement, we constructed2.0° x 2.0°group velocity maps at various periods that show differences in Earth structure between oceanic and continental crust, specifically faster velocities in the oceanic crust when compared to continental crust. Our results also show small variations in velocity that likely reflect local geology variations; however, such interpretations cannot be confirmed until we invert specifically for shear - wave velocity, which is planned for future work.

6. Conclusions

In this study, we measured Rayleigh surface wave dispersion curves from regional events using data from 15LNSN stations. The Rayleigh wave fundamental mode was checked by examining selected cluster events assuming that these should exhibit very low variations in group velocity. We then inverted for group velocity tomographic maps at various periods and calculated individual dispersion curves for all stations. The maximum number of group velocities obtained is within the period of 40 - 60s. The largest group velocity variation occurs at 20s for Rayleigh waves, while the lowest velocity variation is between periods of 40 - 60s. The resulting inversion dispersion curves maps will be used for a joint inversion scheme that will include other geophysical data (receiver functions and gravity measurements), specifically for creating 1 - D shear wave velocity model for every station in the region.

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