SURFACE WAVE TOMOGRAPHIC STUDY OF CENTRAL ASIA TECTONIC REGIMES

A.L. LEVSHIN, M.H. RITZWOLLER AND L.I. RATNIKOVA

Department of Physics, University of Colorado at Boulder Boulder, CO 80309-0583, U.S.A.

AND

A.A. EGORKIN-JR

Int'l. Institute of Earthquake Prediction Theory and Mathematical Geophysics, Russian Academy of Sciences 79/2 Warshavskoe sh, 113356, Moscow, Russian Federation

1. Abstract

The detailed study of intermediate period surface wave propagation across Central and Southern Asia is presented. Broadband waveform data from about 600 events from 1988 - 1995 recorded at 83 stations from global and regional networks have produced about 9,000 paths for which individual dispersion curves have been estimated. The combination of measurements on global and regional scales helps to optimize path coverage and azimuthal distribution which together determine resolution. The tomographic technique is used to estimate group velocity maps at different periods between 10 and 40 s for Rayleigh and Love waves. 'Checker-board' tests show that resolutions across most of the studied region are about 4°-5° at 20 s and above, but degrade at shorter periods. Resolution is far from uniform spatially, and is generally worst in Western and Southern Iran and in India. Comparison of the estimated group velocity maps with those predicted by the recent global model CRUST-5.1/S16B30 is qualitatively very good, but, because of the coarseness of its grid, CRUST-5.1 misses some of the smaller sedimentary basins and the geometry of crustal thickening in Central Asia cannot be well represented by any gridded 5° model.

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2. Introduction

This paper presents the results of a study of intermediate period (10 - 40 s) Rayleigh and Love wave dispersion across Central Asia, Western China, and regions of the Middle East. The studied region encompasses latitudes from 20°N to 50°N and longitudes from 45°E to 105°E.

There are two main motivations for this study. First, accurate high resolution intermediate period group velocity maps are useful in monitoring clandestine nuclear tests. These maps guide the identification and extraction of surface waveforms which emanate from small seismic events. The estimation of surface wave magnitude, M_s, near 20 s period is thereby facilitated for use as part of, for example, the $M_s : m_b$ method of discriminating underground explosions from naturally occurring earthquakes [21]. In addition, the existence of group velocity maps below 20 s period should allow for the development of a regional surface wave magnitude scale based on a shorter reference period so that the discriminant could be applied to smaller earthquakes and explosions. Second, regional intermediate period dispersion maps provide new constraints on the shear velocity structure of the crust and on crustal thickness. Since surface wave sensitivities compress into the crust at the short period end of our study, group velocity maps below 25 s period are particularly important to help resolve Moho depth from the average shear velocity of the lower crust in seismic inversions.

In a recent study [18] we presented Rayleigh and Love wave group velocity maps on a larger spatial scale (all of Eurasia) and for a broader period band (20 - 200 s) than considered here. There have also been other studies on larger scales and at longer periods that have produced dispersion maps (usually phase velocities) across the studied region; e.g., [5] [12] [22] [7] [26] [4], and [1]. In the current paper, we attempt to provide improved resolutions on a regional scale and to extend the group velocity images to shorter periods. The success of such an attempt depends on several factors:

- the use of data from regional networks and arrays in addition to global seismic network data;
- the use of data from events which are smaller in magnitude than those used on a continental scale, (i.e., $M_s \leq 5.0$);
- the combination of measurements made on paths that propagate continental-wide with those made on paths confined to the region of study.

Toward these ends, we have processed data from two networks in Kirgizstan and Kazakstan, KNET [14] [23] and KAZNET [6], following about 200 events with $M_s \leq 5.0$ which occurred largely within the studied region. These data are used in concert with measurements on records from stations distributed continent-wide which follow about 400 larger earthquakes dispersed around the continent, most with $M_s \geq 5.5$. The use of these 'short-path' measurements is mostly intended to help reduce the period range of the study, but also helps to improve resolution in the studied region. The combination of these measurements with 'long-path' measurements helps to improve the homogeneity of ray path coverage and to provide crossing paths, both of which improve resolution and work to reduce sensitivity to event mislocation.

3. Data, Measurement, and Surface Wave Tomography

The data and the methods used to make the dispersion measurements, to estimate measurement uncertainties, and to translate the measurements into group velocity maps are discussed in detail in [18]. A brief overview follows.

Data have been accumulated across Eurasia from the GDSN, GSN, CDSN, GEOSCOPE, MEDNET, KNET, and KAZNET seismic networks. Group travel time, phase travel time, and spectral amplitude measurements are obtained by use of an interactive Frequency-Time ANalysis (FTAN) method (e.g., [8] [20] [10] [16]. Group velocity and phase velocity are computed from the distance between the receiver and the CMT location [3] when it exists, or the PDE location otherwise. As part of FTAN, an analyst interactively designs a group velocity - period filter to reduce contamination from other waves and coda, chooses the frequency band for each measurement, and assigns a qualitative grade (A - F) to each measurement. Data from approximately 600 events across Eurasia, most with $M_s \geq 5.0$, have been processed in this way to yield more than 9,000 measured Rayleigh wave dispersion curves and more than 7,600 Love wave dispersion curves across the continent. These numbers include data from about 200 smaller events ($4.0 < M_s \leq 5.0$) which occurred mostly in the studied region and which were processed only at KNET and KAZNET. The locations of stations and events used are shown in Figure 1.

The resulting data set exhibits considerable redundancy, which allows for consistency tests, outlier rejection, and the estimation of measurement uncertainties. The use of broadband regional network data, such as those from KNET or KAZNET, are particularly useful for this purpose. Measurements from similar paths are 'clustered' and compared. Paths are considered 'similar' if their starting and ending points both lie within 2% of the path length from one another. About one-third of all measurements form part of some cluster. The algorithm of [2] and [25] is used to construct the group velocity maps. Detailed description of this technique is given in [18] [19] (See also [9], Ch. 6.).

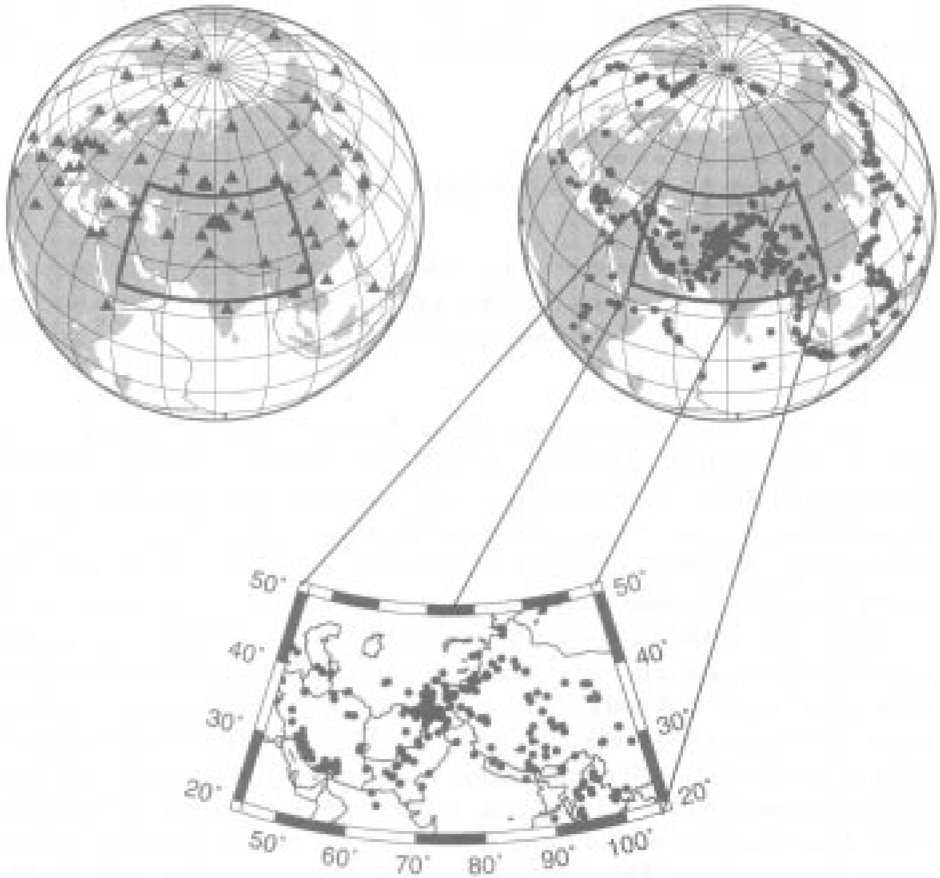


Figure 1. Station and event locations. Stations are shown by triangles and events by circles. At bottom, a blow up of event locations in the region of study are shown.

4. Resolution Analysis

The resolution of the data set depends strongly on geographical location, period, and wave type. Experience shows that all three of the following are required to produce a resolution of 5° or less: high path density, good azimuthal coverage, and a significant number of paths shorter than ~30°. To estimate resolution we perform a standard 'checker-board' test. Detailed description of our resolution analysis is given in [19]. In result of checkerboard tests we claim a resolution of 5° for both Rayleigh and Love waves at 20 s period. Resolution is worst at 20 s period in Northern India, parts of Pakistan, Northwestern Iran and the Southern Caspian, parts of the Persian Gulf, and the Arabian Sea. These are the regions most poorly resolved at all periods, consistent with the observations of path distribution discussed above. Resolution is worsened considerably if only paths from within the studied region are used. This conclusion demonstrates the importance of using group velocity measurements from paths that originate or terminate outside the studied region. The use of such paths improves the homogeneity of path distribution and azimuthal coverage, and, hence, improves resolution.

5. Group Velocity Maps

Using the tomographic method mentioned above, we construct group velocity maps for Rayleigh and Love waves at the following periods: 10, 15, 20, 25, 30, 40 s. A sampling of the estimated group velocity maps is presented in Figures 2a - 2b. These maps represent lateral group velocity variations relative to the regional average and are constructed using all data that cross the studied region. Comparison with maps obtained from paths inside the region indicates what was also apparent from the resolution analyses of these two different data sets. Much more accurate and more highly resolved group velocity maps are produced if short path data from within the region of study are combined with longer path data that originate and/or terminate outside the studied region.

There have been numerous studies of surface wave dispersion across the studied region within the past 20 years, the list of them is too long to be included into this brief paper. Most of these studies have been concentrated on Tibet and have been non-tomographic, multi-station or multi-event phase velocity studies. None of the studies other than our own have resulted in group velocity maps at periods as short as those presented here.

[?] discuss the interpretation of group velocity maps in some detail. However, a number of the features in the group velocity maps shown in Figures 2a - 2b are worthy of further note here. The resolution analysis found that the 10 s maps are suspect throughout much of the studied

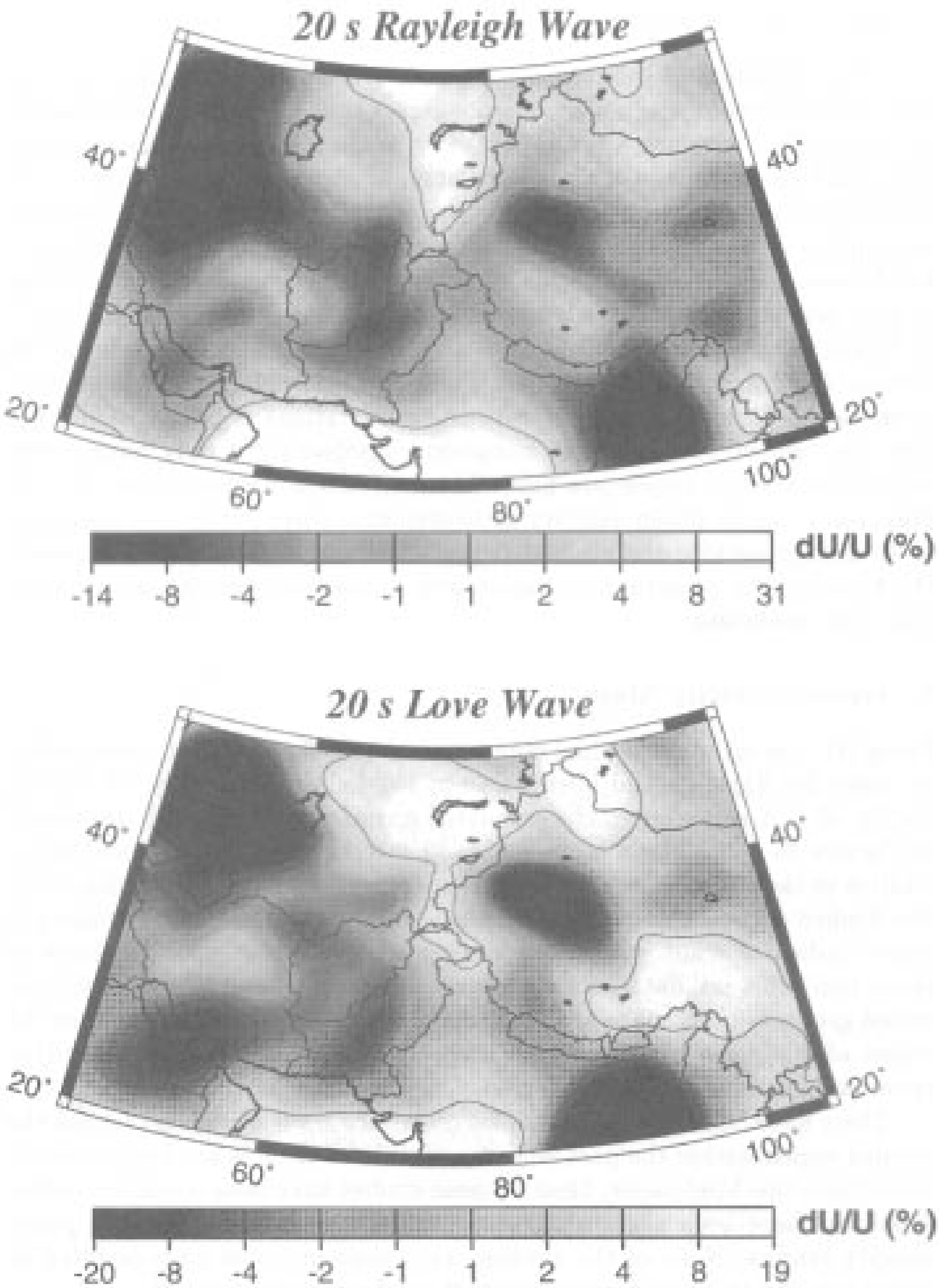
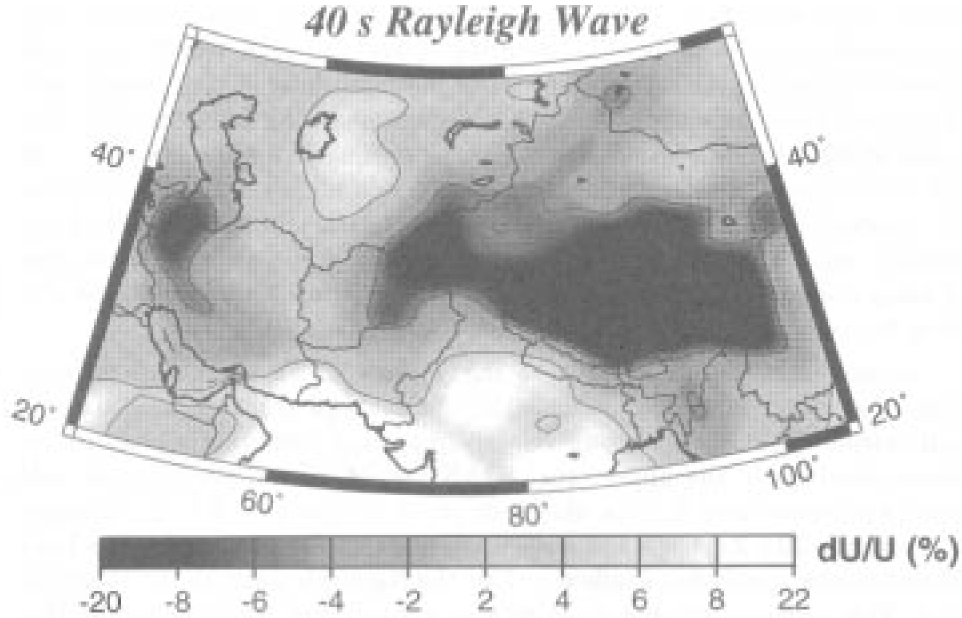


Figure 2a. Group velocity maps for Rayleigh and Love waves at the 20 s period



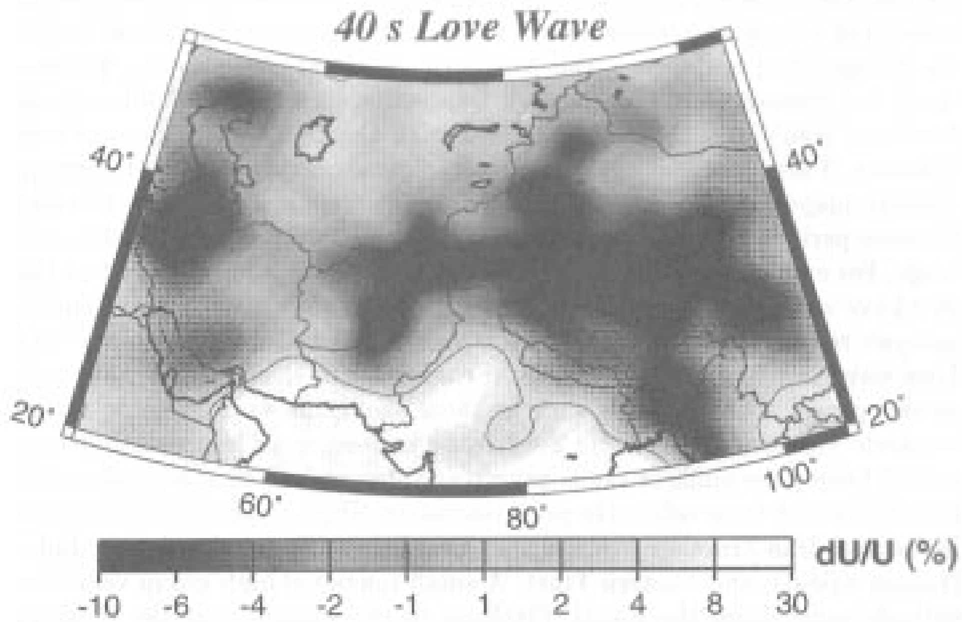


Figure 2b. Group velocity maps for Rayleigh and Love waves at the 40 s period

region, and inspection of these maps reveals that very few features have been resolved successfully. The smearing of low and high velocity features toward the edge of the maps is a result of the smoothing in the tomographic inversion. There is very little path coverage near the boundaries of the maps at 10 s period. These maps gives us optimism for the possibility of the construction of more uniformly accurate and higher resolution maps at 10 s period, but should not yet be interpreted seriously across most of the studied region. At 15 s and above, however, the group velocity signatures of many crustal features begin to emerge clearly, consistent with the results from the resolution analyses.

At the short period end of the study (15 - 25 s), the group velocity maps show the imprint of sedimentary basins and continental platforms and shields. That is, the group velocity maps are dominantly sensitive to shear velocities in the upper crust which are, of course, very slow in sedimentary basins and fast in shield or platform regions. As an example, consider the 20 s Rayleigh and Love wave maps in Figure 2a. The 20 s Love wave samples somewhat shallower than the Rayleigh wave at the same period. This provides greater sensitivity to sedimentary features, but at this period their sensitivities in continental regions are not substantially different and the maps are seen to be quite similar. Low velocity features are all associated with known sedimentary basins. These include the Tarim Basin, the Ganges Fan and Delta, the Northern and Southern Caspian Depressions, the Persian Gulf, the Tadzhyk Depression (north of Afghanistan and Northern Iran), and a basin associated with the Indus River in Southern Pakistan. These basins provide a characteristic signature on all of the group velocity maps from 15 s - 25 s period. The discrepancies in these features between periods and wave types are attributable to differences in path coverage. For example, the Southern Caspian Depression is not resolved on the 20 s Love wave map but it is on the 20 s Rayleigh wave map. The resolution analysis reveals that the Southern Caspian is not well resolved by the 20 s Love wave and, hence, we have greater confidence in the Rayleigh wave map at this period. Discrepancies such as these should be used to guide future research. Concentrated efforts need to be expended to improve the short period Love wave maps in the Southern Caspian region, as in all regions believed to suffer from relatively poor resolution. High velocity features exist in Central Iran (Iranian Plateau), in Kazakstan (Kazak Platform), India (Indian Shield), and Eastern Tibet. A small tongue of high group velocities extends south from the Kazak Platform to the Pamir (near the Western syntaxis of the Indian-Eurasian plate boundary), which are known to be characterized by very high velocities near the surface.

At the long period end of this study, the group velocities are dominantly sensitive to crustal thickness. This is particularly true for the Rayleigh waves that sample deeper at each period than the Love waves. Thick crust causes low group velocities. As an example, consider the 40 s Rayleigh and Love wave maps in Figure 2b. By 40 s period, both types of waves possess considerable sensitivity to Moho depth, although the Love wave continues to have substantial sensitivity to upper crustal and sedimentary velocities. The effects of crustal thickness on the estimated group velocity maps are most striking under Tibet where the Moho extends to depths greater than 70 km. Low velocity anomalies are associated with Tibet, the Pamir and the Hindu Kush, the Altai Range in Mongolia, and the Zagros Mountains in Western Iran. The 40 s Love wave map continues to be imprinted with low velocities associated with the deepest basins; e.g., the Tarim, the Caspian, and the Ganges.

In summary, a qualitative inspection of the group velocity maps in Figures 2a - 2b reveals that:

- the observed group velocity features are repeatable in that similar features are observed at different periods and wave types which sample the Earth similarly;
- these repeatable features are qualitatively understandable in terms of known geological and tectonic structures, particularly sedimentary basins, continental platforms and shields, and crustal thicknesses;
- discrepancies that exist between the maps are understandable in terms of differences in path coverage;
- the features observed on the group velocity maps at 20 s period differ substantially from those observed at 40 s period since different crustal structures dominate the maps at these two periods.

The final comment indicates that it would be a mistake to use group velocity maps constructed around 40 s period and attempt to extrapolate them for use at much shorter periods. This is particularly true in Central Asia which is characterized by extremely thick crust and deep sedimentary basins.

Detailed comparison of our maps with those predicted by the hybrid model CRUST-5.1/S16B30 of [13], and [11] showed that observed maps should prove superior in predicting group arrival times and should prove useful in calibrating crustal models such as CRUST-5.1. However, improvements at periods below 20 s period are still needed. In particular, the incorporation of off-pure-path propagation at these periods may be necessary to provide better fits to the data. In addition, the resolution analyses indicate that there are parts of the studied region which remain poorly constrained at all periods.

6. Conclusions

We have reported the results of a systematic study of intermediate period (10 s - 40 s) Rayleigh and Love wave dispersion across Central Asia, Western China, and parts of the Middle East. There are three main reasons why we believe that this study represents a significant improvement in the understanding of intermediate period surface wave dispersion across the studied region. The first has to do with the data used. This study displays denser and more uniform data coverage and demonstrates higher resolution than previous studies that have been performed on this scale and at these periods. Second, the group velocity maps display the signatures of known geological and tectonic features never before revealed in surface wave studies on this scale. In particular, these maps are providing entirely new constraints on sedimentary basins and crustal thicknesses. This both lends credence to the maps and spurs interest in their use to infer information about the features that are observed. Finally, the group velocity maps provide a significant improvement in fit to the observed dispersion curves. For these reasons we believe that the group velocity maps presented here should prove useful to predict group travel times for the identification and extraction of surface wave packets, to calibrate existing crustal models such as CRUST-5.1, and as data in inversions for crustal models (e.g., [17]).

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