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GROUP VELOCITY VARIATIONS ACROSS EURASIA

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ABSTRACT

We report on the status of a systematic study of broadband Rayleigh and Love wave dispersion across Eurasia. The purpose of this study is to provide a more sharply focused model of shear velocity variations in the lithosphere with resolutions in most regions between 500 - 750 km. Group and phase velocity as well as spectral amplitude measurements have been obtained using the method described by Ritzwoller *et al.* (1995). These measurements have resulted from analyses of approximately 6,100 three-component long period seismograms from the GSN, GEOSCOPE, MEDNET, and CDSN networks following 315 events with $M_s \geq 5.0$ that occurred from 1988 through late-1995. This data set exhibits considerable redundancy, which allows for consistency tests, outlier rejection, and error estimation. We 'cluster' measurements from similar paths by combining them into a single measurement defined as the average along the 'unique path' with the estimated standard deviation among the individual measurements. The number of unique paths is period dependent, peaking at about 4,000 in number at 50 s period and falling to smaller numbers at shorter and longer periods.

Interpretation has concentrated on the group velocity measurements for two reasons: (1) they can be interpreted without knowledge of the source and (2) group velocity kernels are compressed nearer to the surface than phase velocity kernels and consequently provide better radial resolution in the crust and uppermost mantle. Group velocity maps have been constructed from 20 s period to 225 s period for Rayleigh waves and up to 150 s period for Love waves. Shown here are group velocity maps for Rayleigh and Love waves at three periods: 30 s, 50 s, and 100 s. These maps appear to provide significantly better resolution than other surface wave studies performed to date. In particular, they contain new information about large sedimentary features, lower crustal structures, Moho topography, and upper mantle structures. For example, Love wave sensitivities are compressed nearer to the surface than Rayleigh waves and the 30 s Love wave map clearly shows the large sedimentary features across Eurasia (Tarim Basin, Ganges Delta, Caspian and Black Sea Depressions, Barents Sea Depression, sediments in the Persian Gulf and Western Siberia). Rayleigh waves at 50 s period are very sensitive to Moho topography and the 50 s Rayleigh wave map exhibits striking correlation with surface topography in the Middle East and Central Asia, particularly under Tibet, the Altai Range, and the Zagros Mountains. The resolution of this study is well demonstrated by the group velocity features in the Far East.

A higher resolution regional-scale study of Central Asia with measurements made at regional networks is the subject of a companion study in this volume (Ritzwoller *et al.*, 1996).

Key Words: Eurasia, surface waves, dispersion, Rayleigh waves, Love waves, group velocity

OBJECTIVE

The purpose of this research is to provide an improved lithospheric (crust and uppermost mantle) shear velocity model for the entire Eurasian continent. The inversion is broken into two parts: (1) the estimation of period-dependent maps of the phase and group velocities of Rayleigh and Love waves across a broad period band (20 s - 250 s) and (2) the use of these maps to estimate shear velocity variations across the continent. The resolution exhibited by the resulting model will depend on path number density (lateral resolution) and the breadth of the frequency band studied (radial resolution). We report here on the first part of this research.

A more sharply focused model of lithospheric shear velocities across the continent is useful in a variety of ways. Most significantly for a CTBT, accurate high resolution structural information is needed to improve location capabilities. Location error ellipses mainly quantify ignorance concerning the structure of the crust (sedimentary thicknesses and velocities, crustal velocities and Moho topography). Studies of broadband surface wave dispersion, such as the one described here, promise much new information about crustal structures across Eurasia and will provide a more sound basis for future regional scale studies (e.g., Ritzwoller *et al.*, 1996; this volume).

RESEARCH ACCOMPLISHED

Research to date has proceeded in three steps: (1) data acquisition and dispersion measurement, (2) determination of measurement reliability, and (3) group velocity map construction. We will discuss each of these steps briefly in turn.

Data Acquisition and Processing

Long period (1 sps) waveform data from more than 450 events with $M_s \geq 5.0$ in and surrounding Eurasia from 1988 - late-1995 have been acquired from IRIS' DMC and the GEOSCOPE Data Center. These include data from the GSN, CDSN, GEOSCOPE, and Mednet networks. Of these events, 315 have been fully processed for the GSN/CDSN/Mednet data and about 190 have been processed for the GEOSCOPE stations. The locations of most of these 315 events are shown in Figure 1. At present, we have completed about 75% of the planned data processing.

By 'data processing' we mean the application of the semi-automated dispersion measurement method described by Ritzwoller *et al.* (1995). In this method, for each waveform an analyst interactively chooses the period band of measurement, defines a group velocity - frequency filter used to remove unwanted signals, and assigns a qualitative grade to the measurement (A - F). The measurement is automatically obtained on the filtered waveform. About 6,100 3-component seismograms have been processed to date yielding surface wave dispersion measurements from less than 10 s to more than 300 s period. Because the average path length is about 5,900 km, measurements less than 20 s period are rare. Significant numbers of measurements have been accumulated from 20 - 225 s for Rayleigh waves and from 20 - 150 s for Love waves.

As can be seen in Figure 2, data distribution is not uniform, but it is quite good over most of Eurasia. The main exceptions are over India and the Middle East, particularly Saudi Arabia. More southerly events are being analyzed now to help correct this problem.

Data Reliability

There are two main reasons to make the very large redundant set of measurements we are obtaining here. The first is to optimize coverage and, hence, lateral resolution. The second is to use the redundancy in the data set to estimate data uncertainties and to reject outliers. In this latter regard, we perform what we call a 'cluster analysis'. Measurements whose path-endpoints lie within 2% of their path lengths are clustered to produce a measurement along a 'unique path'. The average velocity and standard deviation of the cluster is assigned to the unique path. An example of a cluster analysis is shown in Figure 3a. There are about 1100 Rayleigh clusters and 1000 Love clusters. As shown in Figure 3b, most clusters only possess 2 - 3 rays. The average standard deviation over all clusters, after outlier rejection, is shown in Figure 3c as a function of period. We associate this standard deviation with average measurement uncertainty (and this will be used later in Figure 7). The number of unique paths displayed as a function of period for Rayleigh and Love waves is shown in Figure 3d.

Group Velocity Maps

All dispersion measurements have been weighted by results obtained in the cluster analysis and have been used to estimate Eurasian group velocity maps. These maps represent the local group speed of a Rayleigh or Love wave propagating at a particular spatial point. Maps have been constructed for Rayleigh waves ranging between 20 - 225 s and Love waves from 20 - 150 s period. Included here are maps at 30 s, 50 s and 100 s period shown in Figures 4 - 6, respectively.

Cursory Interpretation

Group velocity maps can be interpreted directly, but only tentatively due to the complicated nature of the group velocity sensitivity kernels which can change sign with depth. Both Rayleigh and Love waves are dominantly sensitive to shear velocity, although Rayleigh waves are affected somewhat by compressional velocity as well. Generally, at a given period, Rayleigh wave sensitivity extends deeper than Love wave sensitivity and phase velocity sensitivity extends deeper than group velocity sensitivity. The eigenfunctions shown in the companion paper in this volume (Ritzwoller *et al.*, 1996; Figure 4) demonstrate the compression toward the surface as period decreases. For example, a 30 s Love wave in continental regions is trapped in the crust, insensitive to crustal thickness, but sensitive to crustal velocity variations and sedimentary thickness. Rayleigh waves at 30 s period also possess significant crustal sensitivity but are affected by Moho depth, similar to Love waves at 50 s period. Moho sensitivity maximizes for 50 s Rayleigh waves and 80 s Love waves. Rayleigh waves of 70 s period and greater penetrate into the upper mantle and provide significant information about subcrustal structures. Rayleigh waves at 200 s are sensitive down to about 400 km.

This information illuminates the maps shown in Figures 4 - 6. Space prohibits a detailed analysis, the maps are too rich in detail to discuss all their features here. We mention only a few features from these maps that characterize the types of structures that are constrained by them.

The 30 s Love wave map (most sensitive to shallow structures of the maps presented here) displays low velocity features at the major sedimentary depressions on the continent (e.g., Tarim Basin, Ganges Fan, Caspian and Black Sea Depressions, Barents Sea Depression, sediments in the Persian Gulf and Western Siberia). This map together with shorter period Rayleigh and Love wave maps will allow us resolve crustal from uppermost mantle structures in a way that longer period dispersion studies are incapable.

The 30 s Rayleigh wave samples the lithosphere similarly to the 50 s Love wave, being affected principally by crustal thickness and the integrated shear wave velocity in the crust. Their group velocity maps are consequently quite similar. The 50 s Rayleigh wave is most sensitive to crustal thickness and its group velocity map exhibits a strong correlation with surface tomography: continental roots create group velocity lows. This is particularly true in Central Asia and in the Middle East (e.g., Tibet, the Altai Range of western Mongolia, the Hindu Kush, and the Zagros Mountains in western Iran). At 100 s period, the Archaean shields reveal themselves clearly as continental roots.

The resolving power of this study is well demonstrated by inspecting the features of the group velocity maps in the Far East. The 'island arc' chain comprising Kamchatka, Japan, the Ryukus, and Taiwan is represented as a string of low velocity features at 30 and 50 s periods for both Rayleigh and Love waves. The back arc seas are seen as high velocity regions most clearly on the 30 s maps. On the 100 s Rayleigh wave map, however, the low velocities have shifted toward the back arc, presumably revealing a hot upper mantle continent-ward of the island arc. The ability to resolve island arcs from back arc seas is characteristic of the resolution of this study, ~ 500 km in many regions. Resolving power is considerably degraded in regions of large-scale structures that radically perturb ray paths, such as Tibet.

CONCLUSIONS AND RECOMMENDATIONS

This broad band surface wave dispersion study is important for three main reasons:

- Group velocity maps such as those presented here can be used to test emerging models. For example, Figure 7 presents accumulated continent-wide rms-misfit to the observed group velocity measurements of predictions from two recent global models (S12_WM13 of Su *et al.*, 1994; the combination of Crust 5.0 of Mooney *et al.*, 1996 with S16B30 of Masters *et al.*, 1996).
- A better shear wave lithospheric model under Eurasia is now being constructed. This model should prove useful to help improve location capabilities across the continent.
- This model should also form the basis for more detailed regional studies across the continent.

In the future, resolution can be improved further in three fruitful ways.

- Path corrections due to lateral refractions and multipathing should be incorporated in studying regions of large-scale significant structures (e.g., Iran, Afghanistan, Pakistan, N. India, W. China).
- Concentrated studies of shorter wave paths from regional events to regional networks should be performed in new areas (e.g., Ritzwoller *et al.*,1996 in Central Asia) where regional networks exist (e.g., Poseidon network in the Far East, GRSN in Europe, NARS in European Russia and the Ukraine, Saudi Arabian network, DoD arrays around Eurasia, PASSCAL deployments such as those in Tibet, near Baikal, and so forth).
- Multiple station studies that measure dispersion differences between stations can also be applied to yield sharper focus in regions with good regional instrumentation.

REFERENCES

Masters, G., S. Johnson, G. Laske, and H. Bolton, A shear wave model of the mantle, *Phil. Trans. Roy. Soc. Lond.*, in press, 1996.

Mooney, W.D., G. Laske, and G. Masters, CRUST 5.0: A global crustal model at 5 degrees by 5 degrees, submitted to *J. Geophys. Res.*, 1996.

Ritzwoller, M. H., A. L. Levshin, S. S. Smith, and C. S. Lee, Making accurate continental broadband surface wave measurements. *Proceedings of the 17th Seismic Research Symposium on Monitoring a Comprehensive Ban Treaty*, Phillips Laboratory, Scottsdale, AZ, 482-491, PL-TR-95-2108, Sept., 1995.

Ritzwoller, M. H., A. L. Levshin, L.I. Ratnikova, and D.M. Tremblay, High resolution group velocity variations across Central Asia, this volume, 1996.

Su, W.-J., R. L. Woodward, and A. M. Dziewonski, Degree-12 model of shear velocity heterogeneity in the mantle, *J. Geophys. Res.*, **99**, 6945-6980, 1994.

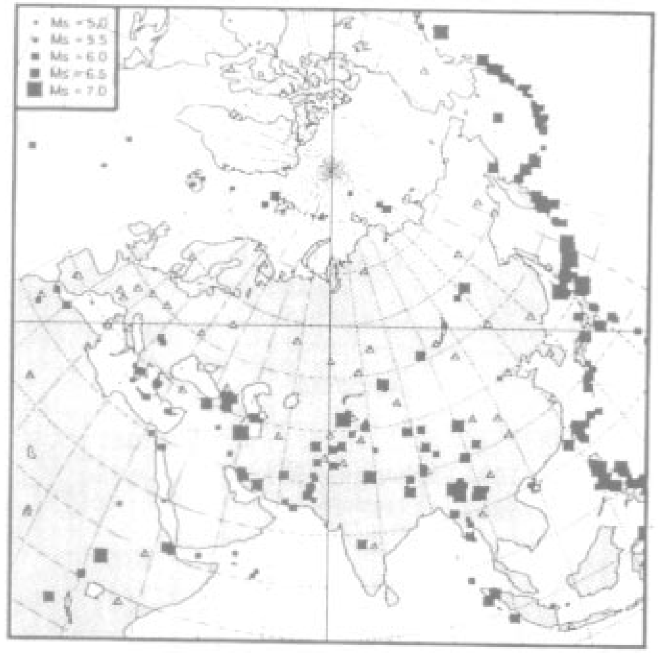


Figure 1. Distribution of sources (squares) and receivers from GSN, MEDNET, GEOSCOPE, KNET & KAZNET (triangles) used in the surface wave studies of Eurasia.

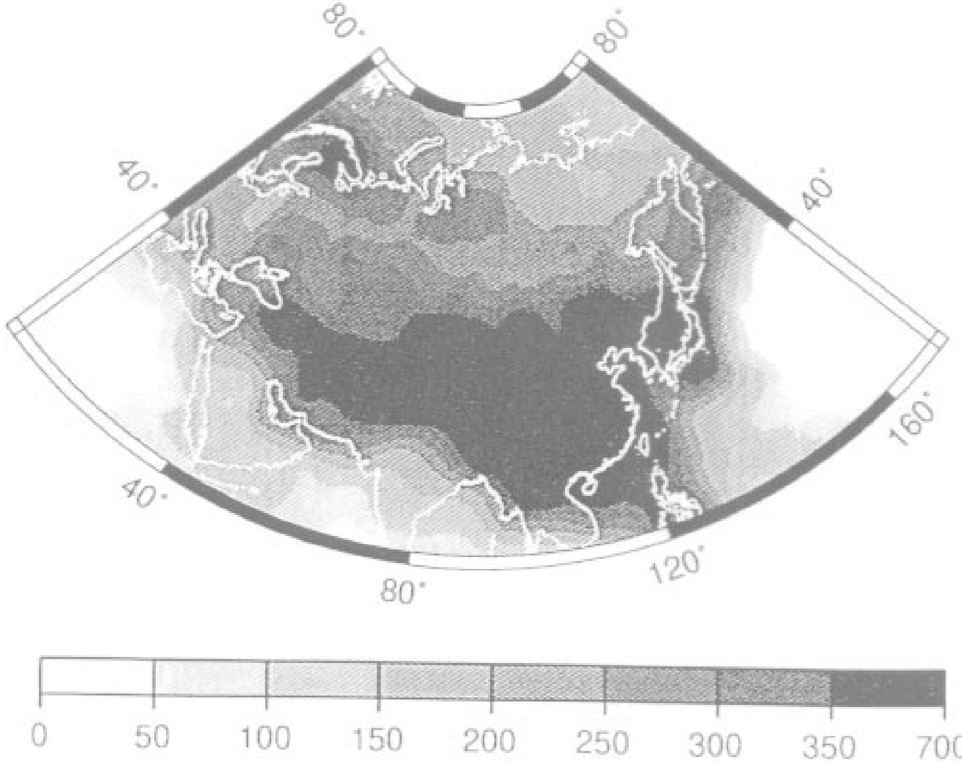


Figure 2. Density of Rayleigh wave paths crossing Eurasia, T =50 s.

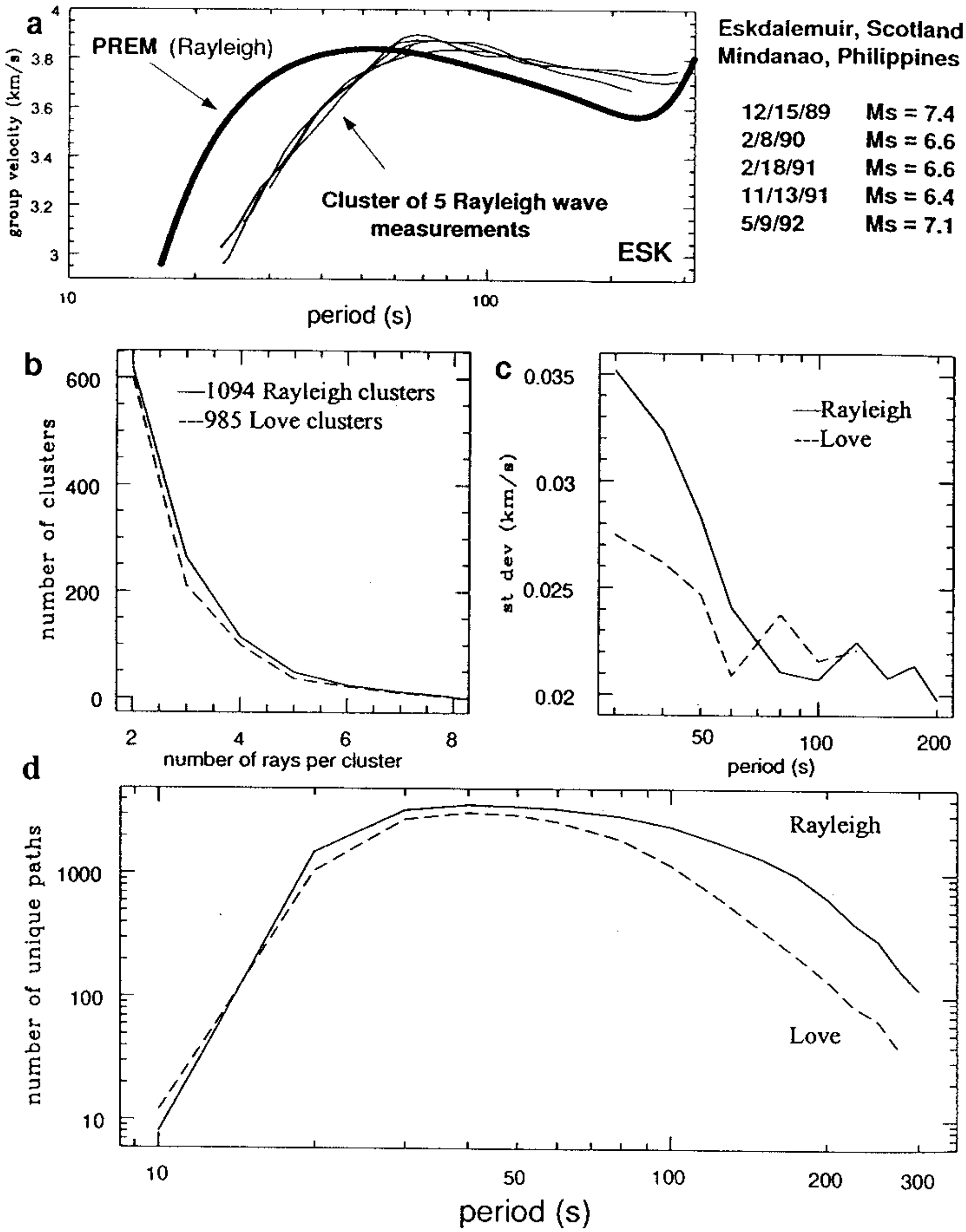


Figure 3. Cluster analysis. (a) Example of clustering for 5 events near Mindanao, Philippines, recorded at ESK, Scotland. (b)-(d) Results of cluster analysis.

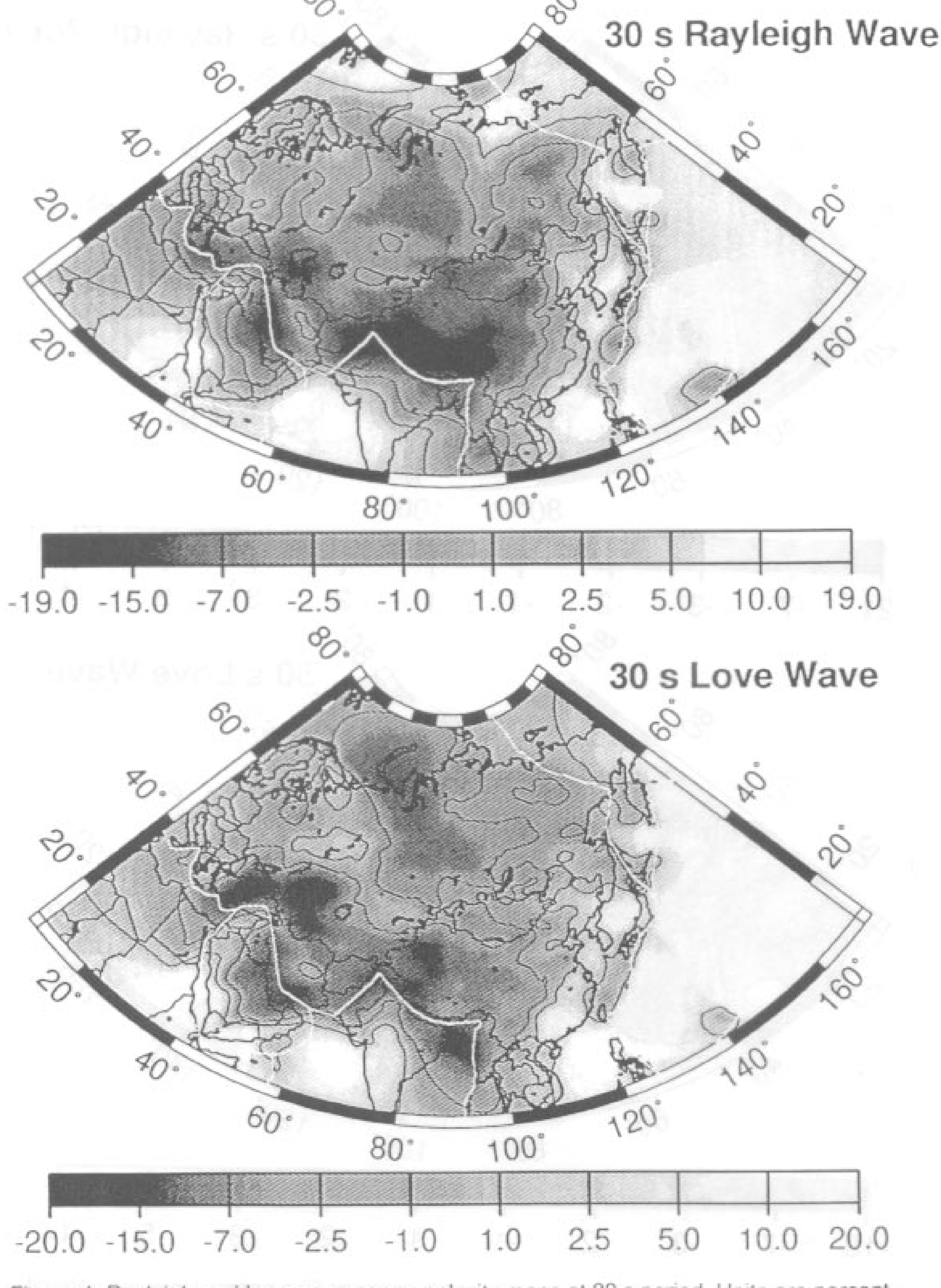


Figure 4. Rayleigh and Love wave group velocity maps at 30 s period. Units are percent deviation from the map average. The positive and negative 2.5% contours are drawn to highlight the regions of significant deviation from the map average.

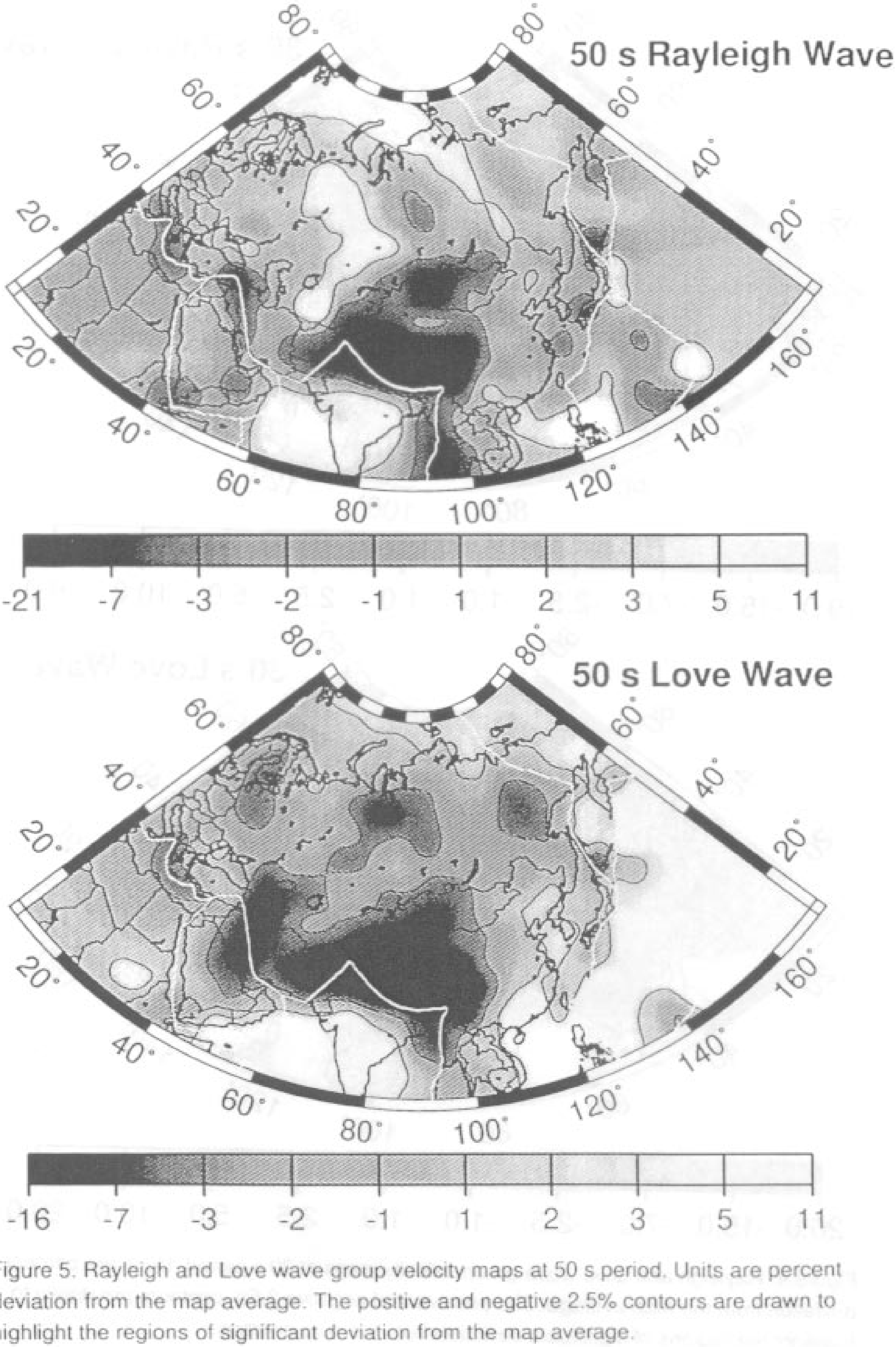
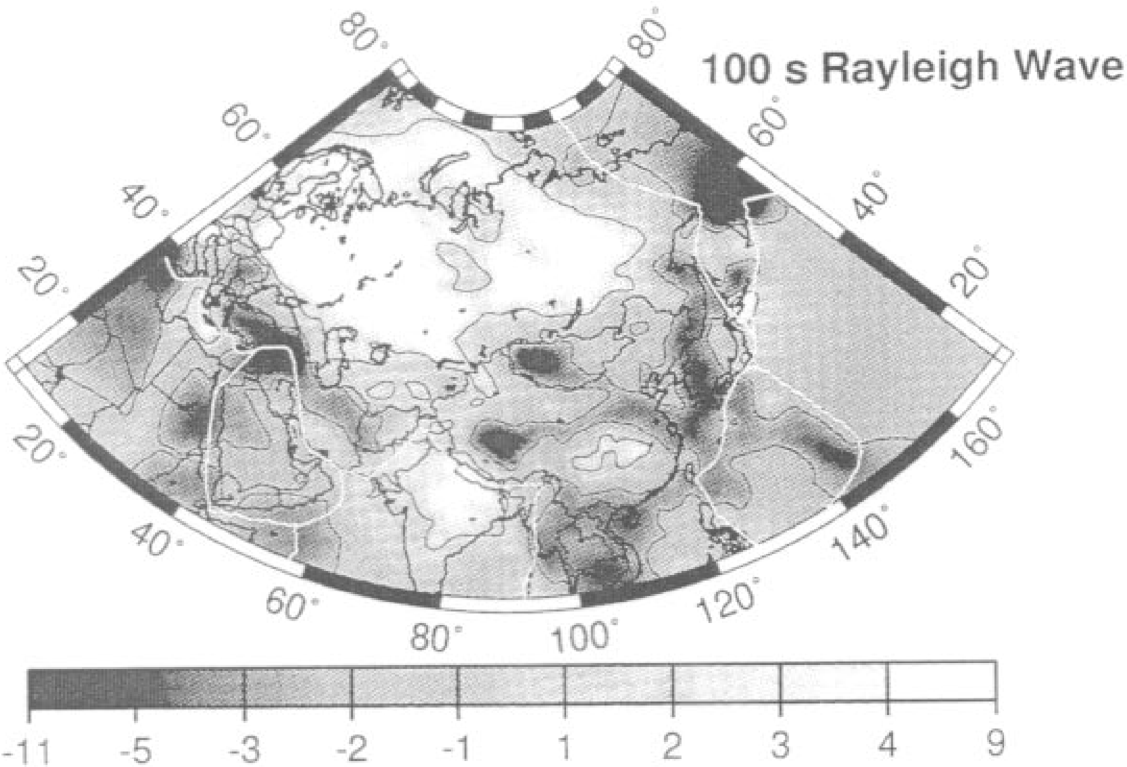


Figure 5. Rayleigh and Love wave group velocity maps at 50 s period. Units are percent deviation from the map average. The positive and negative 2.5% contours are drawn to highlight the regions of significant deviation from the map average.



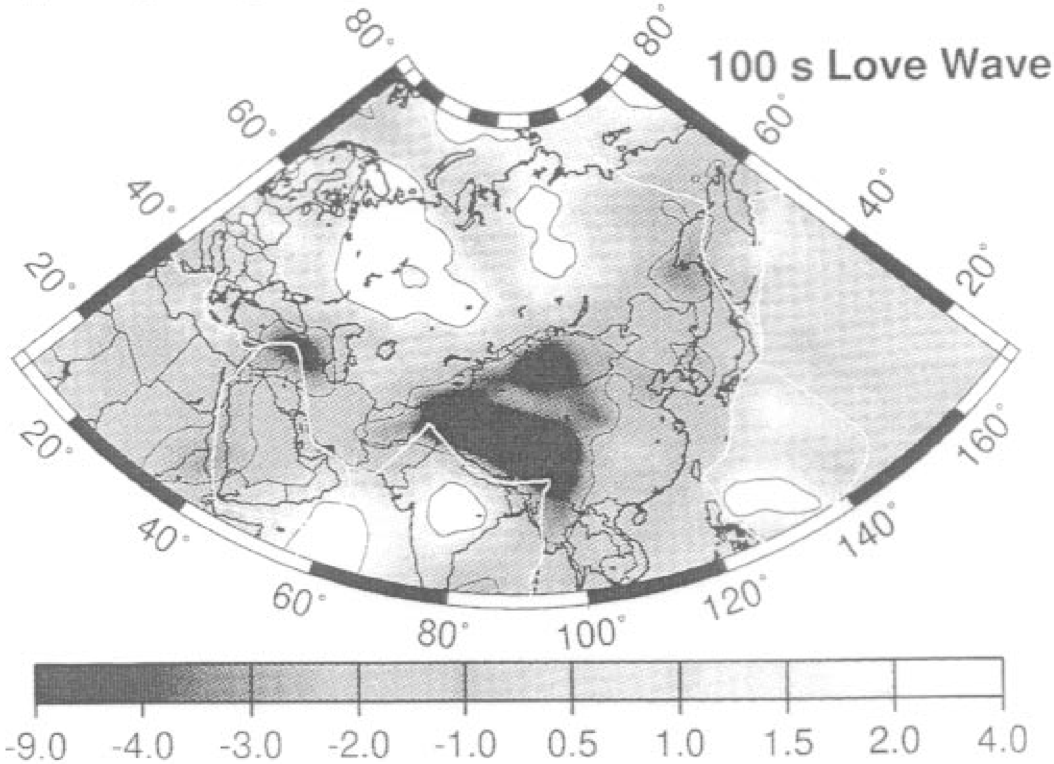


Figure 6. Rayleigh and Love wave group velocity maps at 100 s period. Units are percent deviation from the map average. The positive and negative 2% contours are drawn to highlight the regions of significant deviation from the map average.

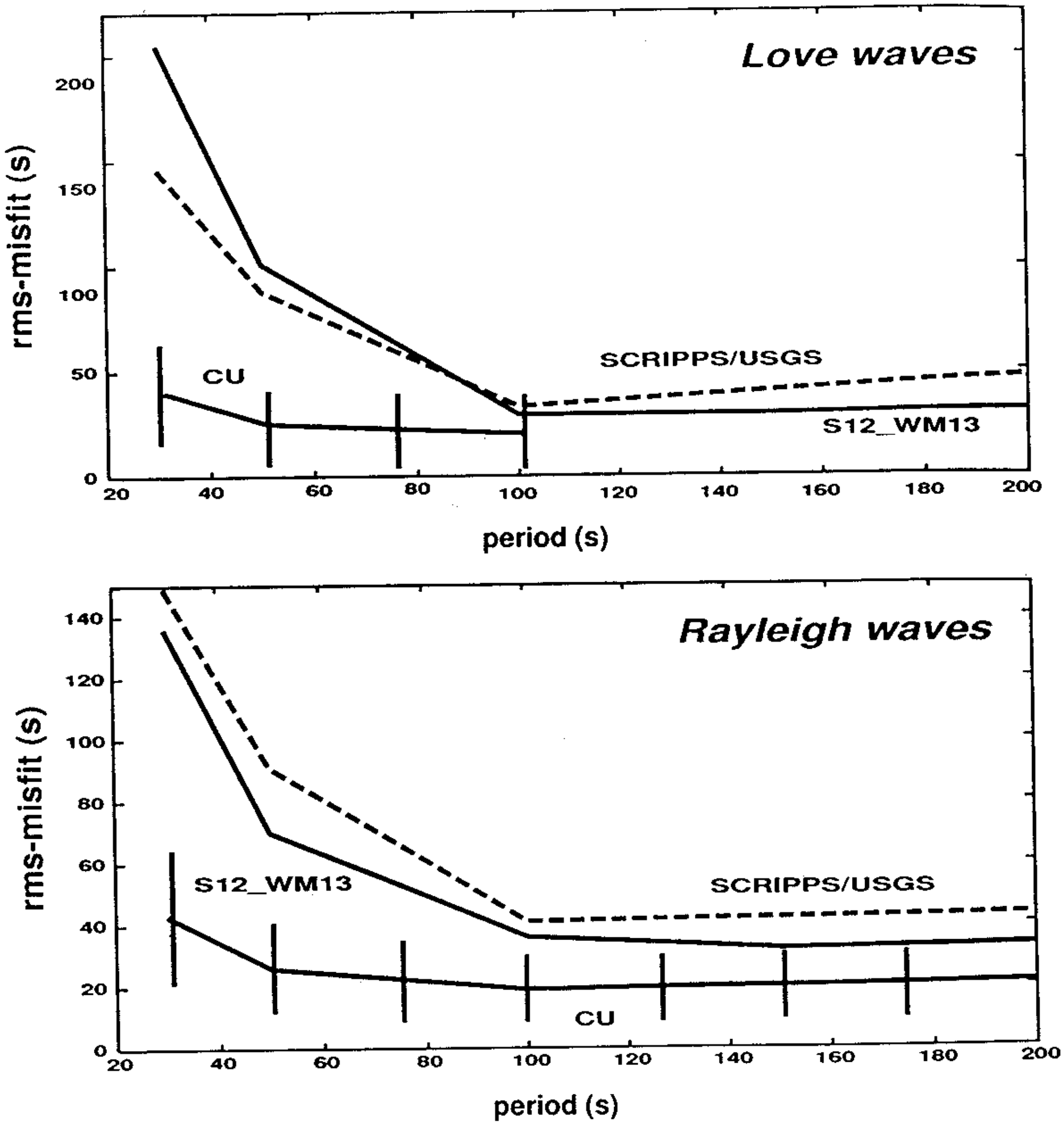


Figure 7. Total accumulated RMS-misfit over all paths between observed and predicted group times. Error bars for our measurements (CU) result from the cluster analysis and are centered at the misfit between observations and predictions from our group velocity maps. Misfit from two global models, S12_WM13 of Su *et al.* (1994) and the Scripps/USGS models S16B30/CRUST 5.0 of Mooney *et al.* (1996) and Masters *et al.* (1996), is also shown. The global models misfit the measurements significantly below about 100 s period where sensitivity is greatest to crustal structure and Moho topography.