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INTERMEDIATE PERIOD GROUP VELOCITY MAPS (15 - 30 s) ACROSS CENTRAL ASIA, WESTERN CHINA, AND PARTS OF THE MIDDLE EAST

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ABSTRACT

This paper presents a report on the status of a study of the dispersion characteristics of intermediate period broad-band fundamental surface waves propagating across Central Asia, Western China, and parts of the Middle East. We present Rayleigh wave group velocity maps from 15 s to 30 s period. (Love wave and longer period maps have also been constructed.) Broad-band waveform data from about 770 events from 1988 - 1995 recorded at 103 individual stations from 'global' (GDSN, IRIS/GSN, GEOSCOPE, CDSN) and 'regional' networks (MEDNET, KNET, KAZNET, Saudi Network) have been processed and produce about 11,000 paths for which individual dispersion curves have been estimated. Resolution is estimated from 'checker-board' tests and we report which regions at each period appear to have resolutions better than 5°. More than 80% of the studied region is resolved at 20 s and above, but resolution degrades at shorter periods so that we have little confidence in the 10 s group velocity maps and do not show them here. Resolution is far from uniform spatially, and is generally worst in NW Iran, India, the Arabian Sea, Egypt, and parts of Central and W. China. The misfit to the data from the estimated maps is about half the misfit from the crustal model CRUST-5.1 (Mooney, *et al.*, 1997). Many known geological and tectonic structures are observed in the group velocity maps. Of particular note are the signatures of sedimentary basins and crustal thickness variations due to mountain roots and deformation resulting from continental collisions. Work is proceeding to further improve the resolution and accuracy of the estimated group velocity maps in this and other parts of Eurasia. All of the measurements and group velocity maps are available at our web site. Shear velocity models that result from the dispersion maps are also at our web site and at Cornell University's Geophysical Database Server.

Keywords: Central Asia, Western China, Middle East, Tarim Basin, Lop Nor, Tibet, Iran, Saudi Arabia, Afghanistan, Pakistan, Kirgizstan, Kazakstan, surface wave dispersion, Rayleigh waves, Love waves, group velocity, M_s: m_b discriminant

OBJECTIVE

The objective of this research is to produce high resolution ($\sim 3° - 4°$) intermediate period (10 - 40 s) group velocity maps across Central Asia, W. China, and parts of the Middle East. These maps are designed to help identify Rayleigh wave packets in noisy seismic recordings so that more accurate amplitude measurements can be obtained for increasingly smaller events to be used as part of the $M_s : m_b$ method of discriminating explosions from earthquakes (e.g., Stevens and Day, 1985).

RESEARCH ACCOMPLISHED

Data Set

To date, Rayleigh and Love wave group velocity curves have been obtained from 770 events across Eurasia measured at 103 broad-band stations from the following networks: CNSN, CDSN, GEOCOPE, GSN, KAZNET, KNET, MEDNET, Saudi Network (Vernon *et al.*, 1996). Figure 1 summarizes the distribution of sources and receivers. Table 1 presents the number of Rayleigh wave measurements as a function of period for three subset of our data set: rays intersecting Eurasia, rays intersecting the region of study (shown in Figure 1), and rays contained within the region of study. The measurements come from a total of more than 11,000 paths across the continent. The method of measurement has been summarized at some length by Ritzwoller *et al.* (1995) and Ritzwoller and Levshin (1997). Ritzwoller *et al.* (1996a) and Ritzwoller *et al.* (1997) argued that in order to optimize resolution in a region, the azimuthal distribution of rays at each point in the region should be as uniform as possible. The use of measurements made for events which occur outside the region of study is important in optimizing the azimuthal distribution of rays in the region, and is the reason we have in the past and will continue to analyze data from large numbers of events outside the studied region. Our measurements are being used by other researchers in addition to ourselves (e.g., Stevens and McLaughlin, 1997).

Table 1. Number of Rayleigh Wave Measurements

period	*Eurasia*	*Intersecting Studied Region*	*Within Studied Region*
10 s	522	503	451
15 s	1388	1061	451
20 s	3486	2160	812
30 s	7866	4828	948
40 s	8523	5471	837

We have shown intermediate period (10 - 40 s) and broad-band (20 s - 200 s) group velocity maps in several recent papers (e.g., Levshin *et al.*, 1996; Ritzwoller and Levshin, 1997, Ritzwoller *et al.*, 1997). We have begun to add more data designed to improve the resolution of these maps across Central Asia, W. China, and the Middle East. New data processed in the summer of 1997 are of four types: (1) events in the region of study observed at high latitude stations in the Western Hemisphere (e.g., Canadian National Seismic Network); (2) events in and around Eurasia observed at GEOSCOPE stations around Eurasia; (3) events in and around Eurasia observed at GSN, CDSN, MEDNET stations around Eurasia, and (4) events in and around Eurasia observed at the nine-station Saudi Network. The most useful of these are data from the Saudi Network and from the GEOSCOPE station at Hyderabad, India. At the time of writing, about 2,000 new

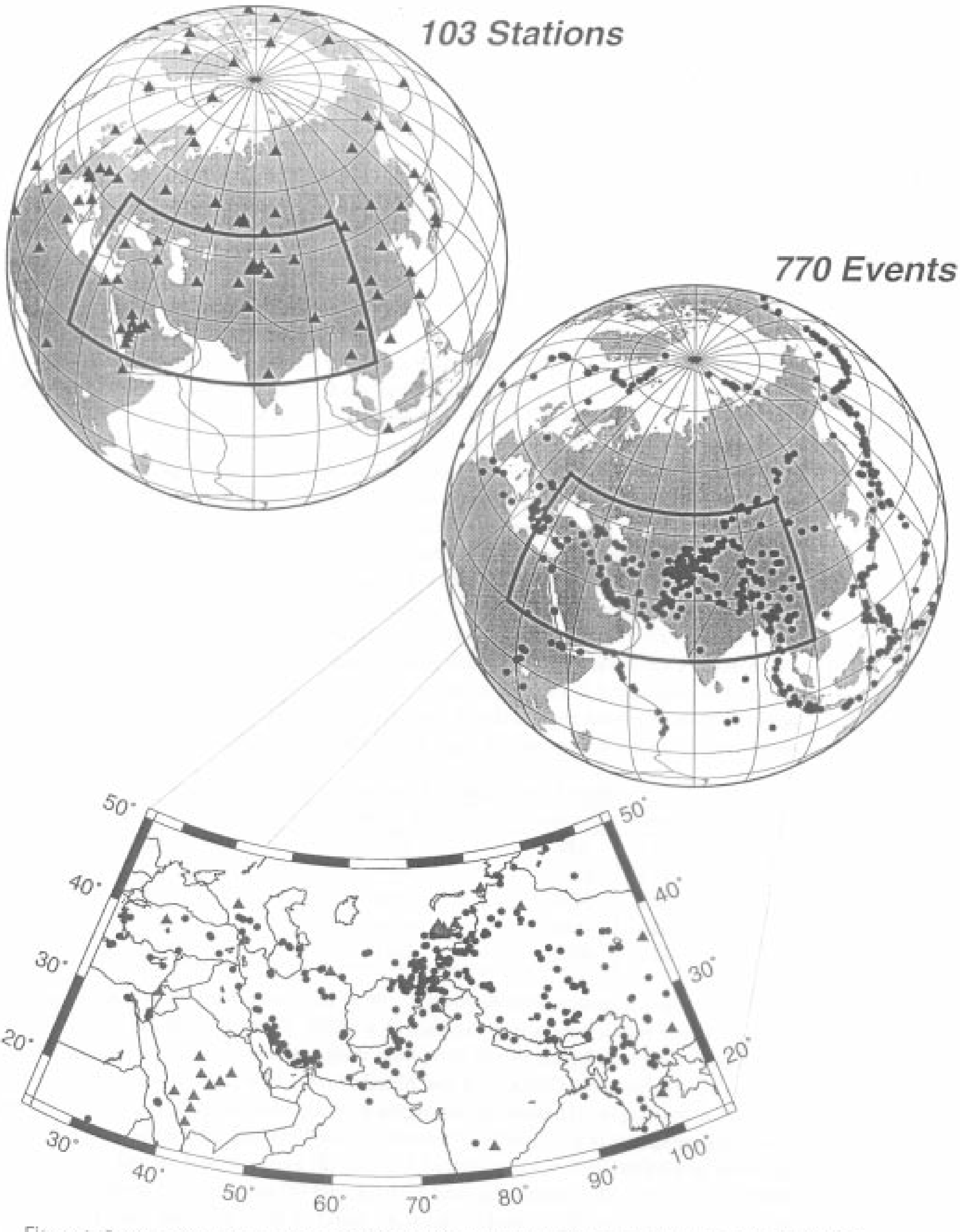

Figure 1. Stations and events used in this study. Stations come from the following networks: CDSN, GEOSCOPE, GSN, KNET, KAZNET, MEDNET, Saudi-Net.

paths have been added in the summer of 1997 and continue to be added. As shown in Figure 2, the addition of these data has significantly improved path density in Iran, Afghanistan, Saudi Arabia, India, and the Arabian Sea.

Analyses of the repeatability of measurements in summary rays or measurement clusters (similar starting and ending points of rays) indicate that measurement uncertainties are about 0.04 km/s at 20 s and 30 s period, and about 0.05 km/s at 15 s.

All of our measurements, sporadically updated, are available through our web site at:

http://phys-geophys.colorado.edu/geophysics/eurasia.dir/eurasia.html.

Resolution

To estimate resolution we perform a standard 'checker-board' test. Each model is divided into cells of equal area with each cell possessing a velocity perturbation of ±10% of the average across each map. Travel time perturbations are accumulated along the great circle linking each source and receiver. We estimate resolution as a function of wave type and period by computing synthetic travel times through the checker-board model for the paths and with the inversion method used to construct the group velocity maps. Checker-board plots at the resolutions of this study are difficult to interpret since the cells are very small. To simplify interpretation, we assign a 'Resolution Index', $\mathcal{R}_i$, to each cell:

$$\mathcal{R}_i = \frac{v_{\max}}{v_{\text{input}}} \qquad \text{(in percent)}. \tag{1}$$

Here, $v_{\max}$ is the estimated velocity perturbation whose absolute value is maximum in the cell and v_{input} is the input velocity perturbation in the same cell (±10%). Perfect resolution would result in $\mathcal{R}_i = 100\%$, poor resolution results in $\mathcal{R}_i \leq 30\%$. The resolution index can be less than zero if the sign of $v_{\max}$ is opposite from the input value of the cell or greater than 100% if the estimated magnitude is higher than the input.

Figure 3 displays the resolution index for 5° cells at three periods: 15 s, 20 s, and 30 s. The light grey areas indicate that the resolution in the area is estimated to be no worse than 5°. Resolution improves with increasing period. At 15 s, ~60% of the 5° cells that compose the region of study are resolved; at 20 s, 82% are resolved; and at 30 s, 89% are resolved. The Arabian Sea, India, NW Iran, E. Egypt, and parts of Central and NW China are the most difficult areas to resolve and are particularly problematic below 20 s period.

Group Velocity Maps

The method used to estimate group velocity maps is described at some length in Ritzwoller and Levshin (1997). Ritzwoller *et al.* (1997) argue that although many measurements of 10 s Rayleigh and Love waves are made, path distributions are not sufficiently homogeneous to construct useful group velocity maps for most of the region of study at 10 s period. Rayleigh wave group velocity maps are shown in Figure 4 for periods of 15 s, 20 s, and 30 s. Maps are displayed as the percent deviation from the average across each map: 2.856 km/s at 15 s, 2.960 km/s at 20 s, 3.265 km/s at 30 s period. Longer period and Love wave maps have also been constructed. Group velocity maps are also available through our web site.

The geological and tectonic interpretation of group velocity maps is discussed at some length by Ritzwoller and Levshin (1997) and Ritzwoller *et al.* (1997). The 15 s and 20 s Rayleigh waves are most sensitive to crustal velocity variations. In particular, low velocities result from known

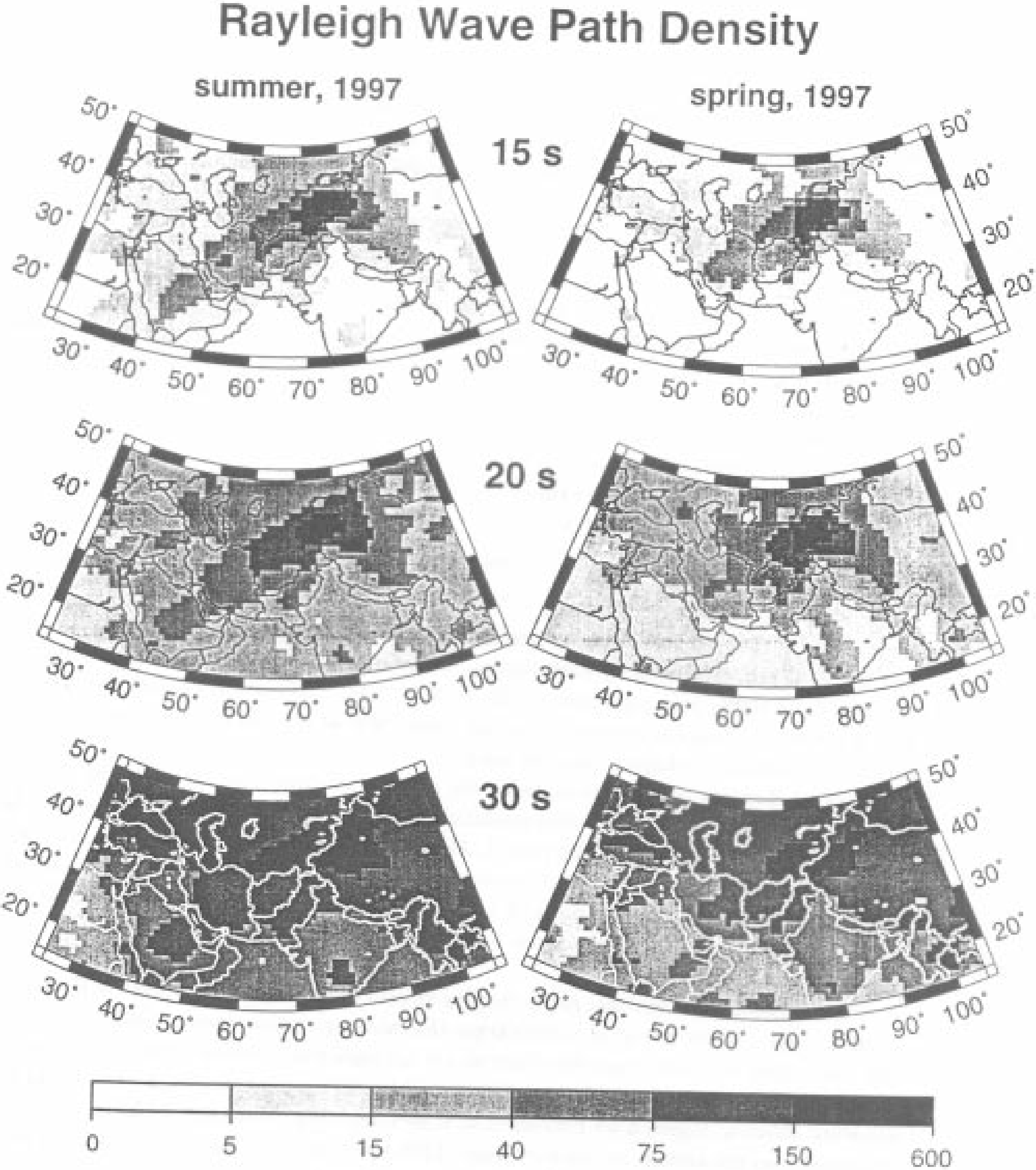

Figure 2. Path density for Rayleigh waves at three periods: (Top) 15 s, (Middle) 20 s, and (Bottom) 30 s. Path density is defined as the number of rays which touch each 2 degree square bin (~50,000 square km). The left column is path density including measurements made in the summer of 1997. These measurements include data from 140 events measured at the Saudi network and a large amount of new data from the GEOCOPE network, most importantly measurements made at Hyderabad, India. The right column displays path densities prior to the summer of 1997.

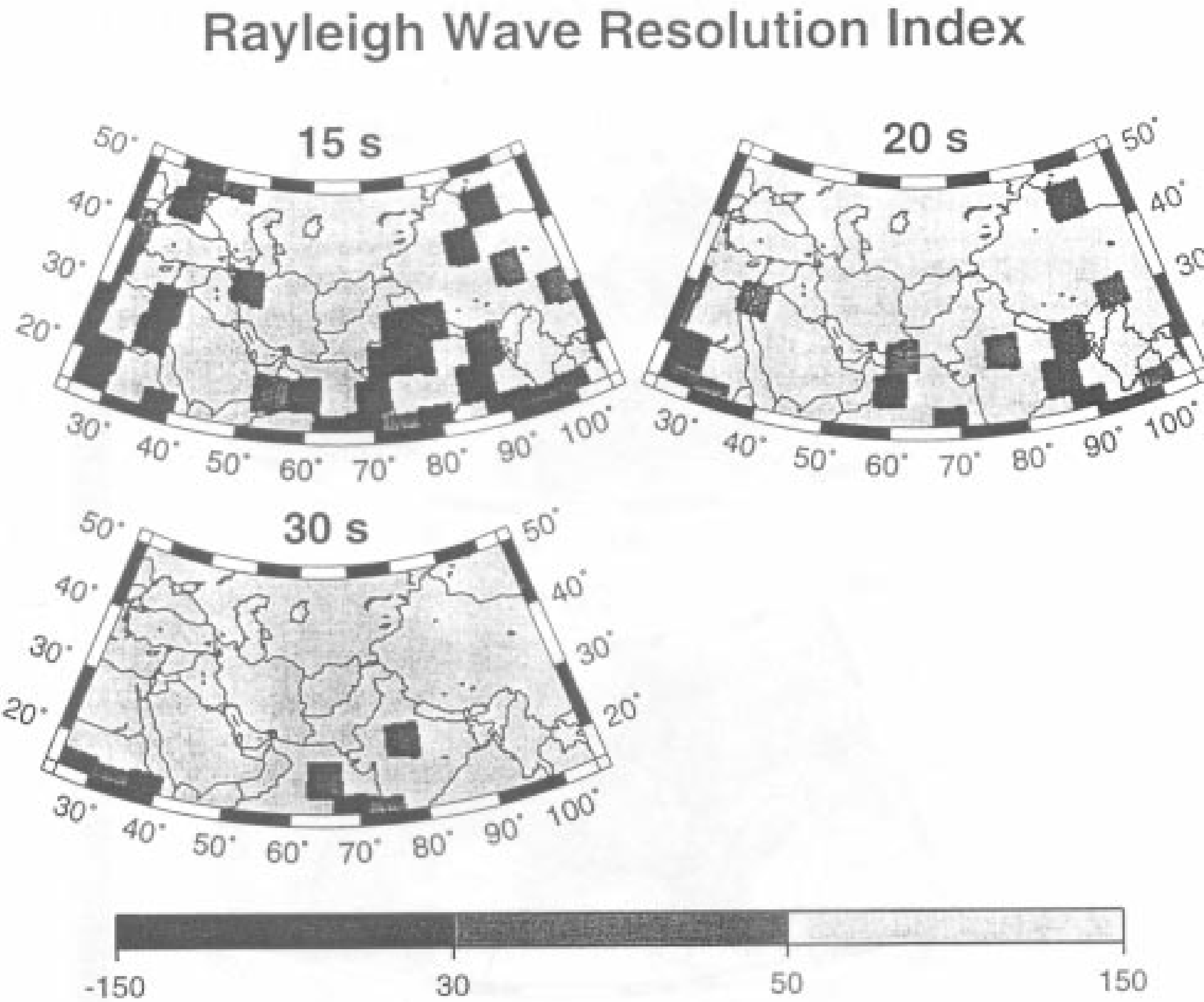

Figure 3. Resolution index (eqn. (1)) for the 15 s, 20 s, and 30 s Rayleigh waves and 5 degree cells. The grey-scale values are presented, the lighest indicates what we consider to be good resolution, increasingly dark cells reveal poorer resolutions.

sedimentary basins; e.g., Black Sea, E. Mediterranean, 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. By 30 s period, group velocities have become increasingly sensitive to crustal thicknesses, and the low velocities result dominantly from thickened crust under mountain ranges; e.g., Tibet, Pamir, Hindu Kush, Tien Shan, Zagros, etc.

Data Misfit: Comparison with CRUST-5.1

Table 2 presents misfit-statistics for three group velocity maps across the studied region. Misfit is defined as the RMS-difference between the group velocities predicted from each map and our group velocity measurements for those ray paths contained entirely within the region of study. The three maps are: (1) the average of our (CU) group velocity maps across the region of

Rayleigh Wave Group Velocity Maps

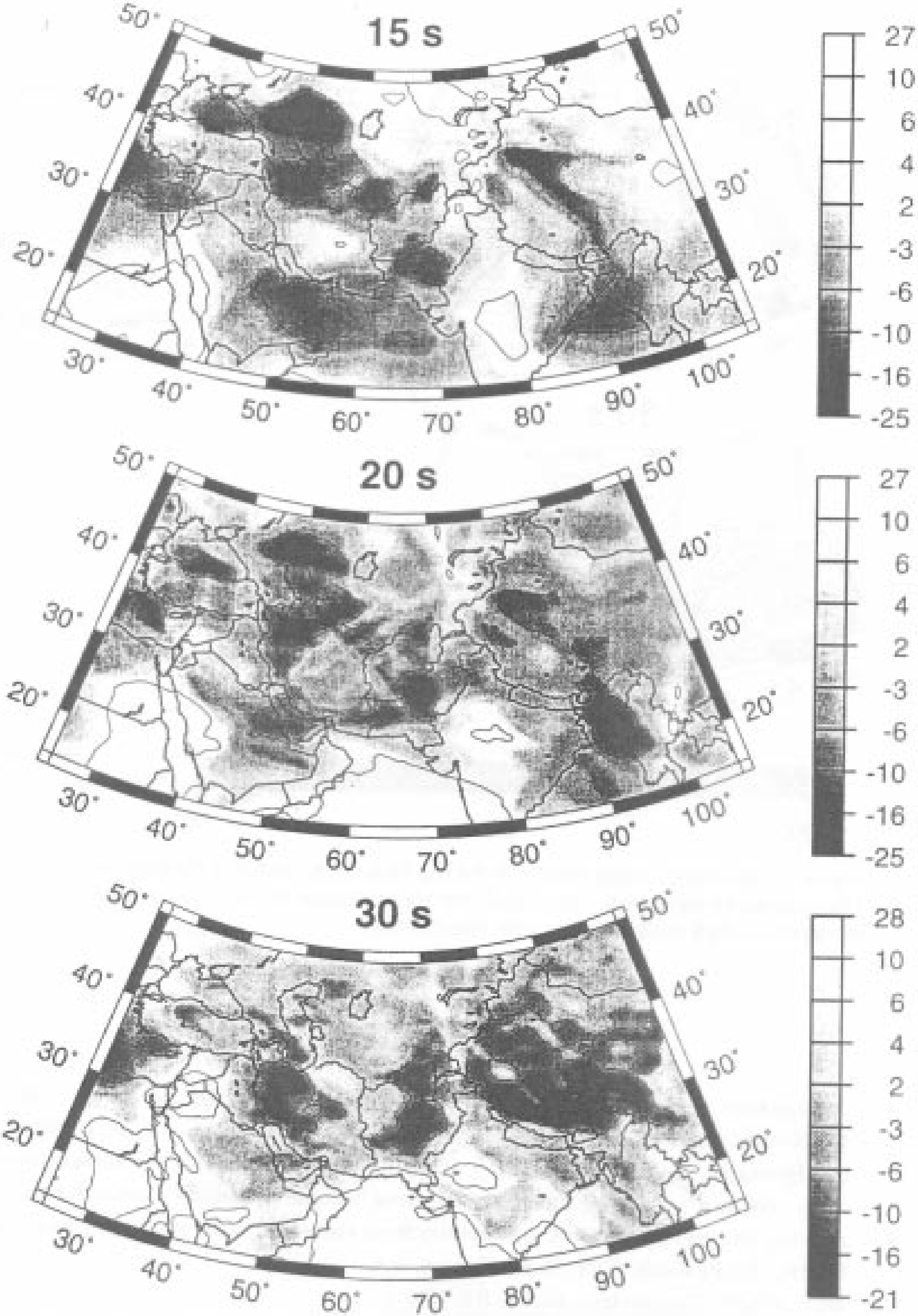

Figure 4. Group velocity variations at the indicated periods expressed in percent deviation from the average across each map (15 s: 2.856 km/s; 20 s: 2.960 km/s; 30 s: 3.268 km/s). The +/-10% contours are drawn.

study, (2) our group velocity maps, and (3) the maps derived from the crustal model CRUST-5.1 (Mooney *et al.*, 1997) together with the mantle model S16B30 (Masters *et al.*, 1997). The CU maps provide considerable improvement in the fit to the measurements relative to the reference model (CRUST-5.1/S16B30) and to the average velocity across the region. Our group velocity maps approximately halve the misfit relative to CRUST-5.1/S16B30 and to the average maps. Variance reductions relative to the average across the CU maps are listed in Table 3.

Table 2. RMS-Misfit of Group Velocity Maps to Group Velocity Measurements

period	*Average Across CU Maps*	*CU Maps*	*CRUST-5.1*
15 s	0.180 km/s	0.095 km/s	0.167 km/s
20 s	0.161 km/s	0.082 km/s	0.148 km/s
30 s	0.256 km/s	0.076 km/s	0.137 km/s

Table 3. Variance Reduction Relative to Average Across CU Maps

period	*CU Maps*	*CRUST-5.1*
15 s	72%	14%
20 s	74%	15%
30 s	91%	72%

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

We have provided a status report on the study of intermediate period (10 s - 40 s) Rayleigh wave group velocities 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 group velocity curves over other existing models.

For these reasons we believe that the group velocity maps that we are developing should be useful in the future 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., Ritzwoller *et al.*, 1996b). Our v_s model of Central Asia is available at our web site and from Cornell University's Geophysical Database Server (Seber *et al.*, 1996): http://atlas.geo.cornell.edu.

There are several key elements to estimating group velocity maps at these periods. First, regional earthquakes need to occur and there must be broad-band instrumentation in the region of study. Second, dispersion measurements must be performed carefully to separate the first arrival from coda and other interfering waves. Third, data from smaller earthquakes than those normally studied on continental or global scales need to be processed (i.e., $M_s \leq 5.0$). Finally, the regional measurements should be combined with measurements made on a larger spatial scale. The inclusion of measurements on paths that propagate more broadly across Eurasia provides greater homogeneity of coverage and azimuthal distribution across the studied region and appreciably improves resolution and accuracy.

Recommendations

The methods described should continue to be applied across the studied region and more generally across Eurasia to new and accumulating data in order to improve resolution and reliability further. In fact, this study is far from complete even across the studied region. For example, we have only analyzed data from small events ($M_s \leq 5.0$) at KNET and KAZNET. The analysis of data from small events recorded at GSN, CDSN, GEOSCOPE, Saudi Network, GEOFON, and PASSCAL installations across the studied region together with historical data before 1988 from the GDSN and ILPA networks, could improve path coverage substantially, particularly below 20 s period where the path coverage is most inhomogeneous. Substantial improvements can still be achieved in the most poorly resolved parts of the studied region; e.g., Northwestern Iran, India, etc.. The methods can also be applied successfully to other areas across Eurasia and to selected regions on other continents.

There remain several shortcomings with the methodology of this study that point the way for future technical enhancements. Most significantly, the use of phase information would help provide tighter constraints on crustal structures. In addition, off-great-circle propagation is significant at the periods studied here. Modeling it by ray tracing through phase velocity maps and potentially using polarization information are also obvious directions to help improve crustal models inferred from the dispersion maps.

The group velocity measurements, maps, and shear-velocity models that are resulting from this research are available at our web site and the models are also at Cornell University's Geophysical Database Server. In the future, research results such as these should be incorporated in data bases that are more commonly accessed by CTBT monitors to be used to help identify surface wave packets as part of, for example, the $M_s : m_b$ method of discrimination.

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