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# HIGH RESOLUTION INTERMEDIATE PERIOD (10 - 40 s) GROUP VELOCITY VARIATIONS ACROSS CENTRAL ASIA

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**13. ABSTRACT** *(Maximum 200 words)*
This research is dedicated to investigating the relevance and use of intermediate period (10 - 40 s) surface wave data in problems of detection, discrimination, and the accurate location of small events using regional array data. It is focused on the analysis of data from events throughout Central and Southern Asia within 27 degrees of the Kyrgyz Telemetered Seismic Network.
The main efforts during the 1 year time period covered by this report were directed to data collection and preprocessing, sofware development, measurements of surface wave characteristics, and constructing group velocity maps. More than 1400 wave paths for Rayleigh waves and 900 paths for Love waves have been used for this purpose. The spatial resolution of obtained maps is 250-400 km, and they exhibit many features related to local tectonic structures, unresolved by previous studies The inversion of these maps for the 3D shear-velocity structure of the region is in progress. Such models will provide the means to enhance existing detection and location capabilities in Central and Southern Asia.

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# Contents

# HIGH RESOLUTION INTERMEDIATE PERIOD (10 - 40 s) GROUP VELOCITY VARIATIONS ACROSS CENTRAL ASIA


## SUMMARY

This study is a companion to another study sponsored by the AFOSR (Levshin *et al.*, 1996). The companion study's purpose is to estimate a lithospheric shear velocity model across the entire continent of Eurasia with lateral resolutions lying between 500 - 750 km by using broadband (20 - 225 s) measurements of Rayleigh and (20 - 150 s) Love wave dispersion. The purpose of this study is to attempt to sharpen the focus further in the structurally complex regions of Central Asia (Iran, Afghanistan, Pakistan, southern republics of the FSU, and W. China) where significant off-pure-path propagation has degraded the resolution in the continent-wide study. This is accomplished in two ways. First, we use here much shorter paths which originate from smaller events ($Ms \geq 4.0$) and which have been recorded on regional arrays and networks (KNET, KAZNET, PASSCAL-Tibet, historical FSU) in addition to global stations (GDSN/GSN/CDSN, GEOSCOPE). In this way we significantly improved the spatial resolution of our data set in the target area. Second, shorter path lengths have resulted in dispersion measurements in large numbers down to 10 s period. These shorter period measurements appear robust and provide enhanced radial crustal resolution in Central Asia.

Using this data set, we have constructed group velocity maps from 10 s - 60 s period for both Rayleigh and Love waves. Although there is substantial agreement with the general features of the continent-wide dispersion maps discussed in the companion study, significant improvement in resolution is apparent in Eastern Iran, Afghanistan, Pakistan, the Central Asian Republics of the FSU, and Western China. Unfortunately, regional data coverage is far from uniform, and as a result, some parts of the maps obtained are smeared due to the lack of observations. To overcome this, we have combined continental-scale and regional-scale data into a single data volume and produced another set of group velocity images of Central Asia. Combining all available data, we were able to prevent smearing of the group velocity maps at areas where regional data do not provide the dense coverage and at the same time to preserve a good spatial resolution at areas with high density of regional paths.

The inversion of the obtained maps for the 3D-shear velocity structure of Central Asia is in progress.

## INTRODUCTION

The purpose of this research is to investigate whether the resolution of lithospheric (in particular crustal) shear velocity models in the structurally complex regime of Central Asia (Iran, Afghanistan, Pakistan, southern republics of the FSU, and W. China) can be improved relative to that achieved in continent-wide studies (e.g., Levshin *et al.*, 1996). To improve resolution, we have modified the observational protocol accepted in the continent-wide study in the ways listed below. Rayleigh and Love wave dispersion measurements are obtained:

- on a lowered period band (10 - 60 s period) which provides improved depth resolution;
- on shorter surface wave paths (average path length is less than 2,000 km contrasted with the 6,000 km average path length in the continent-wide study) which reduces uncertainties in path locations;
- from relatively small earthquakes ($M_s \geq 4.0$) more densely spaced in Central Asia than in the companion study;
- at regional networks and arrays (KNET, KAZNET, PASSCAL-Tibet, historical FSU) as well as global stations (GSN/CDSN, GEOSCOPE) in Central Asia.

A more sharply focused model of lithospheric shear velocities in Central Asia is useful in a variety of ways. Most significantly for a CTBT, accurate high resolution structural information is needed to improve location capabilities in the structurally complex regions of Iran, Pakistan, Afghanistan, Western China, and Northern India. Location error ellipses mainly quantify ignorance concerning the structure of the crust (sedimentary thicknesses and velocities, crustal velocities and Moho topography). Focused studies of intermediate period surface wave dispersion using regional earthquakes and seismic networks, such as the one described here, promise significantly improved crustal models on regional scales.

## 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*

The territory under study is constrained by latitudes $20^o$ and $50^o$ N and by longitudes $50^o$ and $100^o$ E. It includes Western China and Mongolia, Northern India, Nepal, Butan, Bangladesh, Iran, Afganistan, Pakistan, Kazakhstan, and the Central Asian Republics of the FSU. It contains dramatically different geographic and tectonic regimes: the highest mountain ranges of the world, like the Himalaya, Tien Shan, Karakorum, Hindukush; high mountain plateaus, like Tibet and Pamir, parts of Kazakh and Indian shields, the Caspian Sea, etc. Differences in altitudes reach more than 8 km. To study the crustal and upper mantle structures of this territory we have used records of 340 events with $Ms \geq 4.0$ and at depths $\leq$ 100 km which occured there since 1980 through late-1995 (Figure 1). Records obtained by 51 stations (Figure 2 and Table 1) from global and regional networks have been analyzed. Epicenters of all selected events, as well as all selected stations, were lying inside within 27 degrees of the GSN station AAK (Ala-Archa, near Bishkek, Kyrgyzstan, at $42.63^o$N, $74.48^o$ E).

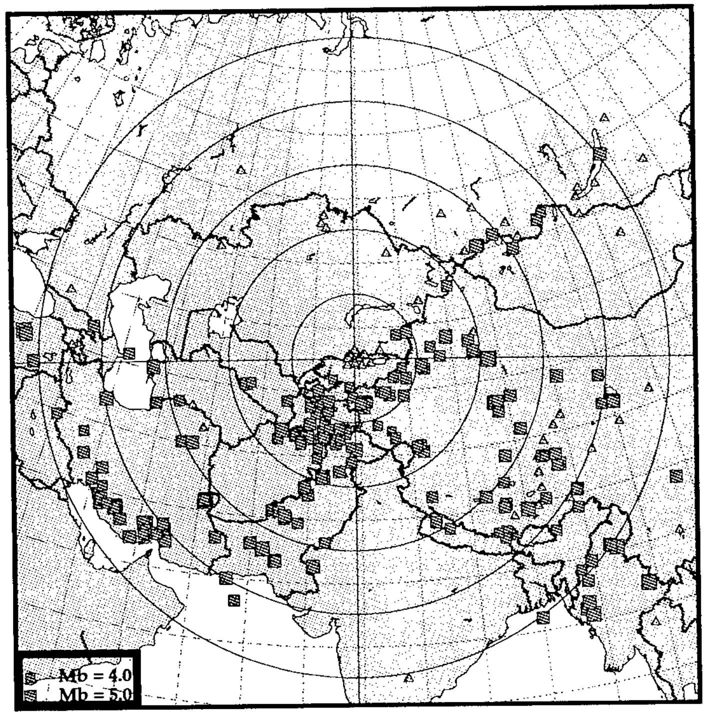



Figure 1. Distribution of sources (squares) and receivers from GSN, GEOSCOPE, KNET, KAZNET, PASSCAL & FSU networks used in the surface wave studies of Central Asia

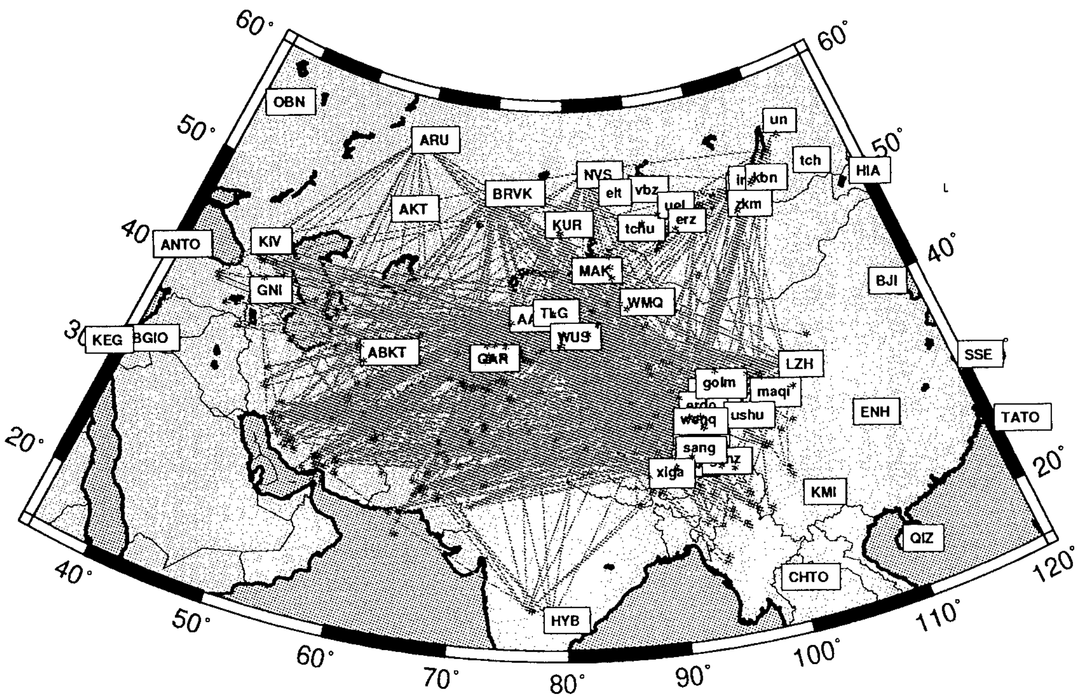



Figure 2. Source - station paths used for tomographic inversion of Central Asia group velocity data

Group velocity measurements for most of the records (including records of GSN/CDSN, GEOSCOPE, KNET and KAZNET) have been done using the technique described in detail in our previous reports and paper. ( Ritzwoller *et al.* (1995) and Levshin *et al.* (1996)). Part of the measurements related to the PASSCAL-Tibet Experiment (Owens *et al.*, 1993) and some CDSN records have been provided by F. Wu (Wu *et al.*, 1994, 1996). Measurements obtained from digitized analog records of the FSU network were provided by V. Kozhevnikov (Kozhevnikov & Barmin, 1989). The use of group times rather than phase times allows us to use earthquakes for which there is no detailed source information beyond a location estimate. Phase velocity measurements require moment tensor estimates.

More than 1400 vertical component records and 900 transverse component records were analyzed. The path number density for Raileigh and Love waves is displayed in Figures 3a,b. Path number density peaks in Kyrgyzstan where KNET (e.g., Vernon, 1994; Pavlis *et al.*, 1994) is located, but is also quite good in Eastern Iran, Afghanistan, Pakistan, Northernmost India, and Western China.

The existence of regional networks such as KNET and KAZNET (Kazakhstan Network, Kim *et al.*, 1995) allows for detailed reliability studies across the network to be performed which are impossible using global stations alone.

Due to the clustering of many events in relatively small seismically active zones, and the dense deployment of KNET and KAZNET stations within corresponding networks, this data set exhibits considerable redundancy, which allows for consistency tests, outlier rejection, and error estimation. Measurements whose path-endpoints lie within 2% of their path lengths are clustered to produce a measurement on a 'unique path'. The average velocity and standard deviation of the cluster is assigned to the unique path. The number of unique paths is period dependent, peaking at about 850 for Rayleigh waves and 550 for Love waves at 25 s period and falling to smaller numbers at shorter and longer periods (Figure 4). An average path length is on the order of 1900 km (contrasted with the 6000 km average path length in the continental scale study). This information is summarized in Table 1.

**Table 1. Origin of Data (All within 27$^o$ of KNET)**

| *Network* | *Number of stations* | *Number of events* |
|---|---|---|
| GSN/GDSN | 13 (3 CDSN) | 61 |
| GEOSCOPE | 2 | 9 |
| KNET | 11 | 191 |
| KAZNET | 7 | 37 |
| PASSCAL (Tibet) | 11 | 21 |
| FSU | 7 | 21 |
| Total | 51 | 340 |

Figure 6 illustrates the use of regional network data, KNET here, to estimate uncertainties in dispersion measurements.

*Construction and Interpetation of Group Velocity Maps.*

All dispersion measurements have been weighted by the results of the cluster and reliability studies discussed above, and have then been used to estimate the Central Asian group velocity maps. The technique of 2D-tomographic imaging of group velocity data used for the map construction has

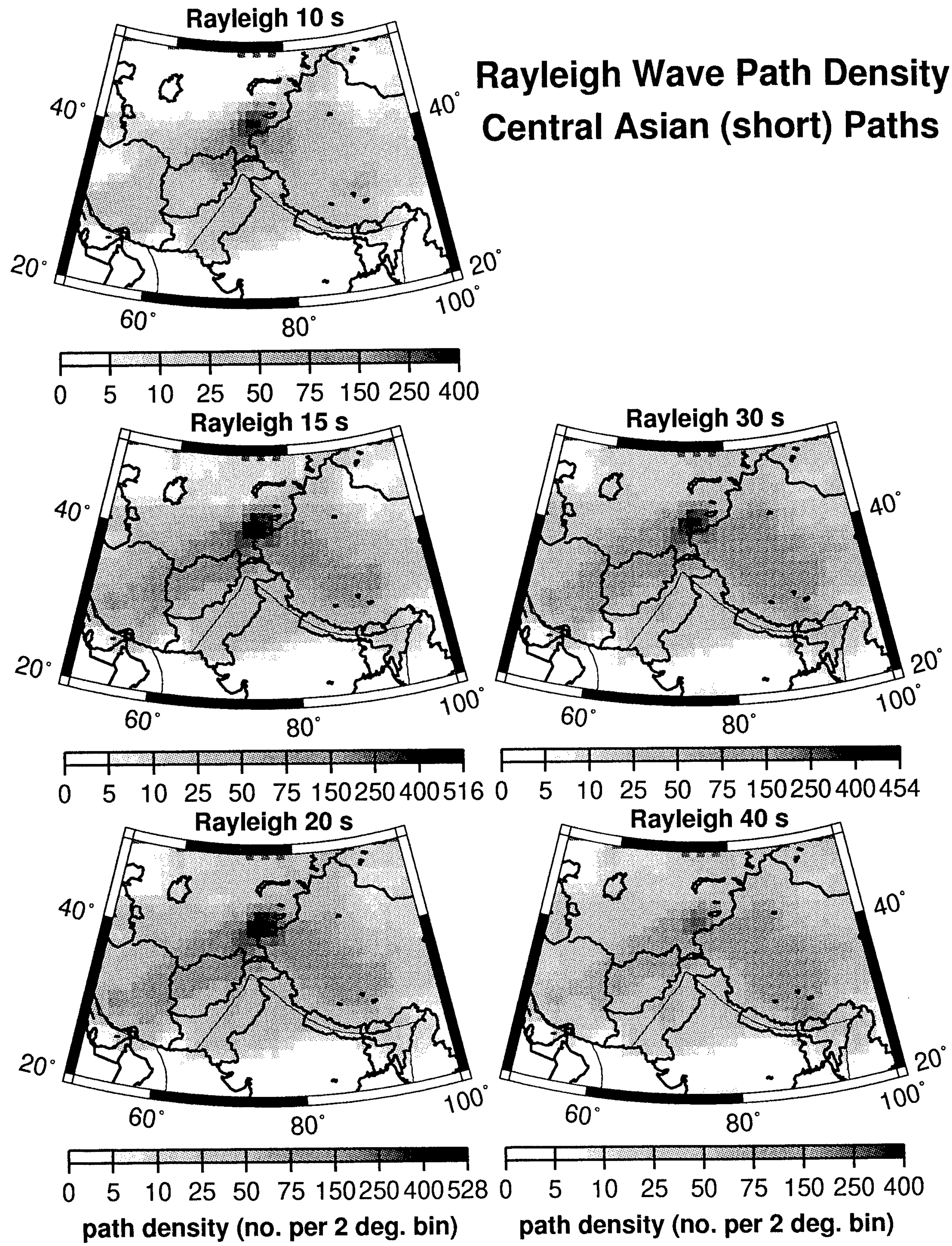



Figure 3a. Path density for (short) paths confined to Central Asia. Path density is defined as the number of paths in a 2 degree square bin (~50,000 sq. km).

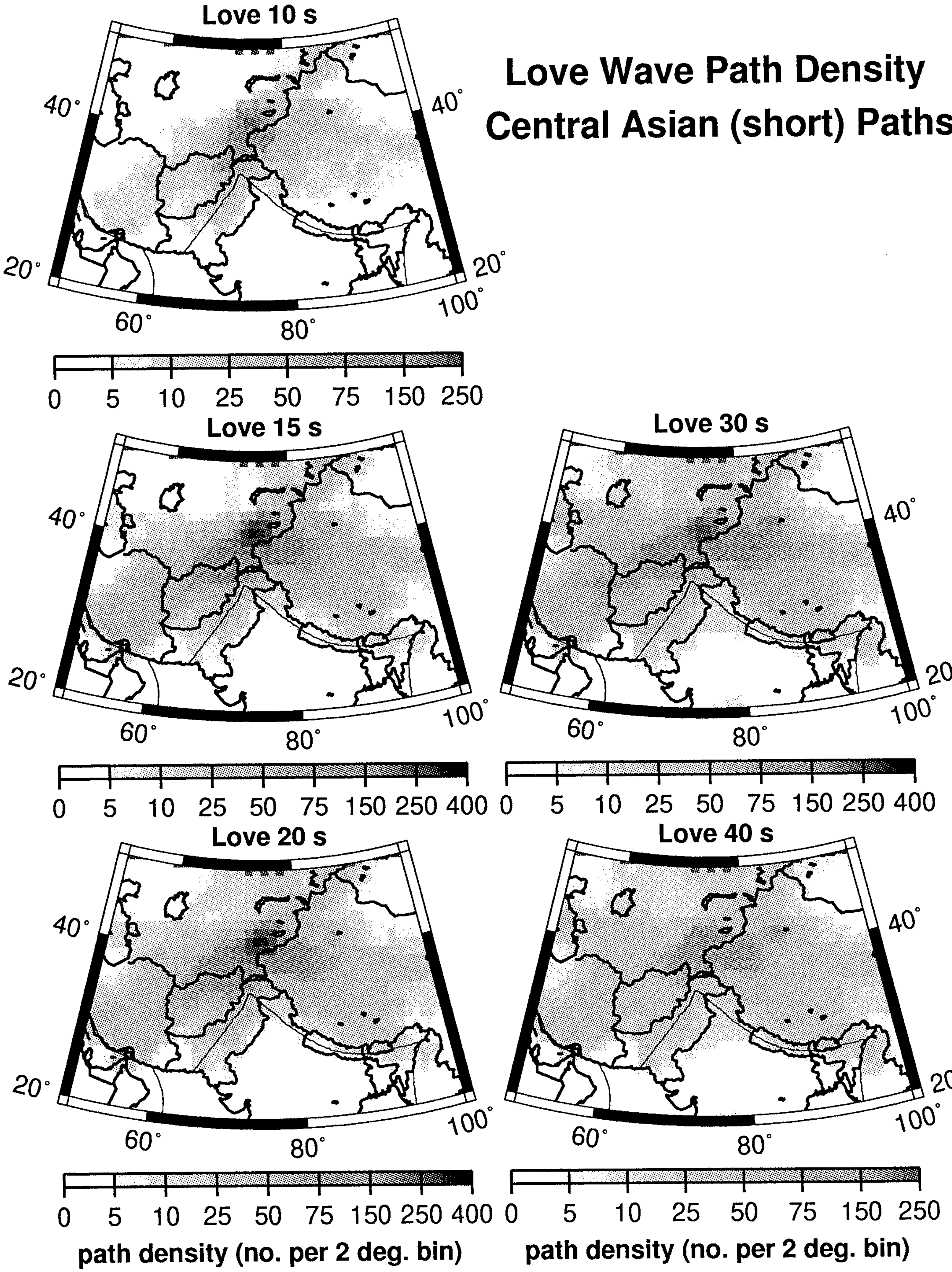



Figure 3b. Same as Fig. 3a, but for Love waves.

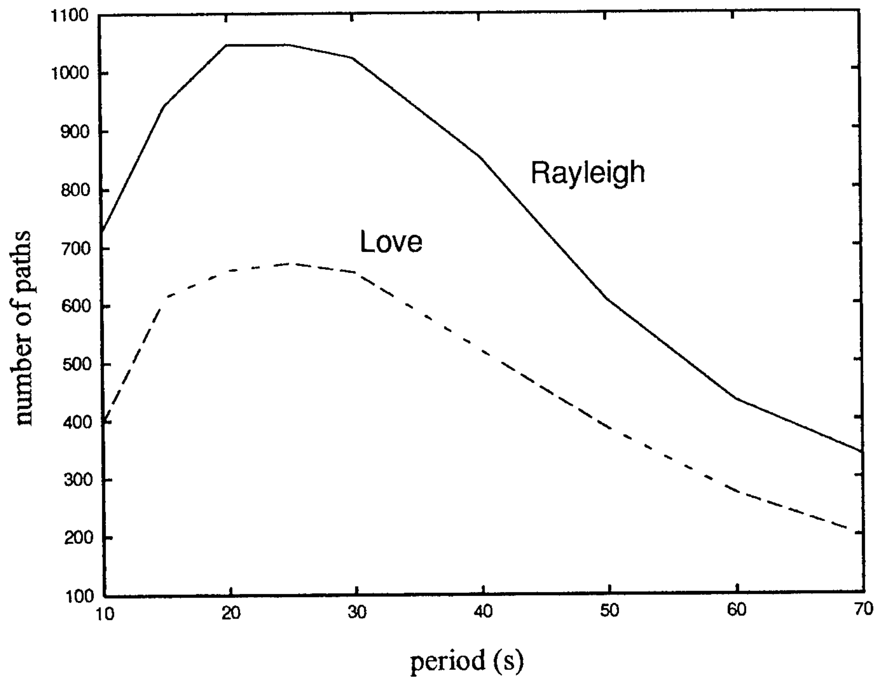



Figure 4. Number of surface wave paths as a function of period.

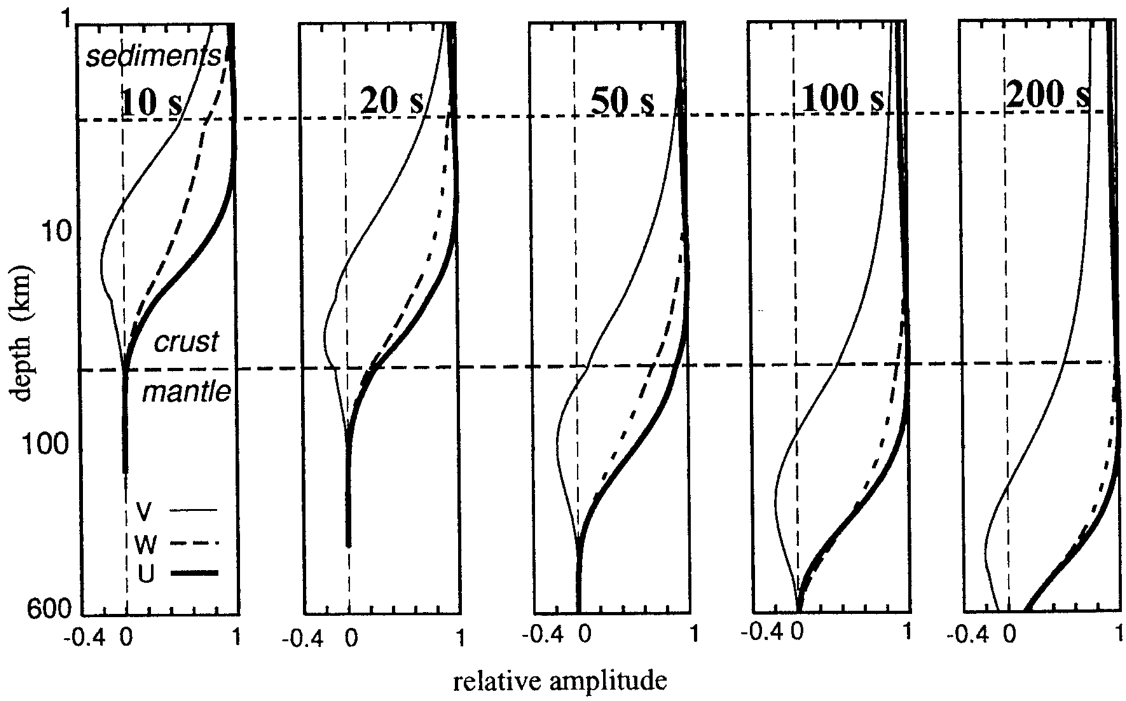



Figure 5. Eigenfunctions of Rayleigh (U, V) and Love (W) waves for different periods in the continental Earth model.

been described earlier (Yanovskaya & Ditmar, 1990; Wu & Levshin, 1994). These maps represent the local group speed of a Rayleigh or Love wave of a given period propagating at a particular spatial point.

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 Figure 4 demonstrate the compression toward the surface as period decreases. Short-period surface waves ($T \leq 10$ s ) are very sensitive to the thickness of sediments and shear velocities in the upper crust. 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 a 30 s period also possess significant crustal sensitivity but are affected by Moho depth, similar to Love waves at a 50 s period.

*Group Velocity Maps Based on Regional-scale Data.*

Let us first consider maps obtained using only regional data. Maps have been constructed for Rayleigh and Love waves ranging between 10 - 60 s periods. Included here are maps at 10 s, 20 s, 40 s periods shown in Figures 7 - 9, respectively. There are several interesting features which are seen in the central part of these maps, approximately between latitudes $25^o - 42^o$ N. Several high velocity spots can be associated with the Pamir and Southern Tibet, and low velocity features are related to the Caspian Sea , the Afgan-Tajik depression, the Tarim Basin and the Indus Delta. The size of some of these features is quite small, on the order of $2 - 3^o$. As the period increases some of them persist indicating that the observed anomalies reflect variations in the deeper parts of the crust. The general similarity of maps for Rayleigh and Love waves of close periods is evident. As these observations are independent, it gives additional support for the credibility of observed features inside the mentioned latitude limits. At the same time some of observed anomalies outside the limited area look suspicious, like low velocities at 20 s in the Northern part of the Arabian Sea where high velocities in the oceanic type crust should be expected. The reason for doubts is quite evident. As is seen in Figures 2 and 3 the regional path coverage is highly nonuniform and rather poor at the most southern part below the latitude $25^o$ N, and the most northern part above the latitudes $42 - 43^o$ N. This lack of data produces the smearing and artifacts at these parts of the studied territory. To overcome these effects, we combined the continental-wide data set from the companion study (Levshin *et al.*, 1996) including more than 7000 additional, comparatively long paths together with a regional data set for the same range of periods. As can be seen in Figures 10a,b the coverage at the 10 s period was not improved by this combination, and the coverage at 15 s became slightly more dense only for the northern part of the region. It is understandable, because due to the long propagation range these periods are poorly represented in the continental-wide data set. However, for periods 20 s and above the improvement in coverage is very significant.

*Comparison of Group Velocity Maps Based on Different Data Sets*

Figures 11 - 13 demonstrate the differences between group velocity images obtained using data of a different scale. Maps for periods 15, 20, and 30 s are shown. As could be expected, 15 s maps for regional and combined data are quite similar. The most prominent low velocity

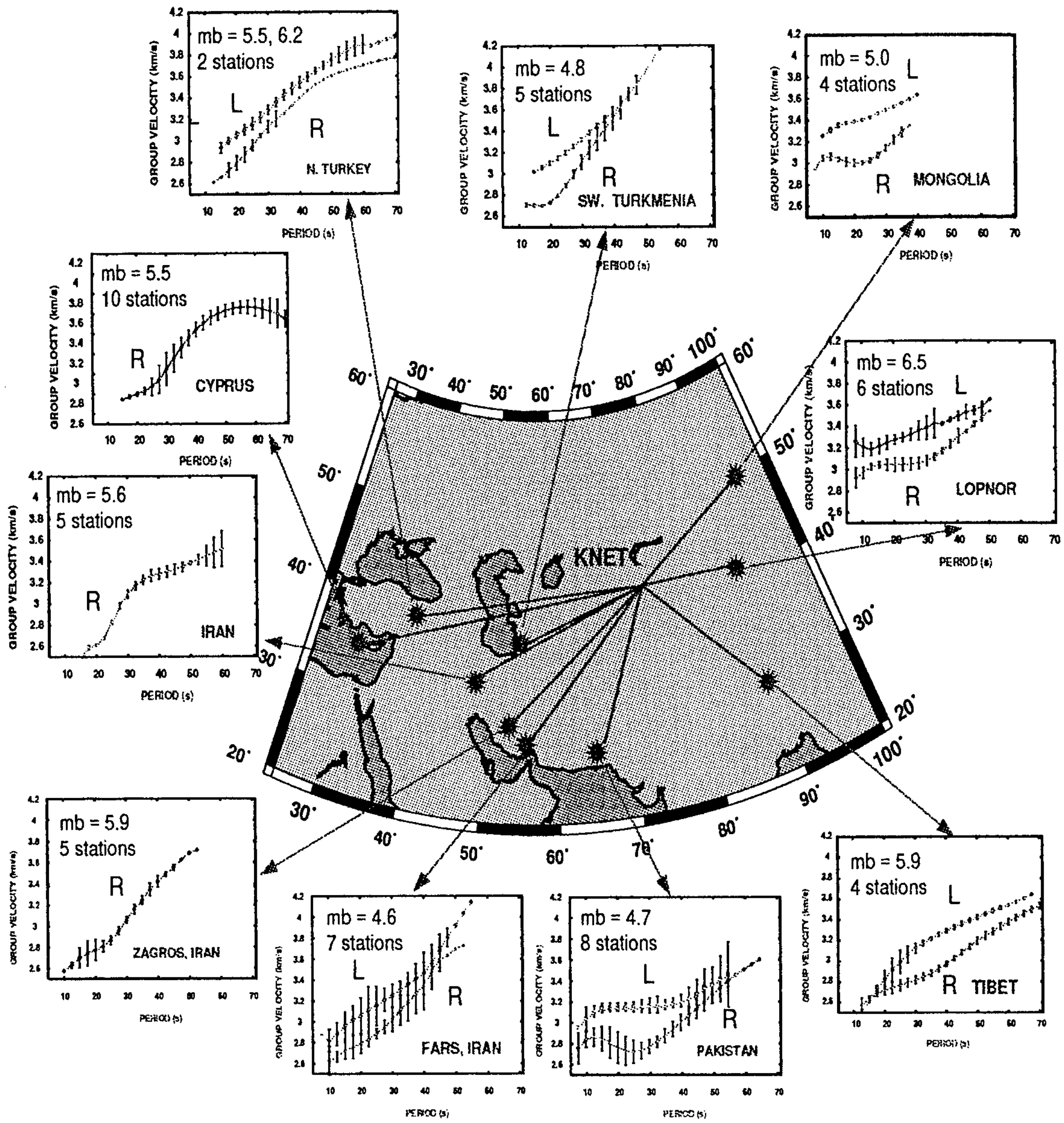



Figure 6. Group velocity variability across KNET is presented for Rayleigh (R) and Love (L) waves. One standard deviation 'error bars' are shown at periods where measurements from at least 3 stations exist, in order to represent variability observed for a variety of source regions around Central and Southern Asia.

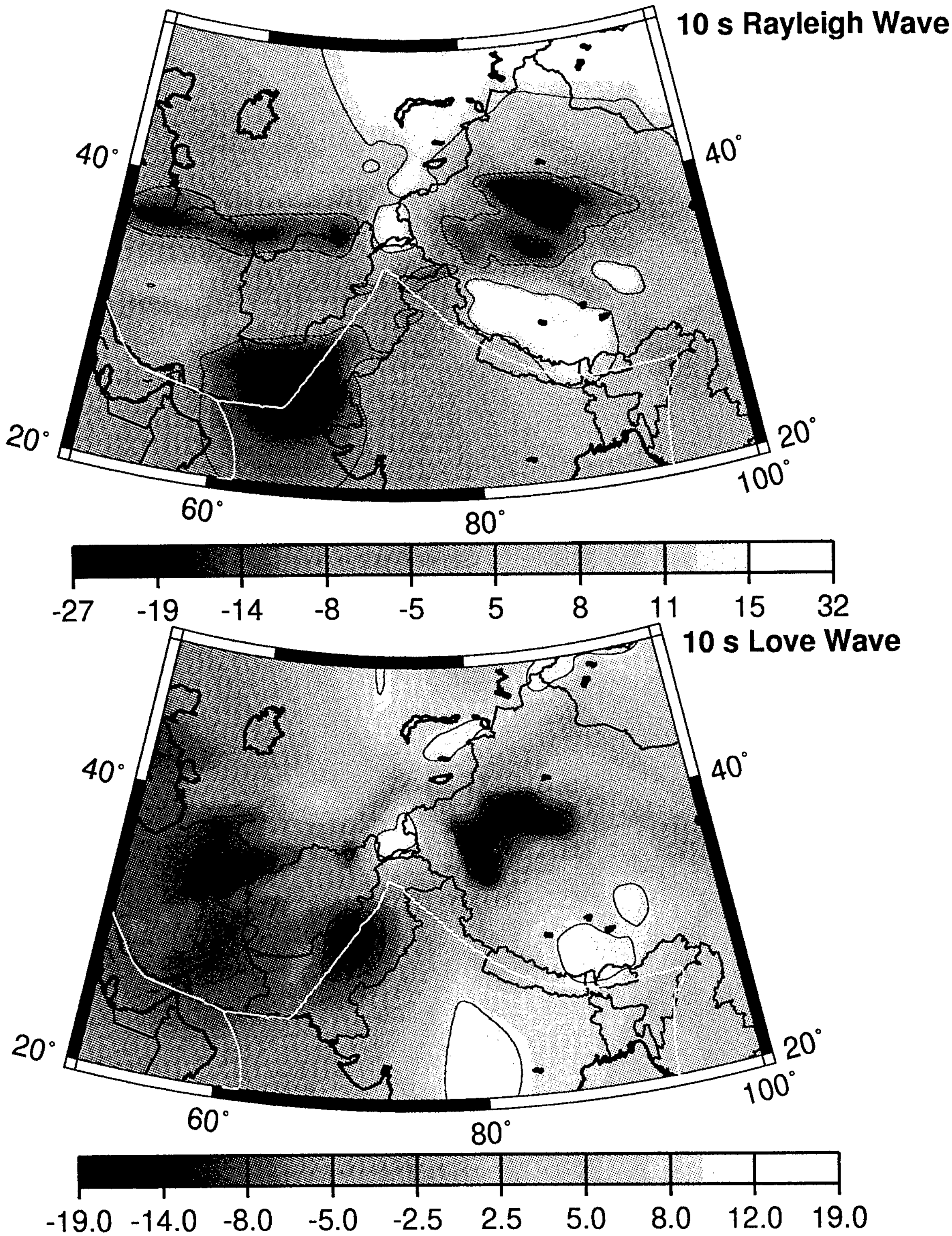



Figure 7. Rayleigh and Love wave group velocity maps at 10 s period. Units are percent deviation from 2.705 km/s for Rayleigh waves and 3.070 km/s for Love waves. The +/-10% contours are drawn to accentuate the high and low velocity regions.

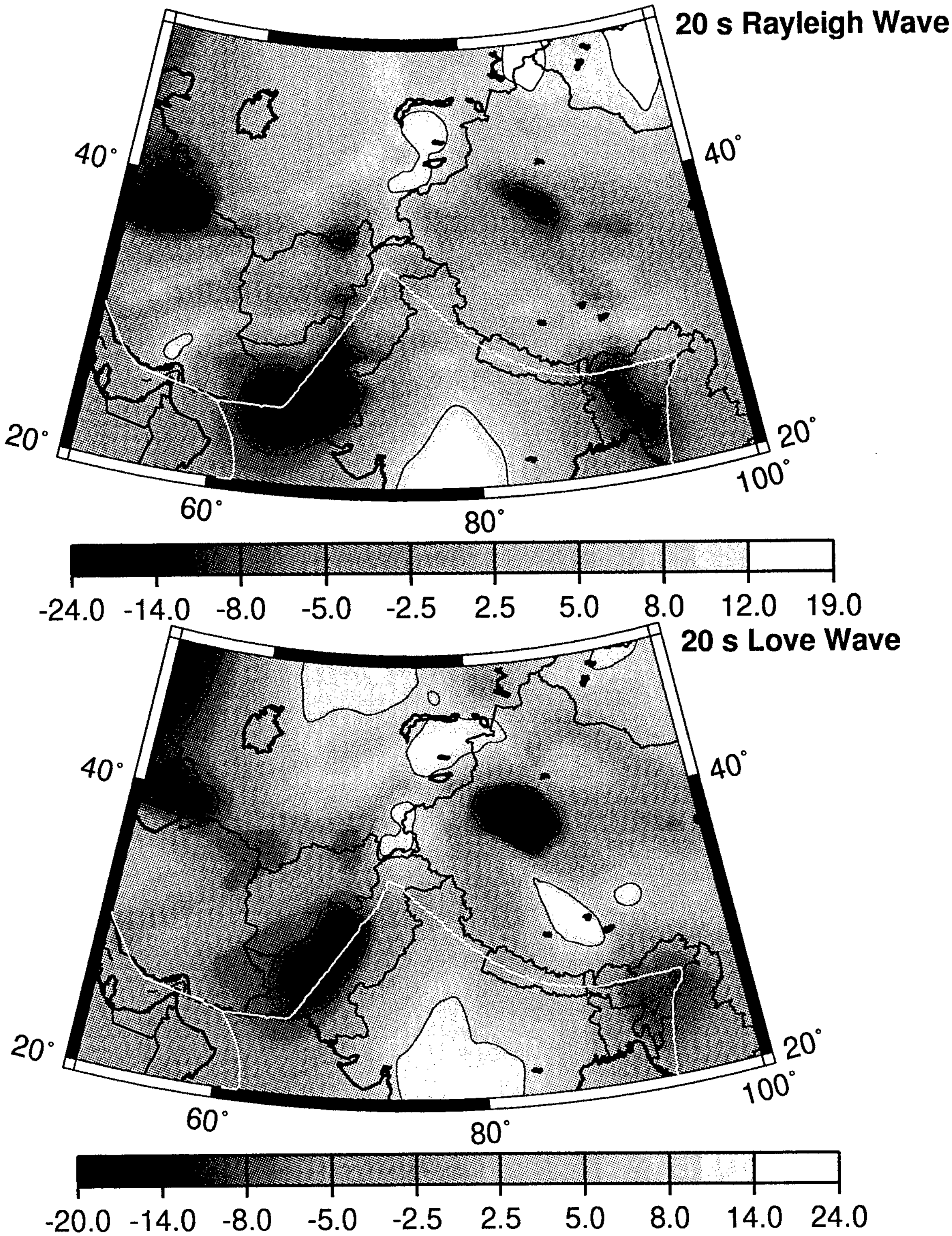
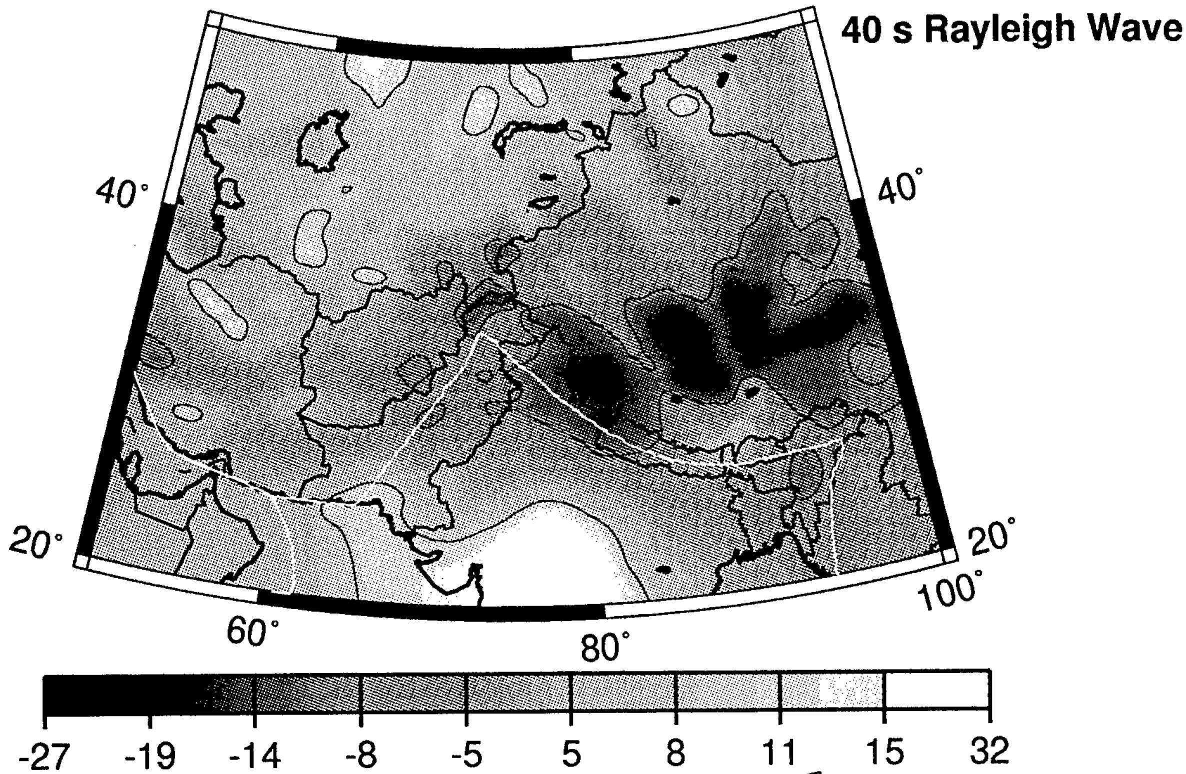



Figure 8. The same as Fig. 7 but for 20 s period. Reference values are 2.822 km/s for Rayleigh waves and 3.166 km/s for Love waves.



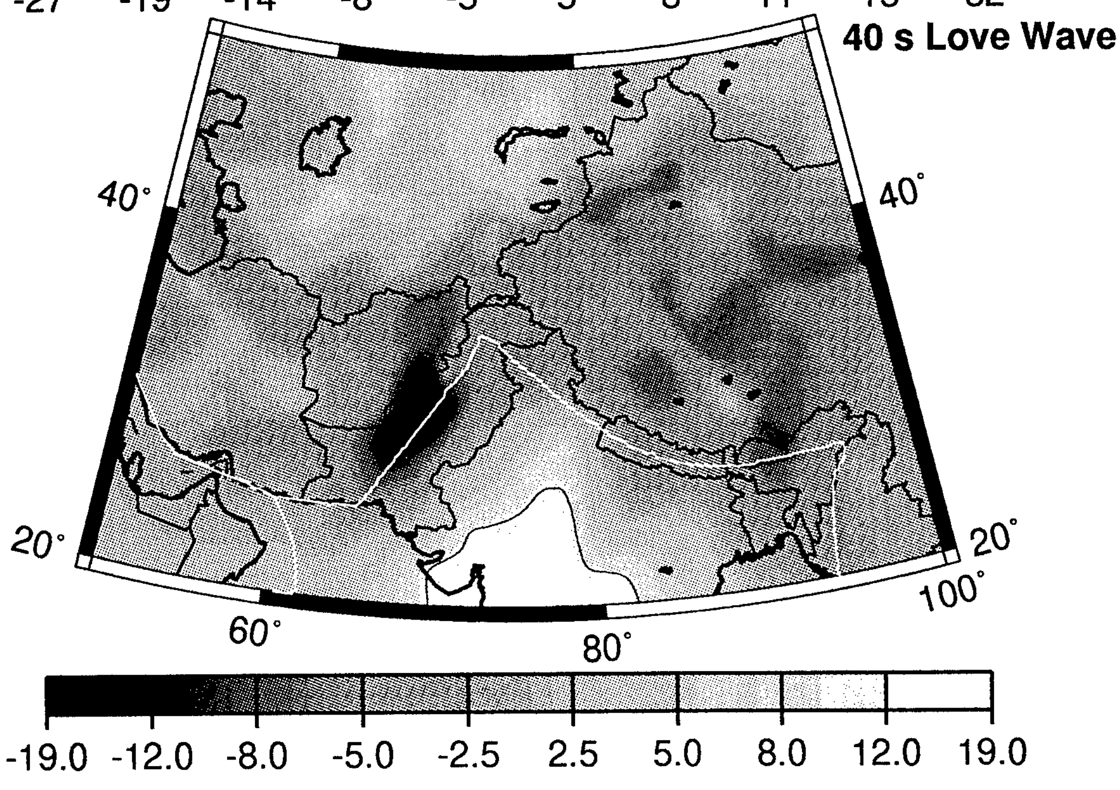




Figure 9. The same as Fig. 7 but for 40 s period. Reference values are 3.305 km/s for Rayleigh waves and 3.527 km/s for Love waves.

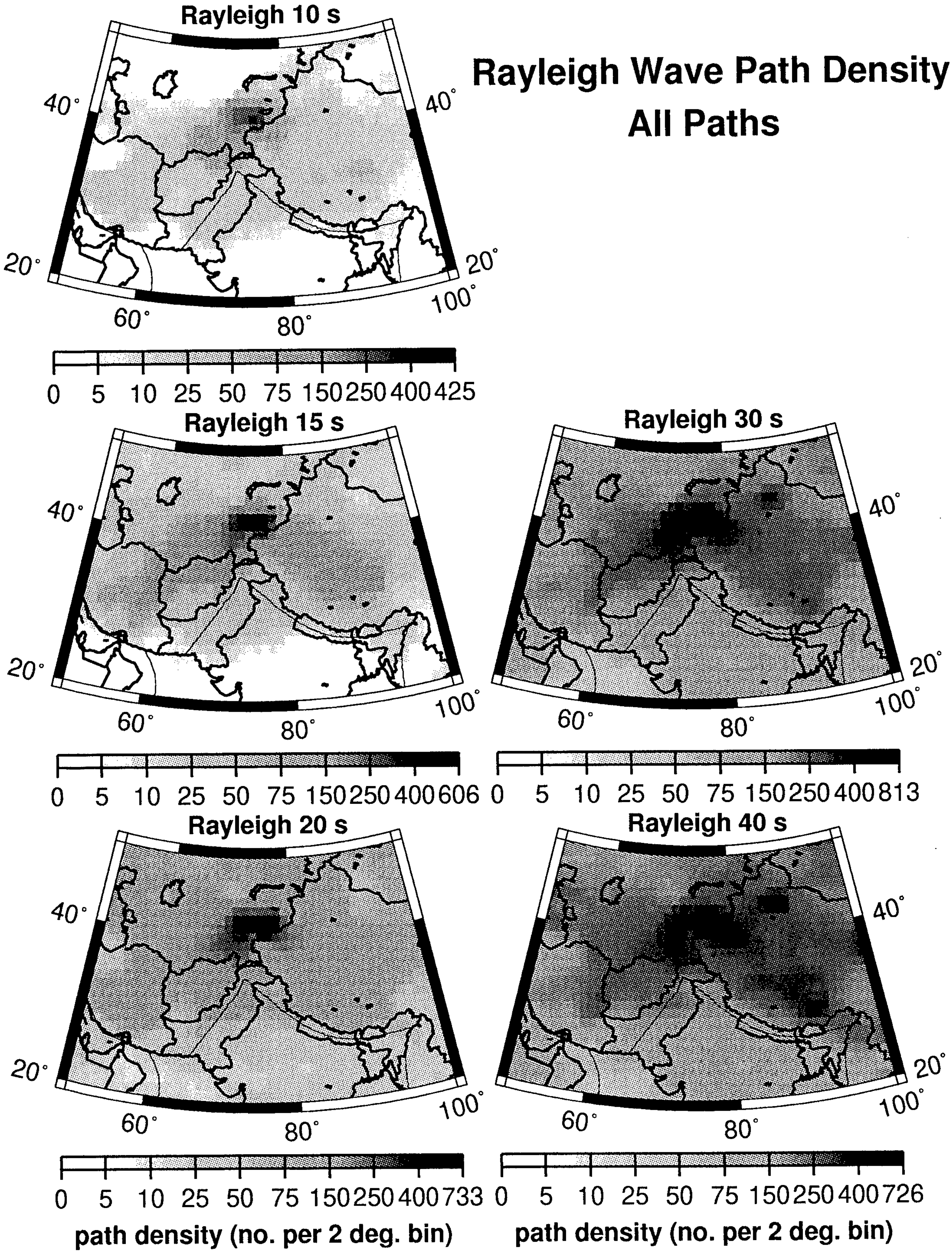



Figure 10a. Same as Fig. 3a, but for all paths crossing Eurasia.

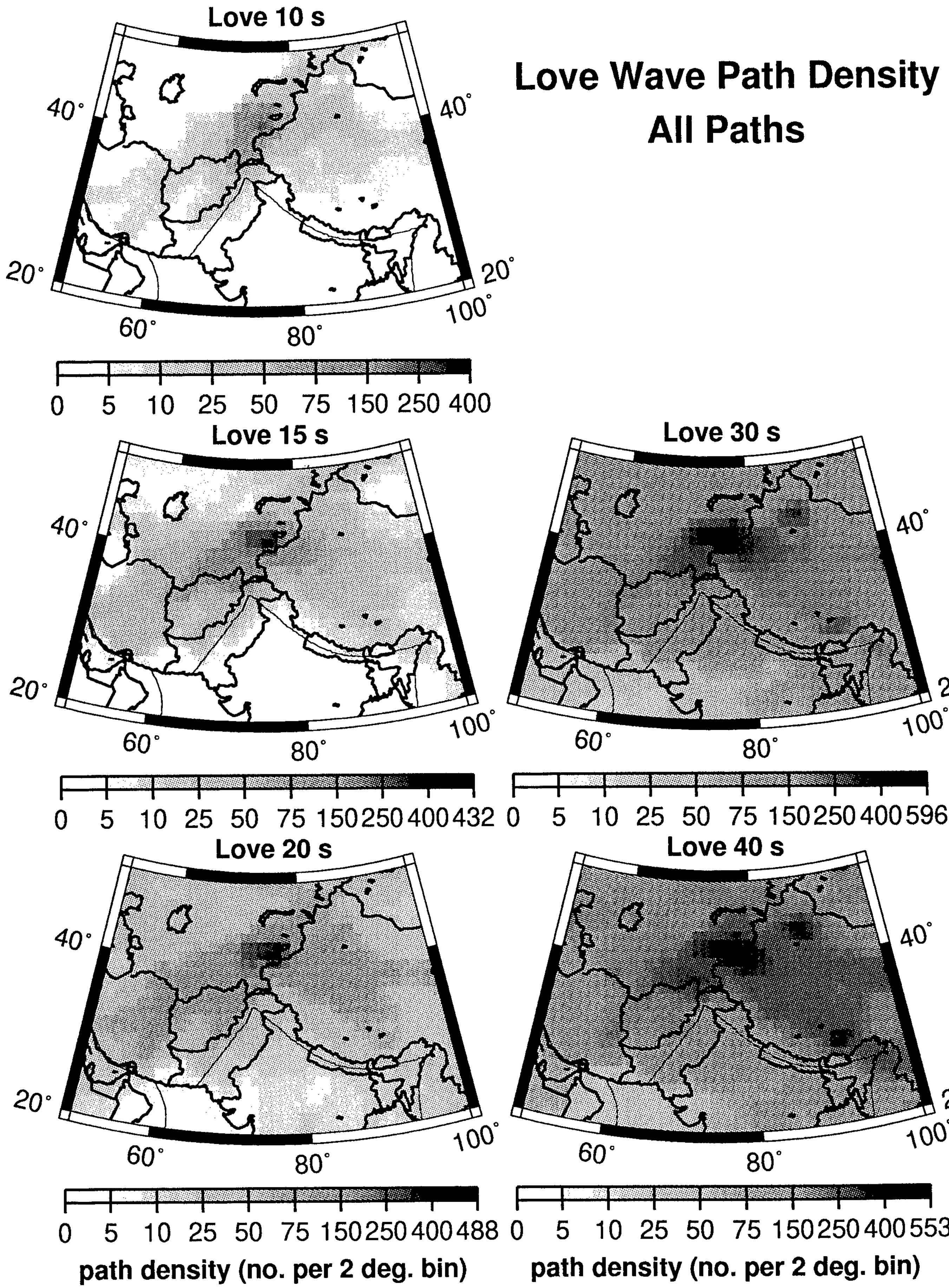



Figure 10b. Same as Fig. 3b, but for all paths crossing Eurasia.

anomalies are associated with the major sedimentary depression of the Caspian Sea, the Afgano-Tajik depression, the Ganges and Indus Deltas. Well defined local high velocity anomaly is seen at the Pamir (~38N, 73E). These high velocities are a clear indicator of consolidated rocks of Archaean and Proterozoic age in the upper crust (Belousov *et al.*, 1991). The high velocity anomaly in southern Tibet is a possible indicator of volcanic rocks in the upper crust. Relatively high velocities seen at the Iranian plateau are well explained by the practical absence of sediments. The observed anomalies have almost the same form and amplitude on maps obtained using regional and combined data. At the same time the map obtained using only continental scale data is much less focused; the relatively small anomalous zones (like the Pamir or the Afgano-Tajik depression) are not seen; the bigger ones, like the Tarim Basin, differ in form and amplitude from ones in the maps discussed above. Moving now to the 20 s maps (Figure 12) we see now much more resemblance between continent-wide and combined maps, especially at the southern and northern parts of the territory studied. The high velocity zone of the Arabian Sea is clearly seen on both maps. At the same time the spatial resolution in the central part is much higher on the combined map. Lower crustal velocities in the Hindukush, Burma, the Tarim Basin, and higher velocities in the Pamir, the Iranian Plateau, the South-Eastern Tibet , the Persian Gulf are well presented. At last, on the 30 s maps (Figure 13) the contribution of regional data becomes comparatively small, only slightly improving the resolution in the central part of the area. The 30 s Rayleigh wave maps are mostly influenced by the Moho topography, indicating a very thick crust in the Tibet-Hindukush-Karakorum area and along the Zagros mountains. The Kazakh Platform and Indian shield are fast on all the maps.

## CONCLUSIONS AND RECOMMENDATIONS

Regional scale surface wave dispersion studies, such as the study of the group velocity variability in Central Asia presented here, can be used to improve both lateral and radial resolution relative to continent-wide studies (e.g., Levshin *et al.*, 1996). This is particularly important in structurally complex regions such as Central Asia, since these regions significantly perturb wave paths propagating on continental scales (i.e., $\geq 5,000$ km). These perturbations create uncertainties about the location of wave paths that manifest themselves as regions of lowered resolution on group velocity maps and, ultimately, on continent-wide models of lithospheric velocity. Additionally, dispersion measurements on regional scales can be extended to shorter periods than continent-wide studies which provides improved radial resolution in the crust. These maps should be merged with those from the companion continent-wide study and then inverted for lithospheric shear velocity structure.

The principal recommendation that emerges from this study is that regional surface wave dispersion studies should be performed elsewhere in Eurasia, in areas of interest to CTBT monitoring that possess regional arrays or networks internal or peripheral to each area. One example is the Far East, centered on North Korea, where there is abundant, well distributed seismicity and where GSN, GEOSCOPE, CDSN, POSEIDON, PASSCAL-Baikal, JNET, and DoD stations and arrays are located. The Middle East, centered on Iran, is a similarly prime region for study, since it possesses well distributed seismicity and GSN, GEOSCOPE, Saudi Network, PASSCAL-Pakistan, and DoD stations provide fairly good peripheral coverage.

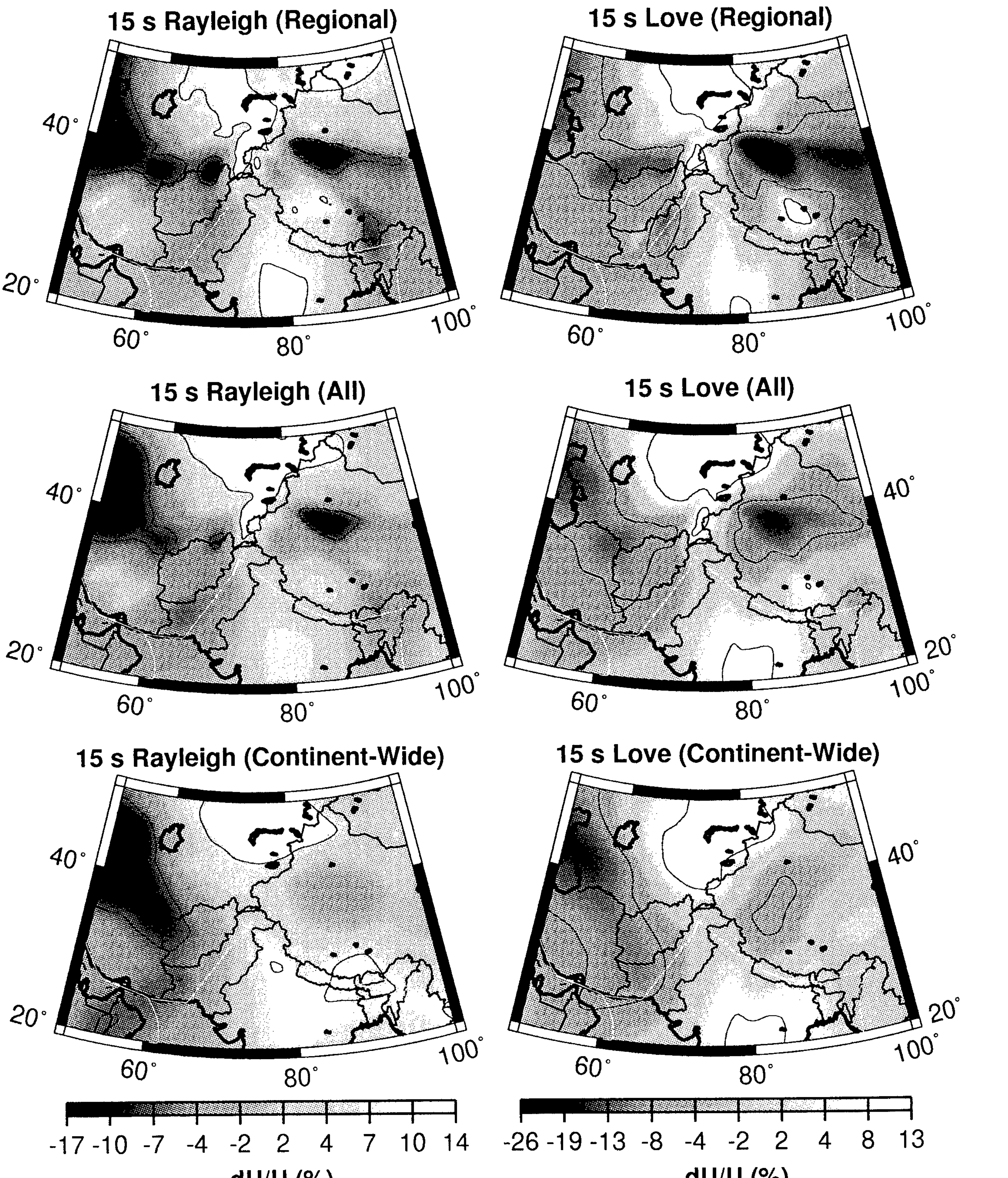



Figure 11. Comparison of 15 s Rayleigh (left column) and Love (right column) wave group velocity maps composed using different data sets. Top Row: Only regional Central Asian (short path) paths were used. Middle Row: All paths were used. Bottom Row: Only paths from the continent-wide data set were used. The color bars correspond to all maps in the column. Units are percent deviation from 2.809 km/s for Rayleigh waves and 3.147 km/s for Love waves. The +/-7% and +/-10% contours are drawn to identify the high and low velocity regions on the Rayleigh and Love wave maps, respectively.

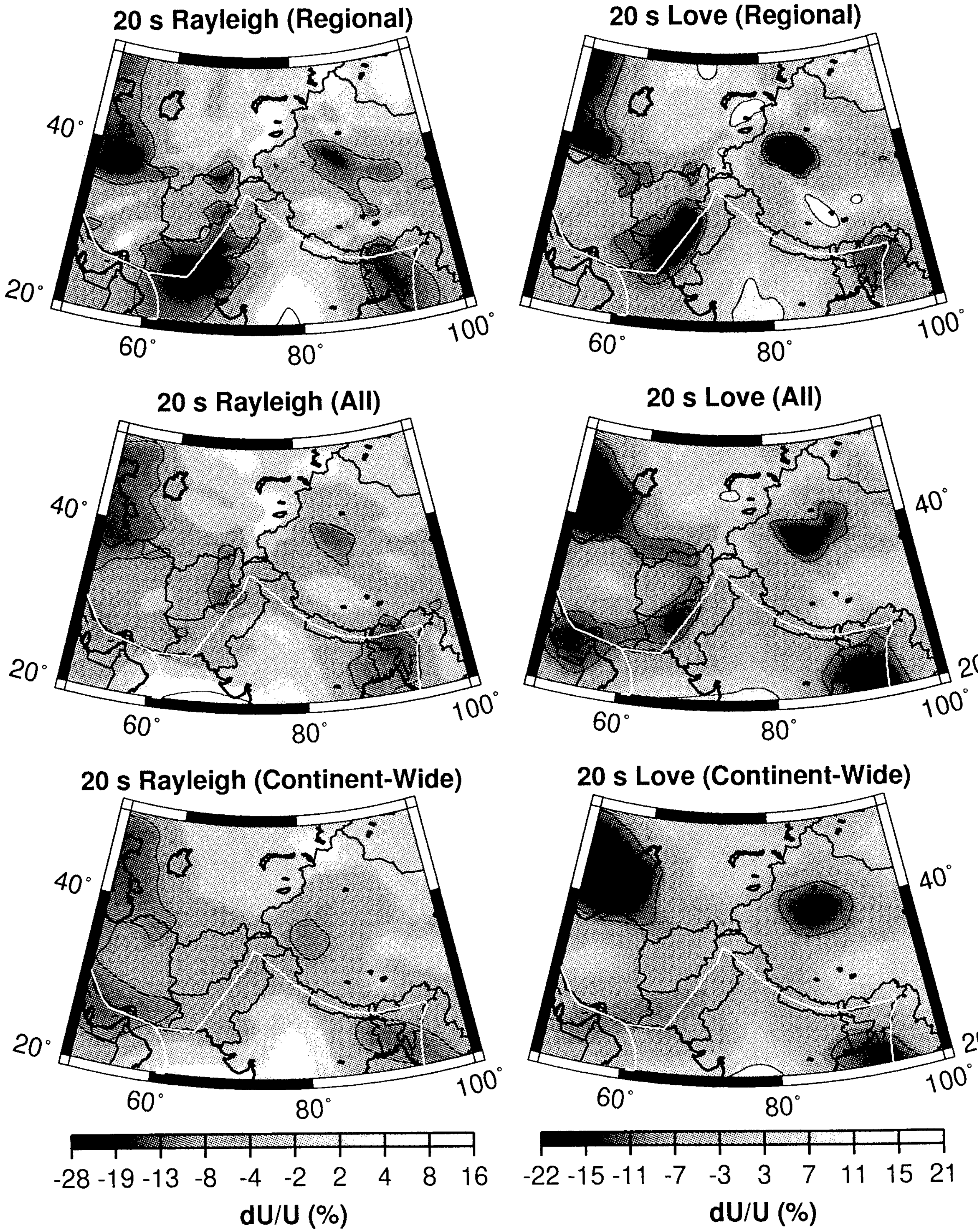



Figure 12. Same as Fig. 11, but for 20 s period. Reference values are 2.993 km/s for Rayleigh waves and 3.250 km/s for Love waves. The +/-10% contours are drawn.

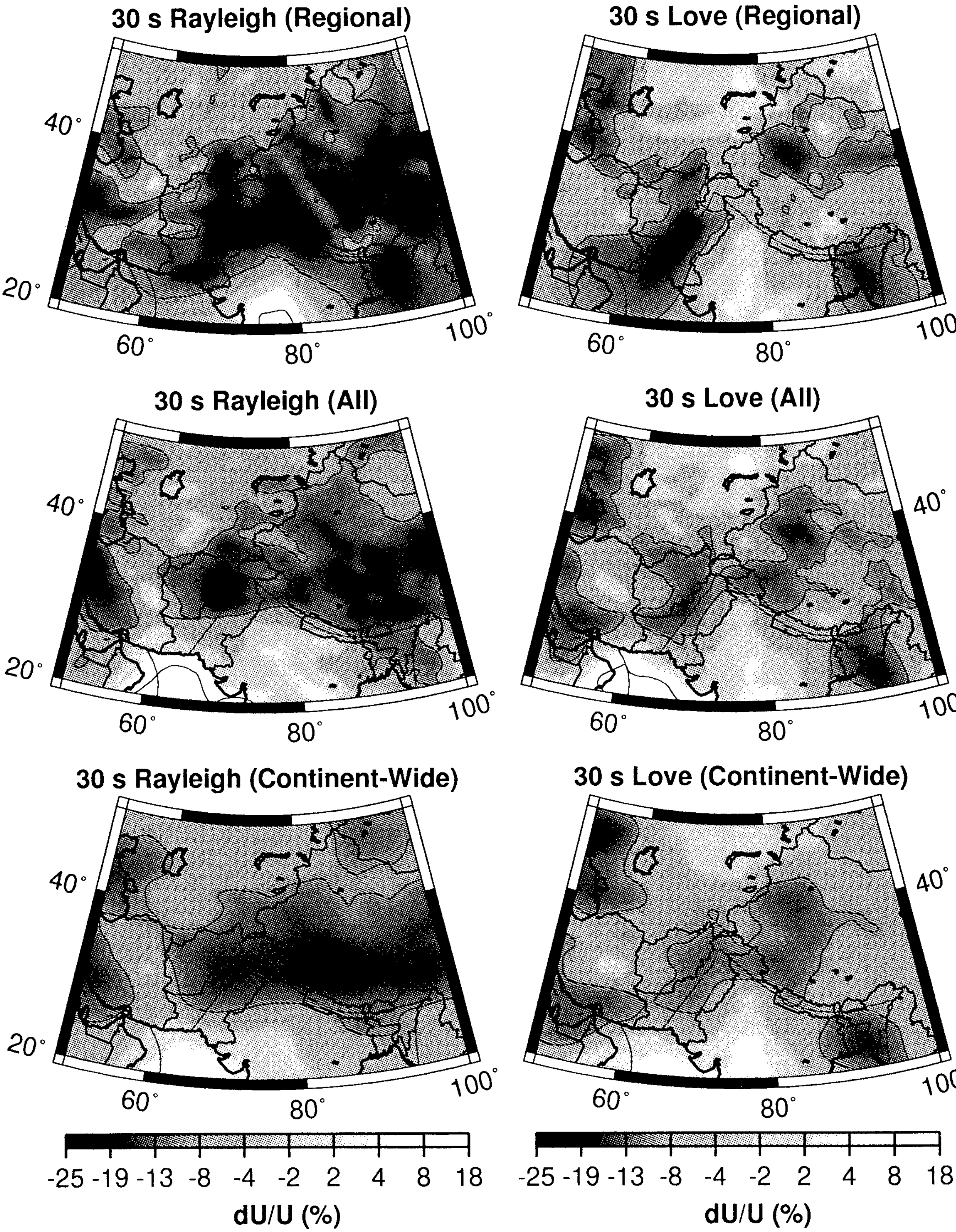



Figure 13. Same as Fig. 11, but for 30 s period. Reference values are 3.431 km/s for Rayleigh waves and 3.589 km/s for Love waves. The +/-10% contours are drawn.

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