MAKING ACCURATE CONTINENTAL BROADBAND SURFACE WAVE MEASUREMENTS

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Abstract

Described herein are methods designed to obtain accurate broadband surface wave dispersion measurements on two spatial/frequency scales: continent-wide (Eurasia; 20 - 300 s) and regional (Central Asia, within 20^0 of KNET; 5 - 50 s). These methods are based on well developed frequency-time and floating-filter analyses, and are included within procedures that utilize relational parametric and waveform database structures with rapid graphics, which allow measurements to be made quickly on relatively large volumes of data from a variety of source regions recorded on heterogeneous networks. These methods are currently being applied systematically to GSN/CDSN/GEOSCOPE/MEDNET data and Kyrghyz Telemetered Seismic Network (KNET) data to yield Rayleigh and Love wave group velocity, phase velocity, polarization, and amplitude measurements.

The complexity of Eurasian structure implies that the crucial problem is to extract the desired signals, related to nearly directly arriving waves that can be interpreted deterministically, from the essentially stochastic interfering multipaths and coda. Continent-wide, 200 events have been processed yielding dispersion measurements for more than 3000 paths to date (Levshin *et al.*, 1995). Regionally, data from KNET's continuous channels have been accumulated for future analysis. All waveform (including 'cleaned' waveforms) and parametric data (including dispersion measurements and frequency-time images) are stored in CSS v. 3.0 (with appropriate extensions).

In the near future, experiments will be performed to automate this method, which currently depends critically on human interaction. The resulting measurements and cleaned waveforms will be used as follows. (1) Group and phase velocity measurements are being inverted for 2D maps of group (Levshin *et al.*, 1995) and phase velocities. (2) These maps will be inverted for lithospheric shear velocity structure which should provide significantly higher resolution than previous models, especially in Central Asia. (3) The cleaned waveforms are ideal targets for surface waveform fitting, which augments and complements the dispersion measurements. (4) Higher resolution phase velocity maps in Central Asia will be used to develop surface wave stacking/array processing methods for regional broadband arrays located in geologically complex settings, such as KNET. Such methods must incorporate differences in the dispersion characteristics among stations in the array.

key words: Eurasia, surface wave propagation, Love waves, Rayleigh waves, group velocity, phase velocity, polarization

Objective

Because approximately two-thirds of Eurasia is surrounded by seismically active regions (some of which extend well into the continent), in principle Eurasia provides the Earth's best laboratory for studying continental wave propagation and for the use of seismic wave characteristics to map crustal and upper mantle structures on a variety of length scales. The development of seismic networks (e.g., GSN, CDSN, GEOSCOPE, KNET) in the Former Soviet Union, China, and the countries of Southern Asia hold out the promise to realize aspects of this potential.

There are two main objectives of the studies described herein. (1) The first objective is to apply well established methods of surface wave analysis to a continent-wide broadband network (GSN, GEOSCOPE, CDSN, MEDNET) and to a broadband regional array (KNET; Kyrghyz Telemetered Seismic Network) to yield Rayleigh and Love wave group velocity, phase velocity, polarization, and amplitude measurements on two spatial scales and frequency bands: continent-wide (Eurasia; 20 - 300 s) and regional (Central Asia, within 20^0 of KNET; 5 - 50 s). These measurements will be used in the future to invert for more sharply focused lithospheric models on these two spatial scales. (2) The second objective is to use the estimated regional phase velocity maps to develop surface wave stacking/array processing methods for large-scale broadband arrays in complex geological settings, such as KNET, to attempt to reduce the magnitude threshold for the analysis of intermediate period (5 - 30 sec) surface waves. To date, preliminary research results have been achieved only for the first objective.

Preliminary Research Results

Measurement Procedures

Problems associated with the estimation of accurate surface wave characteristics (wave velocities, amplitudes, polarizations) do not change in nature with the spatial scale or frequency band of interest, although they do change in magnitude. The most significant issues concern the accrual of high quality data, the identification and extraction of unwanted signals, and the measurement of the signals of interest.

Data quality on both continental (GSN/GEOSCOPE/CDSN/MEDNET) and regional (KNET) scales is quite good, as exemplified by the record sections shown in Figure 1. The main problem to be faced is that continents are complicated. This not only makes interpretation in terms of structural models difficult, but also greatly complicates measurements; or more accurately complicates the identification of the aspects of the waveforms on which measurements are to be applied. Our aim, then, is to extract the signals we desire, related to nearly directly arriving waves that can be interpreted deterministically, from the potentially interfering multipaths and coda that are essentially stochastic in nature. Figures 2 and 3 demonstrate the analysis procedure, in which unwanted signals, in particular surface wave coda, overtones, and body waves are greatly reduced in the filtered seismogram on which measurements are obtained.

The basic characteristics of the current measurement procedure is based on a long history of development of surface wave analysis (e.g., Dziewonski *et al.* 1969, 1972; Levshin *et al.*, 1972, 1989, 1992, 1994; Cara, 1973; Russell *et al.*, 1988). The recent innovation is that code has been developed which allows measurements to be made rapidly on relatively large volumes of data from heterogeneous networks and a variety of source regions. The innovations have required the development of rational parametric and waveform database structures (more on below) and the development of relatively rapid graphical routines for human interaction with the data.

The general form of the measurement procedure is as follows. Group velocity - period diagrams for the vertical, radial, and transverse components are constructed. An analyst manually traces the apparent group velocity curve for the Rayleigh wave (on the vertical and radial components) and the Love wave (on the transverse component). Time-variable filters are applied around the selected curve to separate the desired signal from the 'noise'. This results in filtered group velocity - period diagrams for which contamination from interfering signals should be reduced. Group velocity, phase velocity, amplitude, and polarization measurements are automatically obtained on the filtered images. Figures 2a and 3a attempt to display this procedure.

An unfortunate, but currently still necessary, characteristic of this procedure, is that it depends crucially on direct human interaction with potentially large volumes of seismic waveform data. The success of this method is based on the analyst accurately identifying the main dispersion ridge of the fundamental modes, separating the 'direct arrival' from surface wave coda at periods below about 30 seconds, inspecting interpolation near spectral holes, and truncating the measurements appropriately at long periods as the signals weaken. This interaction limits the speed with which the method can be applied, and, therefore, the volume of data that can be processed.

To date, the method has been applied to waveform data from approximately 200 events surrounding Eurasia. The analysis of significantly larger volumes of data will require the automation of the technique. Attempts at automation will be based on initial continent-wide group and phase velocity maps which are currently under development (Levshin *et al.*, 1995). This will increase the volume of data that can be processed and should result in improved resolution of the group/phase velocity maps and the resulting structural models.

Measurements on a Continental Scale

Due to the high, average efficiency of surface wave propagation across Eurasia, surface wave measurements can be made at periods up to 100 - 150 seconds for earthquakes as small as $M_s =$ 5.0 that propagate across the entire continent. Of course, measurements can be extended to longer periods for substantially larger events. To date, event volumes have been accumulated for GSN/GEOSCOPE/CDSN/MEDNET data from approximately 300 events occurring between 1988 and 1995. Of these events, shown in Figure 4a, approximately 200 have been completely processed, yielding measurements on more than 3000 paths (Levshin *et al.*, 1995).

As an example, group velocity measurements for a single station (KEVO, Finland) for one event (Kuril event, 10/9/94, $M_s = 7.0$) are shown in Figure 3b for the Rayleigh wave (measured on the vertical and radial components) at periods between about 20 and 300 seconds and for the Love wave at periods between about 30 and 250 seconds. Predictions for the spherical model PREM (Dziewonski and Anderson, 1980) are shown for comparison.

A useful by-product of these analyses are 'cleaned' or 'filtered seismograms'. Figure 3b shows a comparison between the raw and filtered seismograms for a single station:event pair. Surface wave coda, overtones and body waves have been greatly diminished from the cleaned seismograms, making them an ideal target for surface wave fitting techniques during a later stage of this research.

Measurements on a Regional Scale

On a regional scale at shorter periods, smaller events ($M_s < 5.0$) can be analyzed similarly. KNET, situated in a complex tectonic setting in Central Asia surrounded to the East, West and South by significant seismicity, is a natural site to focus studies of regional scale measurements. To date, approximately 200 events (Figure 4b) with $M_s > 4.0$ within approximately 20 degrees of

KNET have been extracted from KNET's continuous channels. Analyses of these data are just beginning.

Figure 3b presents an example the analysis of these data. Seven KNET stations were operating during the passage of surface waves from an event in the Qinghai Province, China on 1/17/94 ($\Delta \approx 16$ degrees, $M_s = 4.8$). Rayleigh and Love wave group velocity measurements are shown in Figure 3b. Rayleigh wave measurements are quite similar across the array above about 20 seconds period and for Love waves above about 30 seconds period at this azimuth. Variations across the array at shorter periods result both from real differences along the various wave paths near the network and also from Rayleigh - Love interference, which can be significant since the group velocities of the two wave types are similar in this period range. Cleaned and raw waveforms are presented in Figure 3c.

Data Base Structure

All waveform and parametric data as well as surface wave measurements are stored in the CSS v. 3.0 relational database (Anderson *et al.*, 1990) plus extensions. This data base will be delivered to the funding agents upon completion of the contracts. The standard relations (affiliation, event, gregion, instrument, network, origin, sensor, site, sitechan, sregion, wfdisc) are augmented with two event relations modified slightly from CSS v. 2.8 (centryd, moment) and three extensions (disp, ftdisc, wfedit). The wfedit relation contains information about the time, duration and nature of waveform problems (e.g., clips, gaps, nonlinearities, interfering events, etc.). The disp and ftdisc relations point to dispersion measurements and group velocity - period images, respectively. For each station:event pair, raw and filtered group velocity images are output and pointed to by the ftdisc relation. Dispersion measurements (group velocity, phase velocity, spectral amplitude, polarization) are output and pointed to by the disp relation. Cleaned or filtered waveforms are output and pointed to by a cleaned wfdisc relation.

Conclusions and Future Plans

The ability to make relatively rapid and accurate surface wave measurements (phase and group velocities, amplitudes, polarizations) on fairly large volumes of data has allowed us to begin to process systematically surface waves propagating across Eurasia. Dispersion measurements have been made for approximately 200 events on a continental scale recorded at GSN, GEOSCOPE, CDSN, and MEDNET stations. Data from continuous channels of KNET have been accumulated and are just beginning to be processed in support of a regional scale study of Central Asia. These developing data sets should provide significantly higher resolution than represented in previous models, which promises more accurate lithospheric models.

Future developments will be along three lines.

- To increase the rate of surface wave processing, measurement methods must be automated. This will be based on the use of preliminary group and phase velocity maps resulting from the continental scale study. See Levshin *et al.* (1995) for preliminary group velocity maps.

- Filtered seismograms will be used for surface waveform fitting, which augments and complements current measurement procedures.

- Higher resolution phase velocity maps in Central Asia will be used to develop surface wave stacking/array processing methods for regional broadband arrays located in a geologically complex setting, such as KNET. Such methods must incorporate differences in the dispersion characteristics among stations in the stack.

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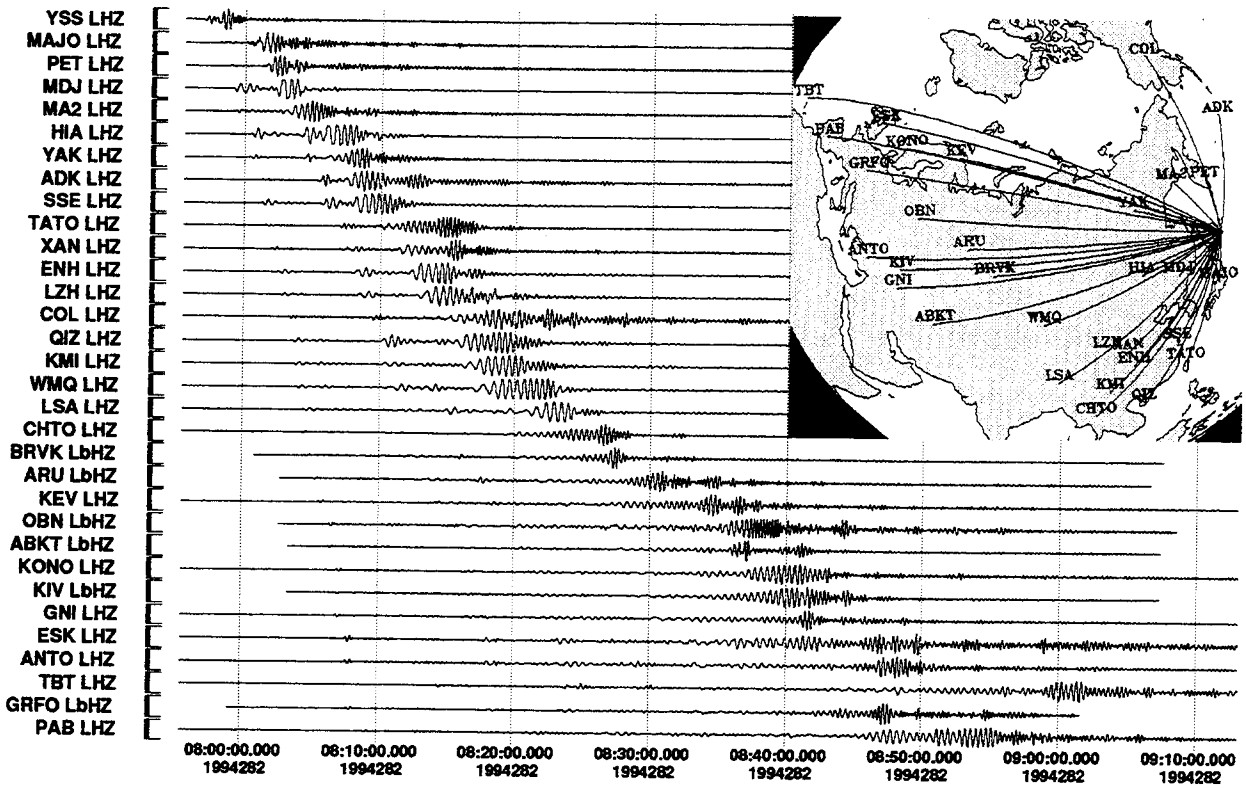
(a) *GSN Kuril Event: 1994 282 Ms=7.0*



(b) *KNET Qinghai Event: 1994 27 Ms=4.8*

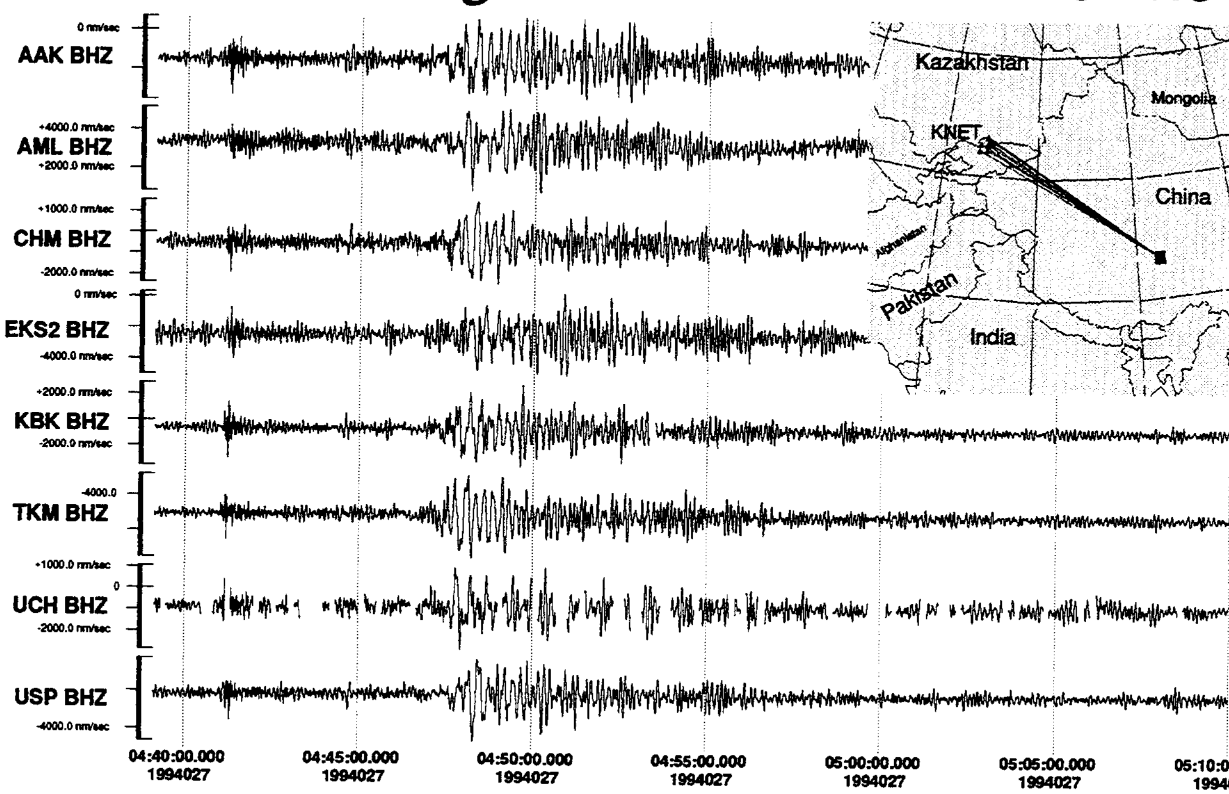


Figure 1. (a) Record section of IRIS/GSN vertical waveforms recorded for the Kuril event of 10/9/95 (Ms = 7.0). Waveforms have been low pass filtered with a lower corner of 20 seconds period. Raypaths are inset. (b) Record section of KNET vertical waveforms recorded for the Qinghai, China Event of 1/27/94 (Ms = 4.8).

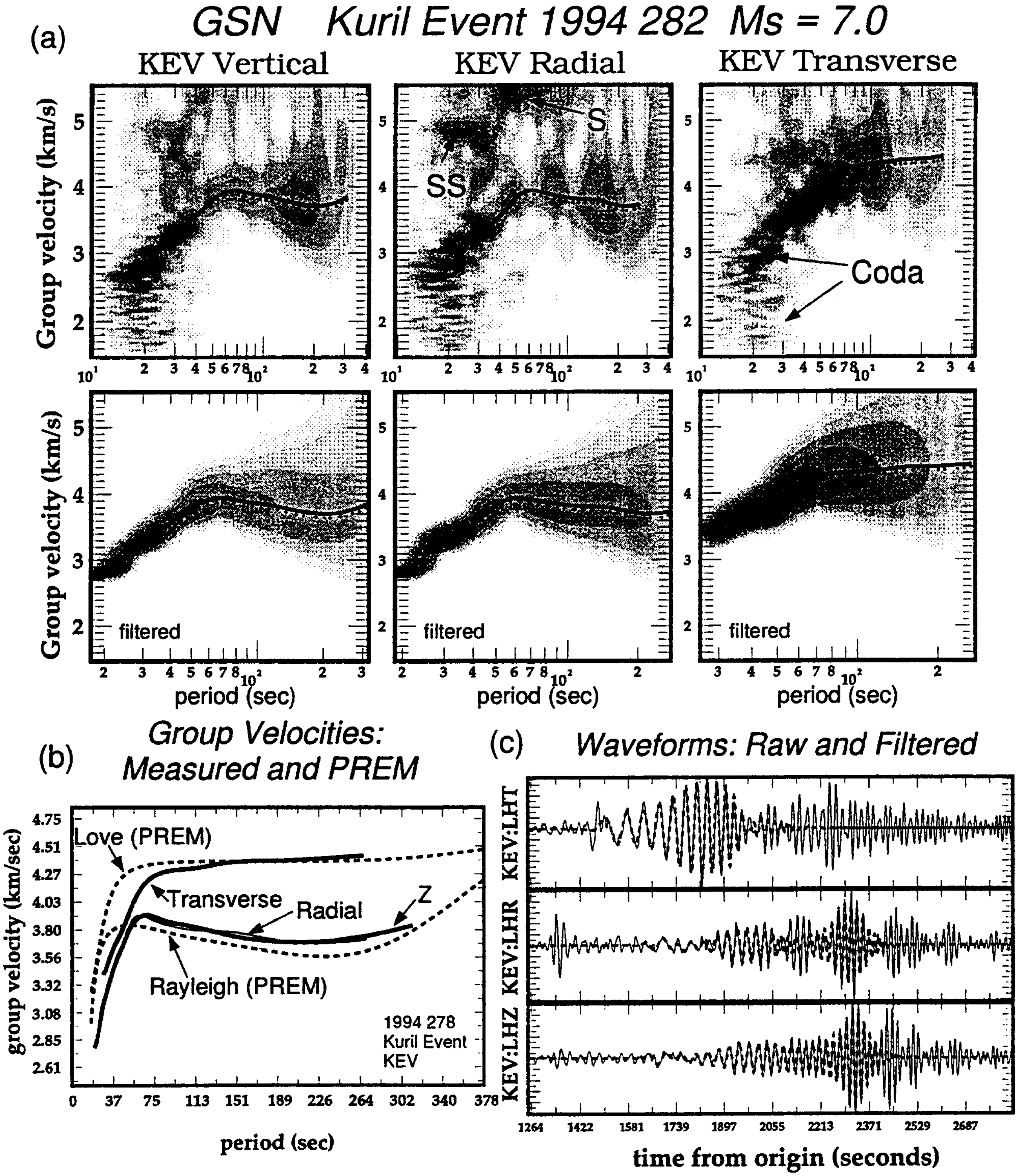


Figure 2. (a) Group velocity - period diagrams for the vertical, radial, and transverse components recorded at the GSN station at Kevo, Finland for an event in the Kurils (10/9/94, Ms = 7.0, Δ = 58.5 degrees). Estimated group velocity curves are shown. (b) Rayleigh and Love wave group velocity measurements compared with predictions from PREM. (c) Raw (thin solid) and filtered (bold dashed lines) waveforms for KEV.

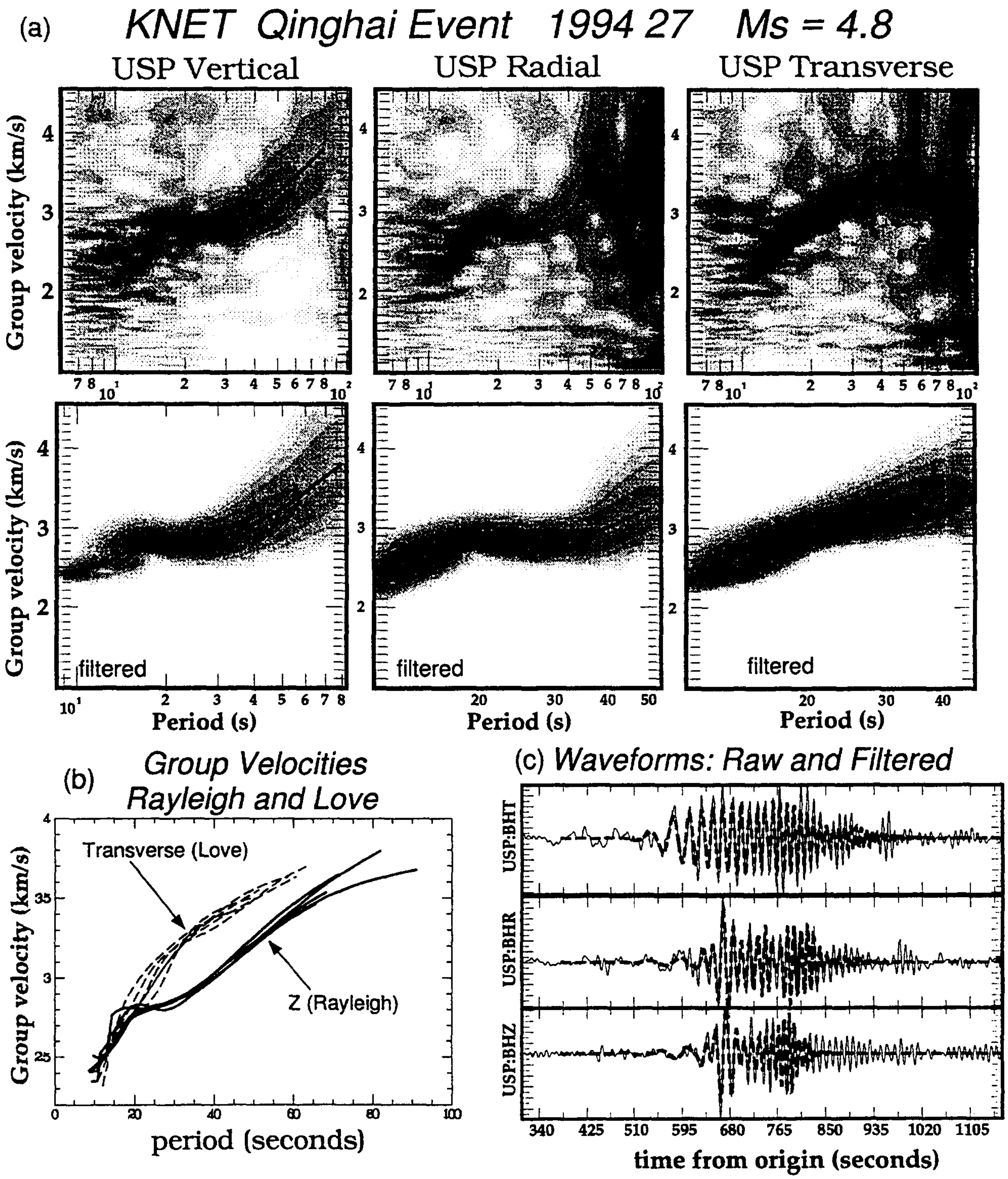


Figure 3. (a) Group velocity - period diagrams for the vertical, radial, and transverse components recorded at the KNET station USP for an event in the Qinghai Province (1/27/94, Ms = 4.8, Δ = 16 degrees). Estimated group velocity curves are shown. (b) Rayleigh and Love wave group velocities measured across the array for the same event. (c) Raw and filtered waveforms for the station USP.

Eurasian Tomography 1988 - 1995

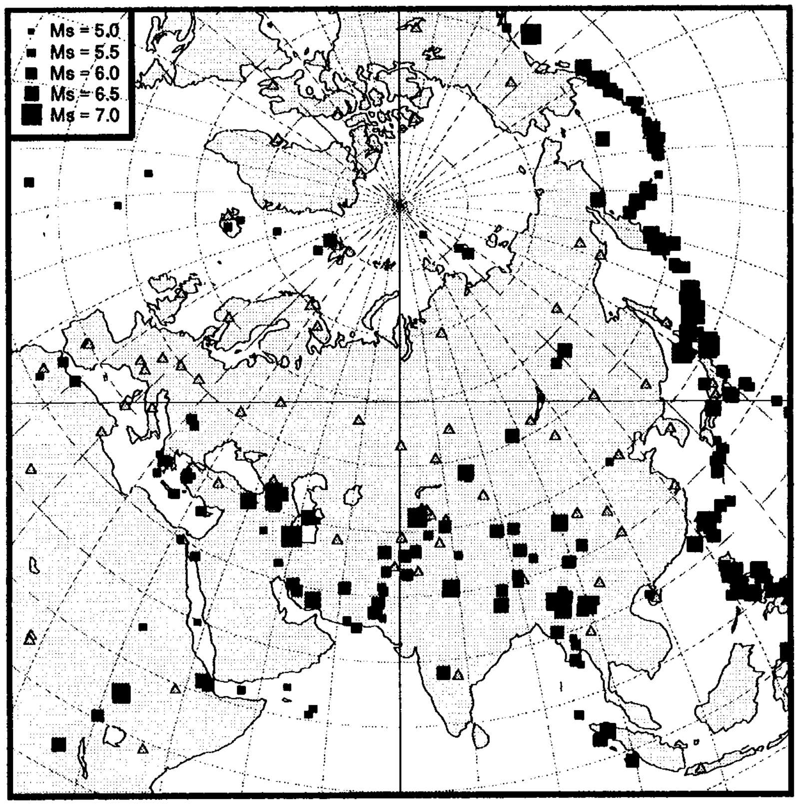


Figure 4a. Distribution of sources (squares) and receivers (triangles) used in the continental scale surface wave study of Eurasia. Source symbol sizes are scaled linearly by surface wave magnitude.

KNET Events 1992 - 1995

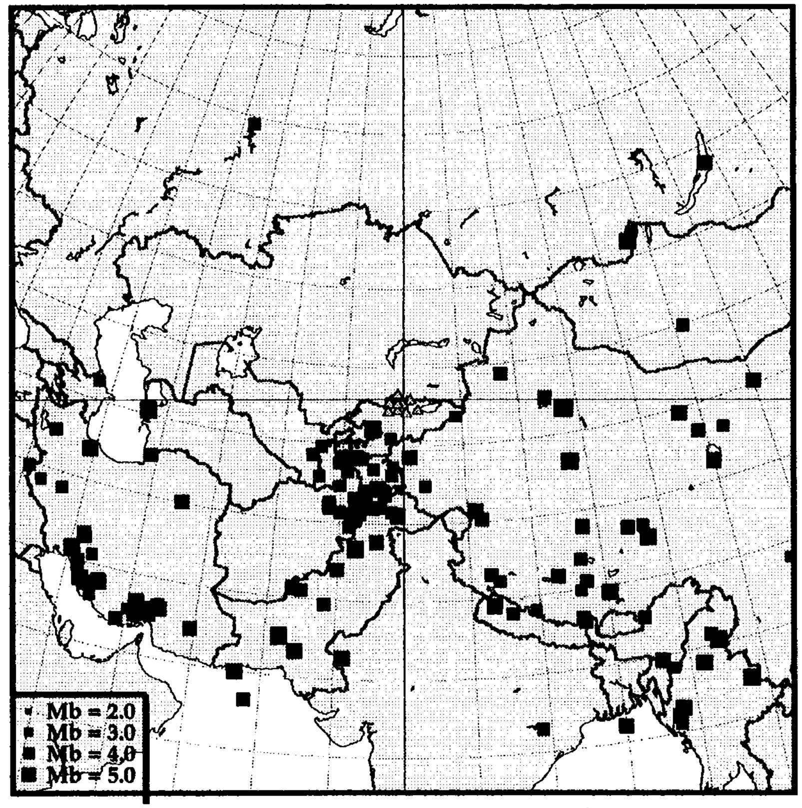


Figure 4b. Distribution of sources (squares) and KNET receivers (triangles) to be analyzed in the regional scale surface wave study of Central Asia. Source symbol sizes are scaled linearly by body wave magnitude.