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Surface Wave Research in the Middle East and North Africa

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ABSTRACT

We present updated results from a large scale study of surface wave group velocity dispersion across the Middle East and North Africa. Our database for the region is populated with seismic data from regional events recorded at broadband, 3-component, digital IMS, MEDNET, GEOSCOPE and IRIS stations, as well as the portable PASSCAL deployment in Saudi Arabia. Data at regional and teleseismic distances is deconvolved to ground displacement and windowed to extract the surface wave. Due to the lack of source information on most of the events, we have concentrated on group velocity measurements. We measure the group velocity using a multiple narrow-band filter method.

Preliminary results of this study were presented by McNamara *et al.,* 1997. This study found that short period structure was sensitive to low velocities associated with large sedimentary features and long period structure was sensitive to crustal thickness and upper mantle shear-wave velocity. In addition to adding more data, we seek to make several improvements. First, we explore the effect of using instantaneous period in our dispersion measurements. Secondly, we replace the backprojection inversion method with the conjugate gradient method. Major differences between the preliminary and updated group velocity maps will be discussed.

Group velocity measurements will allow phase match filtering, which can lower the threshold of Ms. We are particularly interested in using regionally determined Ms measurements to allow us to explore m_b:M_s discriminants at lower magnitude levels. The methodology of Marshall and Basham (1972) is used to estimate regional surface wave magnitudes (M_{sr}). Finally, we present the results of regional single station m_b:M_{sr} discriminants for several regions, including South Asia, at several distances and frequency passbands.

This work is preliminary and performed under the auspices of the U.S. Department of Energy at the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

Key Words: Middle East. North Africa, Rayleigh waves, group velocity, dispersion, magnitude, discrimination

OBJECTIVE

The purpose of this research is to improve surface wave group velocity maps and lithospheric shear wave velocity models for northern Africa and the Middle East. Rayleigh group velocity maps allow phase-match filtering, which has the potential to lower Ms thresholds. Ms is an important discriminant measure and could help identify smaller magnitude events. Improved shear velocity should improve event location capabilities throughout the region. Both improved identification and location capabilities are important to monitoring a CTBT. In order to obtain our objective we first estimate the lateral variation of Rayleigh and Love wave group and phase velocity using several tomography techniques. Second, we invert the group and phase velocities at each grid point within the tomogram for shear-velocity structure. This work is on-going and to date we have concentrated on the Rayleigh wave group velocity component of this study.

Many of the changes in this study from previous years are a direct result of the "Workshop on the U.S. Use of Surface Waves in Monitoring the CTBT", which was held during the 1998 SSA meeting in Boulder, Colorado (The URL for the workshop is http://abdu.colorado.edu/sw_workshop.html). As a consequence of the workshop, we have changed the way that we are making our measurements and the method we are using to invert the observations. At the present time, our results mainly reflect these two major changes. Concurrently, another major endeavor is increasing the number of paths and expanding our coverage of the Middle East - North Africa region. Our database is actively being loaded with seismic data for all events which can yield quality surface wave measurements. We hope to have data from several thousand more paths available in time for the CTBT meeting.

RESEARCH ACCOMPLISHED

Our procedure to accomplish the stated objectives has included the following steps: (1) data selection (2) dispersion measurements (3) group velocity tomography (4) resolution analysis (5) preliminary interpretations and (6) applications. Brief discussions of our procedural steps are presented below.

Data Selection

For the Rayleigh wave study, vertical component teleseismic and regional seismograms were gathered from broadband, 3-component, digital IMS, MEDNET, GEOSCOPE and IRIS stations plus the portable PASSCAL deployment in Saudi Arabia. Figure 1 shows the distribution of earthquakes (circles) and broadband digital seismic stations (triangles) throughout the Middle East / North Africa region that are used in this study. Paths for which we have obtained a Rayleigh wave group velocity measurement (in this case at 30 seconds) are indicated by the grey lines. To date, over 2000 seismograms have been analyzed to determine the individual group velocities of 7-150 second Rayleigh waves.

We have applied strict selection criteria to the earthquakes used in this study order to insure that only high-quality Rayleigh wave travel times are used in the inversion. To eliminate potential errors in the group velocity measurement process, only travel times from high-quality relatively continuous dispersion curves were used. Qualitative assessments were made at the time of calculation and were used to eliminate spurious travel times. Furthermore, in order to eliminate measurements from stations with large timing problems, the surface waves are compared to the dataset of P-wave picks which are more sensitive to timing problems. Finally, travel time residuals with a velocity deviation greater than 25% from the data set mean were eliminated.

Obtaining Rayleigh Wave Group Velocity Dispersion Curves

To obtain the Rayleigh Wave dispersion curve a narrow-band Gaussian filter is applied to the broadband vertical component, displacement seismogram over many different periods (e.g. Herrmann, 1973). The maximum amplitude at each period is picked on the envelope function and the arrival time corresponding to this maximum amplitude is used to compute the Rayleigh wave group velocity. One complication to this methodology is that the period of the narrow-band filter (the "filter period") is not always the same as the period of the peak-to-peak measurement of the filtered waveform (the "instantaneous period"). This can be particularly important when the amplitude of the surface wave is changing very rapidly. During the surface wave workshop it was decided that instantaneous period was the appropriate quantity that all groups should be measuring.

All of our group velocity measurements have been performed using the PGSWMFA (PGplot Surface Wave Multiple Filter Analysis) code designed by Chuck Ammon of St. Louis University. An example of our measurements are shown in Figure 2. The left figure shows the contours of the velocity-period spectrum which are used to make the dispersion measurement along with uncertainty estimates. The center figure shows the Rayleigh wave waveform, while the right figure shows the spectral amplitude as a function of period. Using PGSWMFA, we have remeasured waveforms to determine the group velocities as a function of instantaneous period instead of filter period. Two examples of the differences between the two measurements are shown in Figure 3.

Inversion of Travel Times for Lateral Group Velocity Variation

The Rayleigh wave travel time, for a given period, is expressed simply by $t = d\,s$ where t is the total travel time, d is source to receiver distance, s is slowness profile as a function of depth, $(1/v)$. For estimating lateral group velocity variations, the sampling region is gridded into a single layer and the slowness for each grid cell is determined. The travel time equation then becomes:

(1) $$t = \Sigma d_i\, s_i$$

where d_i is the distance the ray travels in cell i and s_i is the slowness in cell i. For a number of paths, a series of these equations can be represented in matrix form as:

(2) $$\boldsymbol{T} = \boldsymbol{D}\,\boldsymbol{S}$$

There are a number of different methodologies available for inverting measured travel times for group slowness (and velocity). Previously, we used a backprojection technique as the inversion method (McNamara, *et al.* 1997). In most cases, it appeared that the backprojection method was able to resolve the location and pattern of the fast and slow anomalies. Given the relatively small number of surface wave paths, however, it was often unable to recover the full amplitude of the anomalies. In the current rendition, we have replaced the backprojection method with several other inversion methods- the singular value decomposition and the conjugate gradient method. The singular value decomposition has the advantage of being a direct inversion method, as well as being extremely robust and reliable. As the number of paths included in our inversion increases, however, the singular value decomposition becomes less tractable. The conjugate gradient technique is a search technique which works very well on sparse linear systems like the travel time problem. Because there is no matrix inversion involved, it is well-suited for large systems of equations.

Resolution

A first-order, qualitative, measure of data set resolution can be obtained by inspecting the ray path distribution throughout the sampling region (Figure 1). Though ray path density is important, azimuthal sampling is most significant. For a more quantitative assessment, resolution is best investigated with synthetic travel times computed through laterally varying "checkerboard" test velocity models. Using the 60 second period as an example we compute the Rayleigh wave travel time for each path (Figure 4) through a model with 10° x 10° checkers that vary in velocity by 5% about a mean of 3.75 km/s. The synthetic travel times are then inverted using the inversion methods described above. Our ability to reproduce the input model determines the resolution of the data set. As demonstrated in Figure 4, we are able to resolve both the location and the full amplitude of the 10° anomalies throughout much of the Middle East, Mediterranean, Saudi Arabia and North Africa, Resolution is significantly diminished throughout central Africa, northern Eurasia, and the Indian Ocean due to a lack of crossing ray paths but, even with this limited coverage, the location of the anomalies is relatively stable.

Preliminary Results

We are currently in the process of adding significant amounts of additional data. At the meeting, we will present the latest tomography results which will include both the remeasured and new surface wave measurements. In previous inversions using the same data set, we have observed significant lateral group velocity variation at all periods. In general, however, shorter periods (< 30 sec) are sensitive to crustal structures such as the relatively low velocities associated with large sedimentary features (e.g. Mesopotamian Foredeep, Persian Gulf, Eastern Mediterranean, Caspian Sea). At intermediate periods (~50 sec), Rayleigh waves are most sensitive to crustal thickness and topography on the Moho. At the longer periods (> 80 sec), the variations are increasingly sensitive to lateral variations of the upper mantle shear velocity.

A preliminary Rayleigh wave group velocity map at 50 seconds period was performed using the singular value decomposition method (Figure 5). We find fast group velocities associated with thinner crusts in the Red Sea Rift and Arabian Sea. We also find slow group velocities, indicating thicker crust, in the Hindu Kush, the Zagros Mountains, the Caucasus, along Asia Minor, and along the Alpine Belt.

Applications

One of the short term applications of group velocity measurements is that they will allow phase match filtering. Because this methodology is able to use an ideal filter, it is possible to pull signals out of noisy measurements, calculate regionally determined M_s measurements, and lower the threshold of surface wave measurements. We use the formulation of Marshall and Basham (1972) to calculate regional surface wave magnitudes.

$$M_{sr} = \log A + B'(\Delta) + P(T) \qquad (4)$$

where A is the maximum amplitude (in nm), $B'(\Delta)$ is the distance correction, Δ is the distance (in degrees), P(T) is the path correction, and T is the period (in seconds). The path correction can be determined with the appropriate group velocity dispersion curve for the path and the passband of the measurement can be selected where we have the best signal-to-noise ratio.

The discriminant is calculated as M_{sr} - M_{so} where M_{so} is the surface wave magnitude which is predicted from the body wave magnitude m_b. It is derived from equilibrating the energy of the body and surface wave magnitude scales and should effectively remove any magnitude dependence from the discriminant. Figure 6 shows the discriminant calculated in the 10-14 second passband at station NIL (Nilore, Pakistan) for the 11 May 1998 Indian nuclear explosion (diamond) and 28 earthquakes (circles) located near the explosion. The Eurasian path from the Marshall paper is used to generate the appropriate path corrections. The left side of the plots shows the mean (center line) and first and second standard deviations (outer lines) of the earthquake population. The explosion lies outside of the third standard deviation of the earthquake population.

CONCLUSION AND RECOMMENDATIONS

We find that Rayleigh wave group velocity models, for periods ranging from 10-100 sec, vary laterally across the region and diverge from global models obtained using longer periods. For this reason it is important to continue utilizing regional data to more accurately determine the lateral variation of shear-wave velocity across the region. We intend to do this by including additional raypaths in the inversion and expanding our analysis to Rayleigh phase and Love wave group and phase velocity.

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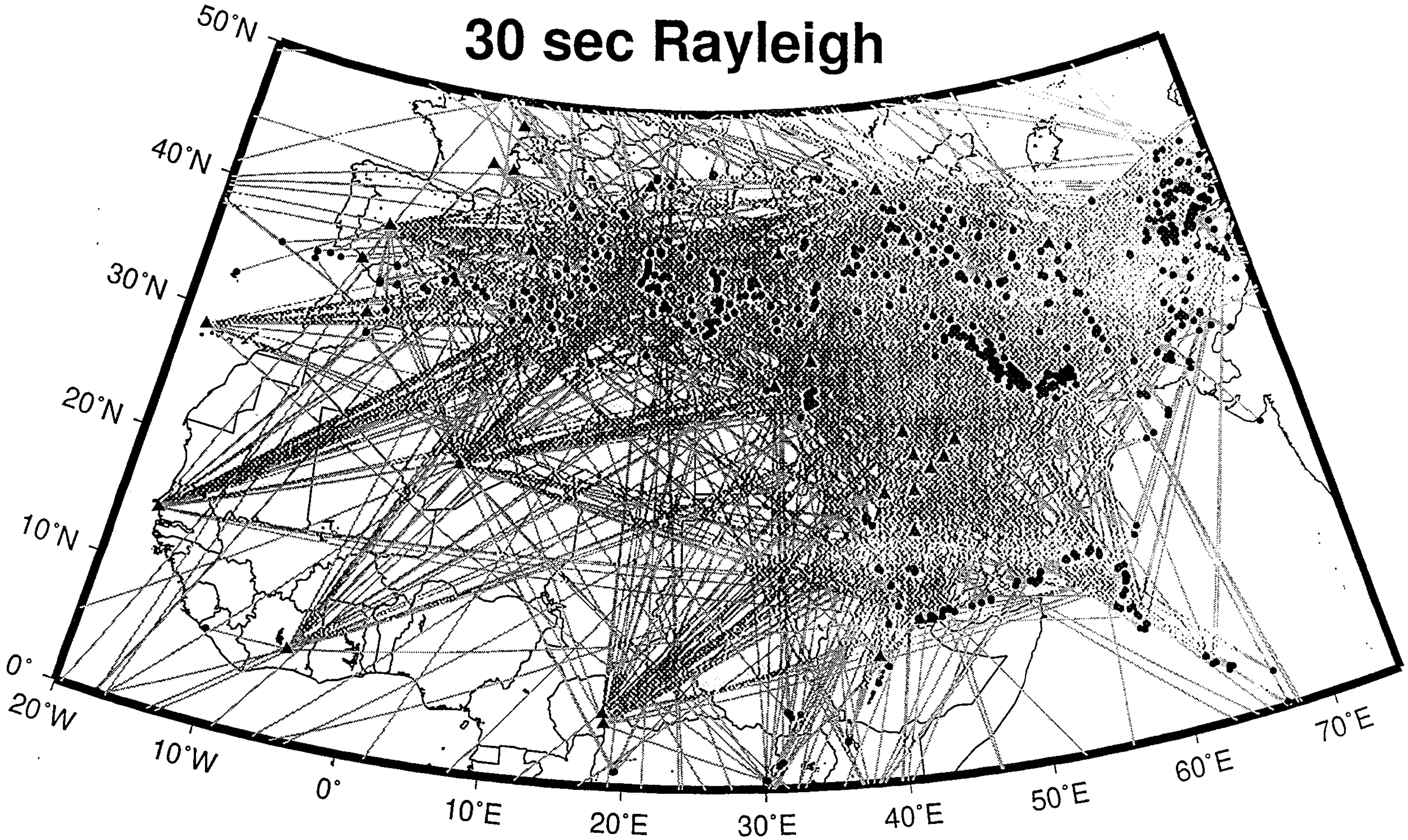

Figure 1. Earthquakes (circles) and broadband stations (triangles) in the Middle East / North Africa region. Paths with 30 second Rayleigh wave group velocity measurements are shown by lines.

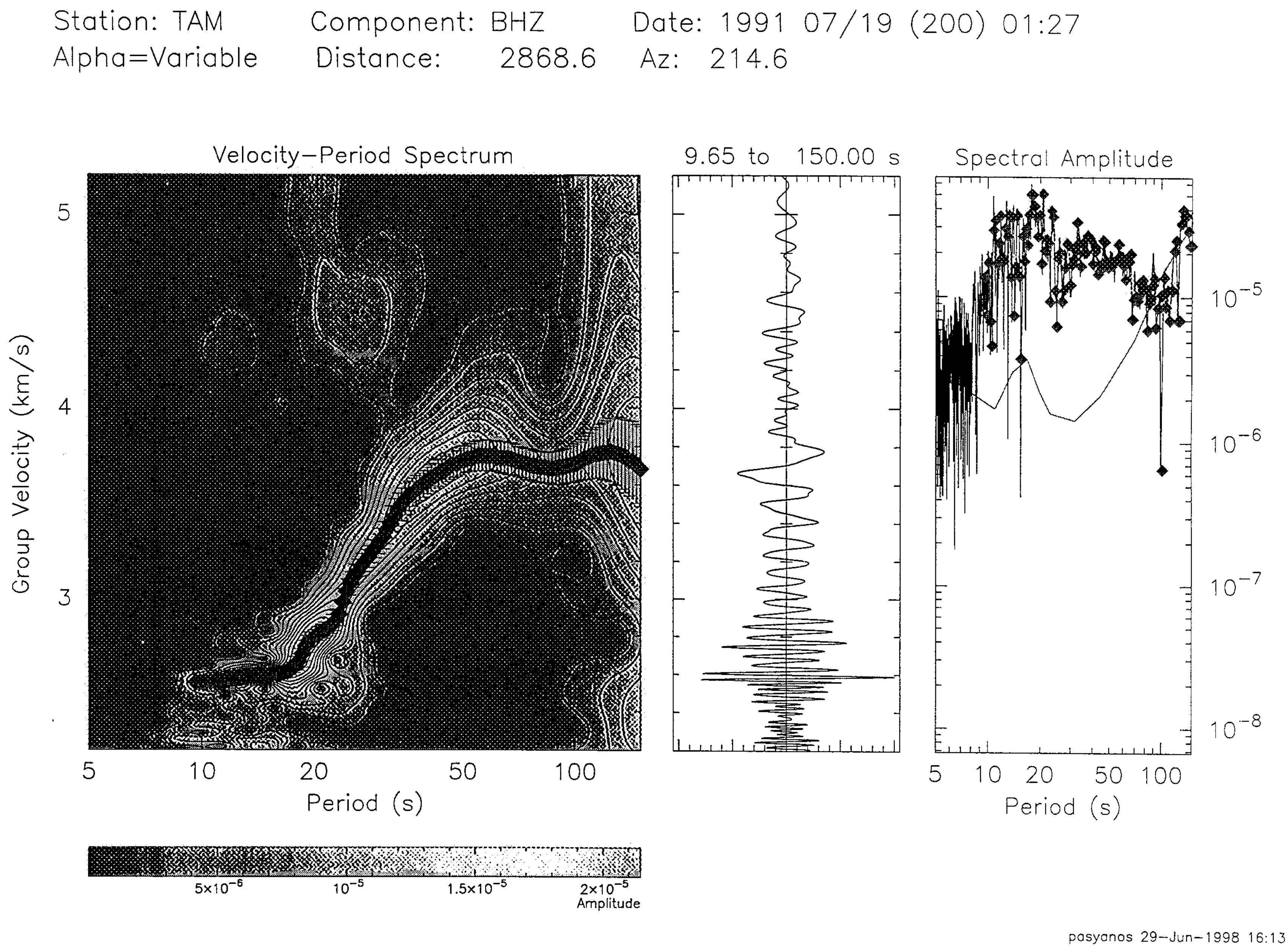

Figure 2. Sample output from PGSWMFA program. From left to right, the figure shows the velocity-period spectrum, the filtered waveform, and the spectral amplitude. Peak measurements and uncertainties are found overlying the contours of the spectrum.

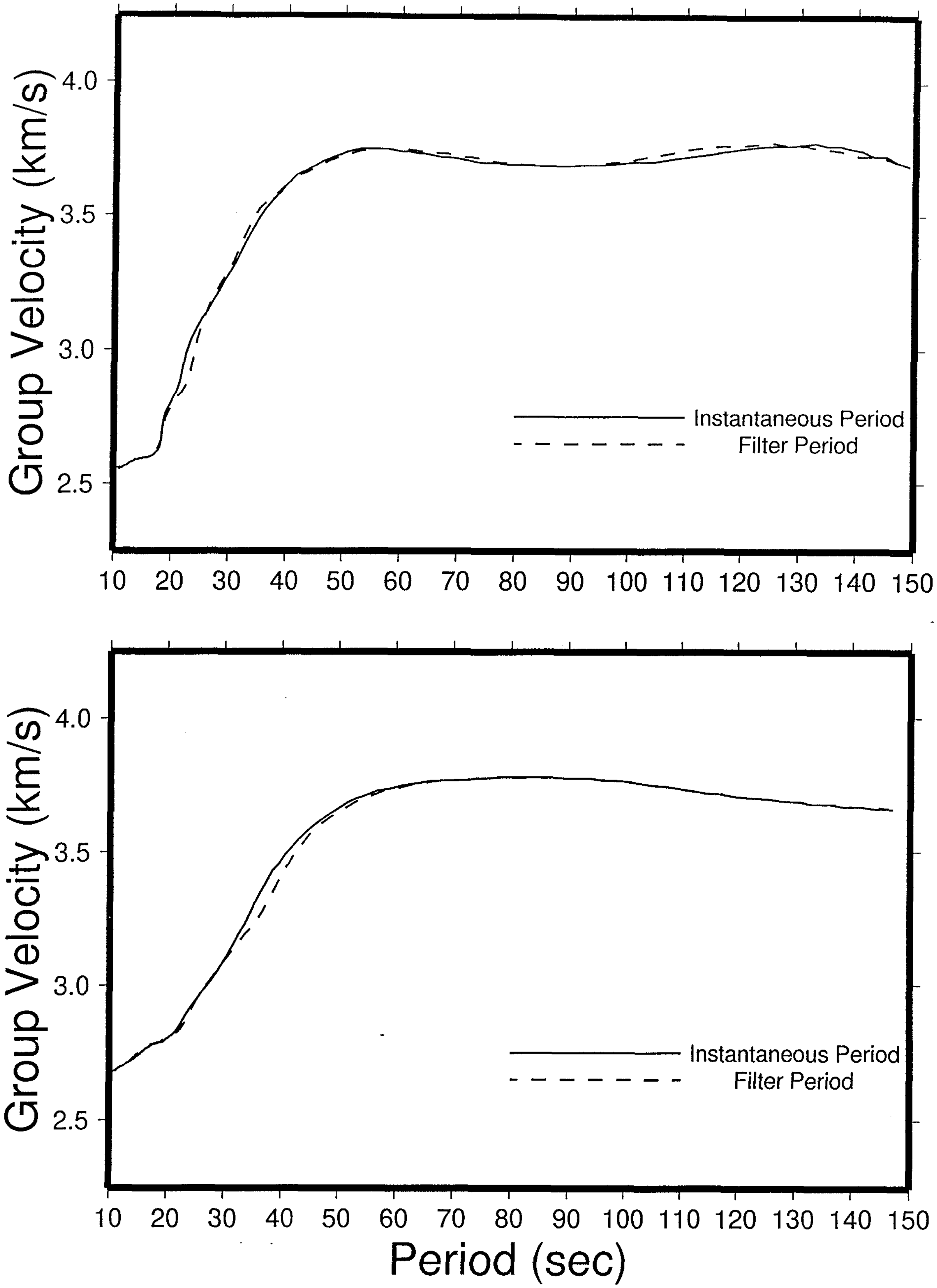

Figure 3. Two examples of group velocity measurements made using the filter period (dotted line) and the instantaneous period (solid line).

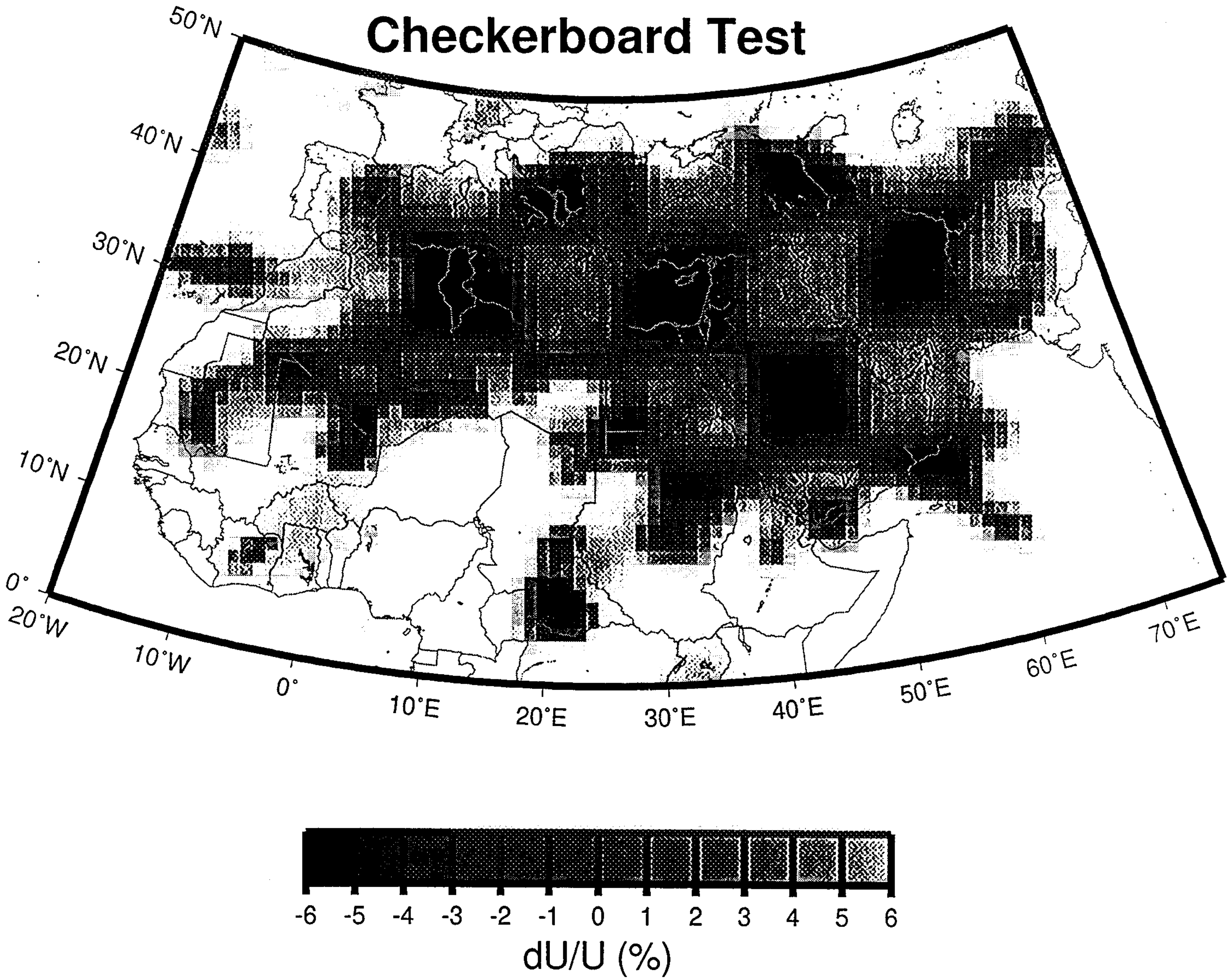

Figure 4. Inversion of a 10 degree by 10 degree checkerboard pattern with a velocity perturbation of 5% from the mean. Velocities are shaded from black (slow) to light gray (fast) with areas of low resolution indicated by white.

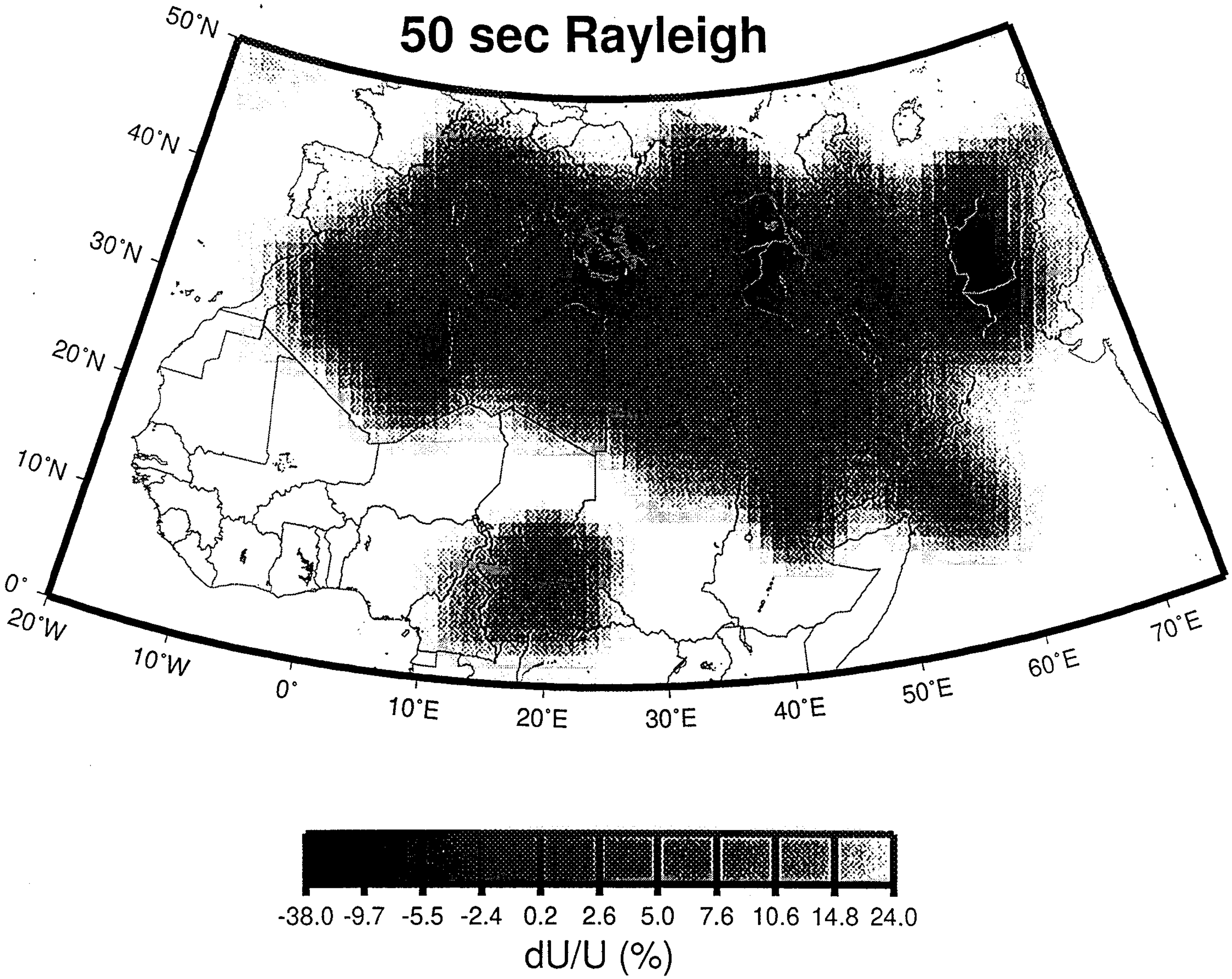

Figure 5. Rayleigh wave group velocity map at 50 seconds period. Color scheme as in Figure 4.

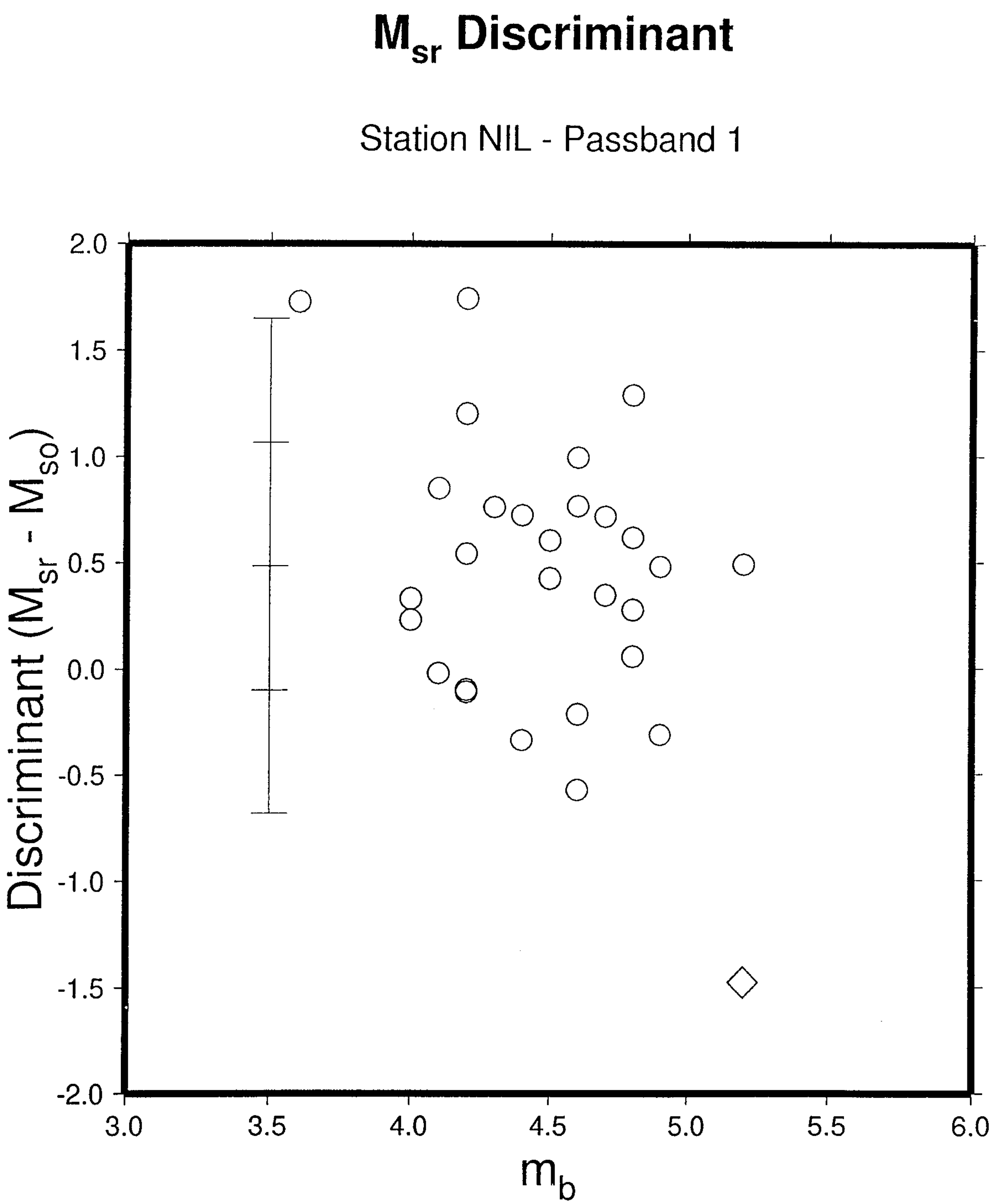

Figure 6. Regional surface wave magnitude (Msr) discriminant for South Asia. Earthquakes are indicated by circles, explosion by the diamond. Lines to the left show the mean (center line) and first and second standard deviations of the earthquake population.