SURFACE WAVE PHASE VELOCITIES BETWEEN BULGARIA AND THE CZECH REPUBLIC

FÁZOVÉ RYCHLOSTI POVRCHOVÝCH VLN MEZI BULHARSKEM A ČR

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Abstract

Surface phase velocities are measured along several profiles between Bulgaria and the Czech Republic using a modified two-station method. Love and Rayleigh waves generated by several earthquakes (Turkey, North Atlantic Ridge) are processed by the Fourier transform-based modified multiple filtering technique which is a classical tool of the frequency-time analysis. Five local maxima of the envelopes of quasiharmonic components are found and the fundamental mode dispersion ridge is estimated from the spectrogram using the criterion of continuity rather than by the traditional amplitude-based approach. Filtered fundamental modes at pairs of stations are correlated and phase velocity of both Love and Rayleigh waves is computed from the delays of propagation times of all quasiharmonic components. Determined phase velocity dispersion curves are inverted for the crust and upper mantle velocity structure. Isometric method is used for the inversion.

Abstrakt

Fázové rychlosti povrchových vln mezi Bulharskem a Českou republikou jsou měřeny podél několika profilů pomocí modifikované metody dvou stanic. Zpracování Loveových a Rayleighových vln, generovaných několika zemětřeseními (z Turecka a ze severního Středoatlantického hřbetu), je provedeno technikou mnohokanálové filtrace založené na Fourierově transformaci. Tato metoda je klasickým nástrojem frekvenčně-časové analýzy. Nejdříve je nalezeno pět lokálních maxim obálek kvaziharmonických komponent. Následně je ze spektrogramu určen disperzní hřbet základního módu a to pomocí kritéria kontinuity a nikoli tradičním přístupem postaveným na měření amplitud. Filtrované základní módy jsou korelovány mezi dvojicemi seismických stanic a ze zpoždění časů šíření všech kvazimarmonických složek je určena fázová rychlost jak Loveových tak i Rayleighových vln. Určené disperzní křivky fázových rychlostí jsou použity pro inverzi na rychlostní strukturu kůry a svrchního pláště. Inverze je prováděna pomocí izometrické metody.

Keywords

surface waves, phase velocity, shear wave velocity, isometric method

1 Introduction

Surface waves are interferential waves emerging in the finite medium with a free surface. Their velocity is frequency-dependent. This property is called dispersion, and the representation of the velocity dependence on the frequency is known as a dispersion curve. The most

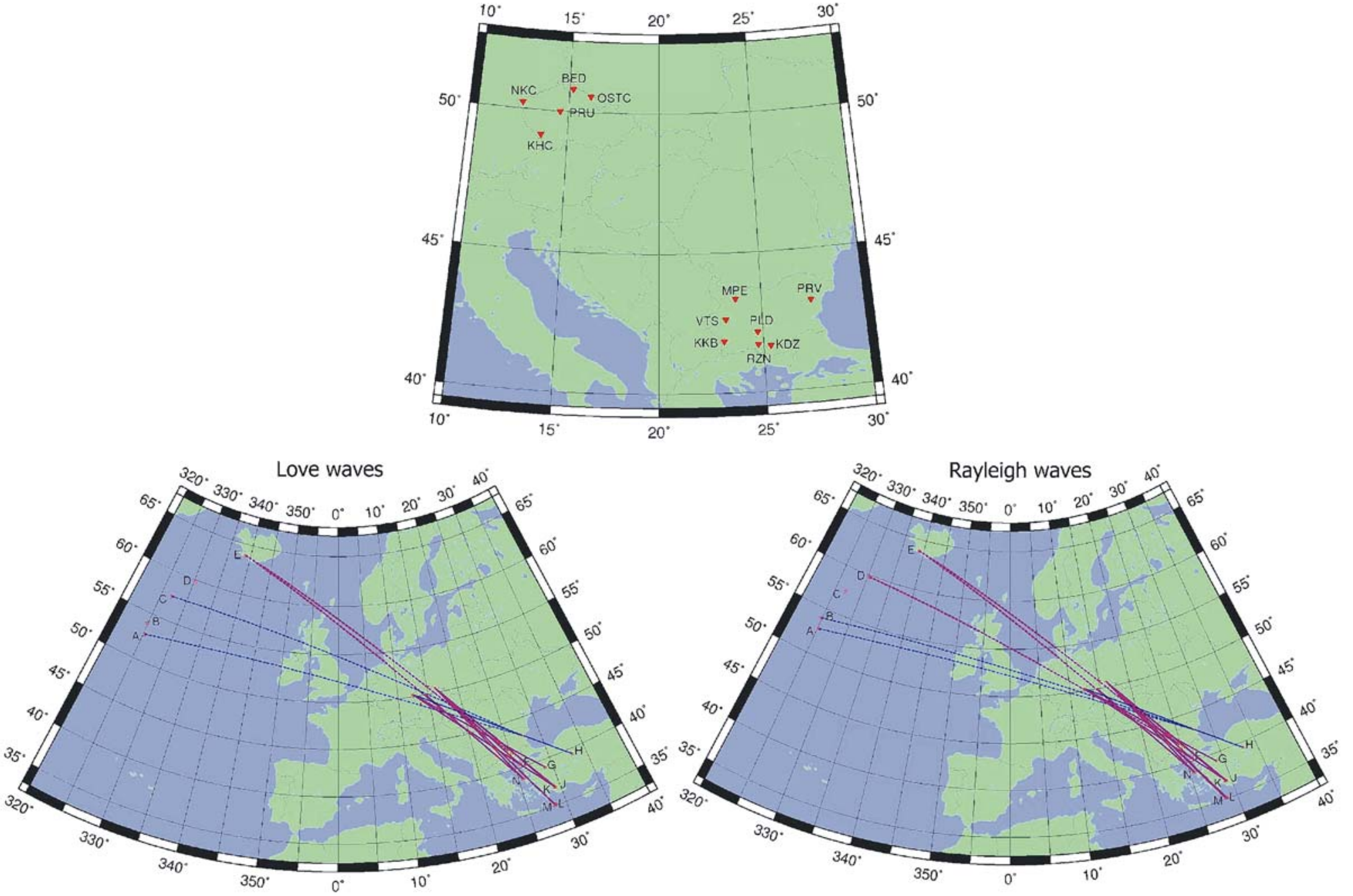

Fig. 1. The uppermost panel represents the map of the used seismic stations. The lower panels depict surface wave profiles for the Love waves (lower left panel) and for the Rayleigh waves (lower right panel). Paths are divided into two groups according to their geometrical azimuth. Blue paths follow more west-east and violet paths more northwest-southeast direction. Solid lines represent paths from Turkey and dashed lines from the North Atlantic Ridge.

Tab 1. List of used earthquakes, defined by their epicentral date and time. Mb means compressional body wave (P-wave) magnitude of the event. Column "Component" shows the components of seismograms, where it was possible determination of the phase velocity dispersion curve.T means transversal component on which the Love wave were determined, Z denotes vertical component where Rayleigh wave were defined

Event	Year	Month	Day	Time	Mb	Stations	Component
A	09	04	28	19:54:40.7	5.0	KHC, PRD	T Z
B	09	11	15	13:10:60.0	5.3	KHC, PRD	Z
C	07	10	02	12:23:46.9	5.0	PRU, PRD	T
D	08	09	03	09:52:45.9	4.8	NKC, PLD	Z
E	08	05	29	15:46:06.2	6.0	BED, PLD; PRU, KKB	T Z
F	08	12	28	22:59:02.7	5.1	VTS, NKC; RZN, OST	T Z
G	09	02	17	05:28:23.9	4.8	MPE, NKC	T Z
H	07	12	20	09:48:32.5	5.2	PRV, NKC	T Z
J	07	10	29	09:23:19.0	4.9	KDZ, OST	T Z
K	07	11	16	09:08:25.3	4.7	RZN, NKC; KDZ, OST	T Z
L	09	06	19	14:05:04.3	5.6	VTS, OST	T Z
M	09	06	18	04:26:15.9	5.0	VTS, OST	Z
N	07	11	09	01:43:09.2	5.0	KKB, PRU; VTS, OST	T Z

important surface waves in seismology are Rayleigh and Love waves. Rayleigh waves are elliptically polarized in the plane which is determined by the normal to the surface and by the direction of propagation and we can determine them on the vertical (Z) and radial (R) component of the seismograms. The particle motion of Love wave is transverse and parallel to the surface and we can measure them on the transversal (T) component of the seismograms. Surface waves are used in seismology mainly for determination of the shear wave velocity model. They are also suitable for estimation of lateral inhomogeneities and also for the determination of seismic source mechanisms (e.g. Keilis-Borok, 1989; Novotný, 1999).

Thanks to the close cooperation between the two Institutes from the Czech Republic and Bulgaria, broadband data exchange has been provided in the last years (since 2007). For the measurement, we use five stations in the Czech Republic (NKC, BED, OSTC, PRU and KHC) as well as seven stations from Bulgaria (MPE, PRD, PLD, KDZ, RZN, KKB and VTS). The map of the used stations is depicted in Fig.1. For the determination of the velocity profile between these two countries we use records of five earthquakes (A - E) from North Atlantic Ridge at the northwest side and eight earthquakes (F - N) from Turkey and Greece at the southeast side (see Tab.1). For these earthquakes, we define several surface wave profiles across Central Europe (see lower panels in Fig.1). For each event, pairs of Czech and Bulgarian stations are selected to provide relative surface wave phase velocity determination. Both Love and Rayleigh waves are used. The used period range is from 8 s to 105 s. Mutual station distances vary from 1000 km to 1400 km.

2 Surface wave phase velocity determination

To analyze dispersive records, the standard method of Fourier transform-based multiple filtering is applied. The spectrum of record is multiplied by a weighting functions cantered at many discrete frequencies. Gaussian filtering with non-constant relative resolution is used, for details see Dziewonski et al. (1969). Examples of estimating the optimum coefficient for controlling the width of the filters can be found in Levshin et al. (1972 and 1992). In the present paper, a linear dependence of the width coefficient on a period is used. For details on estimating this dependence see Kolínský (2004).

For the phase velocity determination we adopt the well known two-station approach assuming the plane-wave propagation to determine the phase velocities of surface waves. This is justified not only by long epicentral distance, but also by the use of sufficiently long-period waves which are not influenced by local lateral heterogeneities. The phase velocity calculation is based on selection of wave-group corresponding to the fundamental mode in each harmonic component. We truncate each of these harmonic components by a window centered at the envelope maximum with cosine taper on both window sides. Parameters are set so that the taper smoothes two periods around one period which is kept unchanged. Because we need to compare the records from different stations, we use the same width of filters in the frequency domain and the same width of truncating windows in the time domain for all stations to ensure the coherency of the records. For details see Kolínský et al., 2011.

An example of filtered surface wave-group of Love and Rayleigh waves in comparison to the measured seismogram is represented in Fig. 2. The resultant phase velocity dispersion curves are depicted in Fig. 3. The individual measured dispersion curves are represented by blue and violet lines. Blue lines are determined from more west-east profiles and violet lines from more northwest-southeast directions; see Fig.3. Differences in phase velocity dispersion curves between the two groups (blue and violet) are not significant. This suggests that all waves in the analyzed period range propagate in the same structure. Hence we decided to invert a mean dispersion curve estimated using all measured curves regardless of the path azimuth for each of the two surface wave types. Measured curves in Fig. 3 are compared to dispersion curves for the Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson, 1981). The PREM is one of the most widely used 1-D models of Earth seismic velocities.

3 Inversion

For the inversion we use the isometric method (IM), which is a fast inverse algorithm developed by Málek et al. (2005 and 2007). It combines features of several standard methods, particularly the simplex method, Newton's least squares method and simulated annealing, see Tarantola (1987). Typical problems, which are effectively solved by the IM, are weakly non-linear problems with tens of parameters and complicated forward modelling. Therefore it is quite suitable for the inversion of dispersion curves. The forward problem – dispersion curve computation – is solved by the modified Thomson-Haskell matrix method; see Proskuryakova et al. (1981). Dispersion curves are computed in a 1-D layered structure above a half-space with constant values of S-wave velocity, P-wave velocity and densities in the individual layers and in the half-space. During the inversion, the phase velocity dispersion curve is computed many times and the distance between theoretical and measured dispersion curves (misfit function) is minimized.

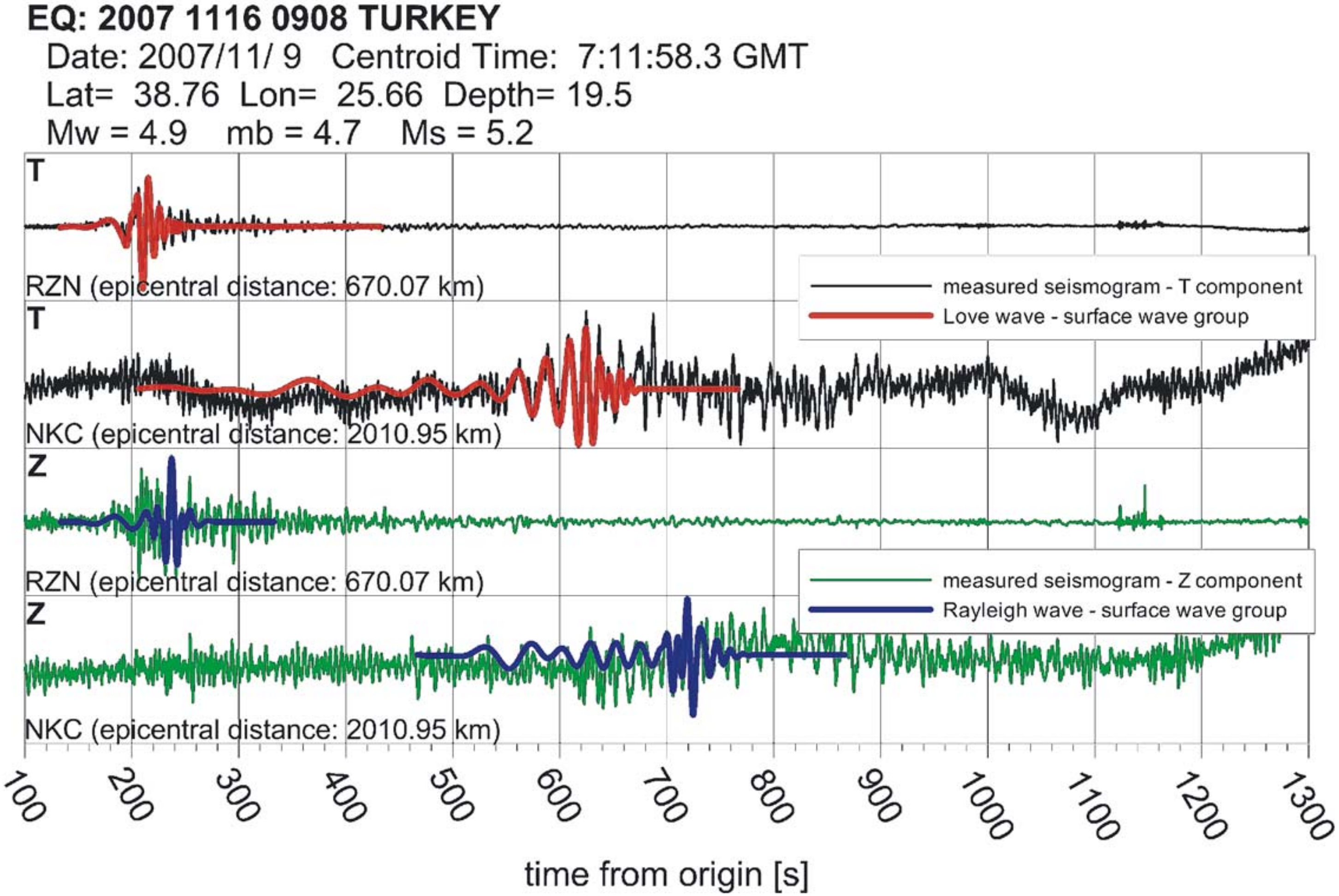

Fig. 2. Seismogram of Icelandic earthquake (event E) measured on transversal (T) component (black lines) and vertical (Z) component (green lines) at Czech (PRU) and Bulgarian (KKB) stations with filtered surface wavegroups of Love waves (red lines) and Rayleigh waves (blue lines).

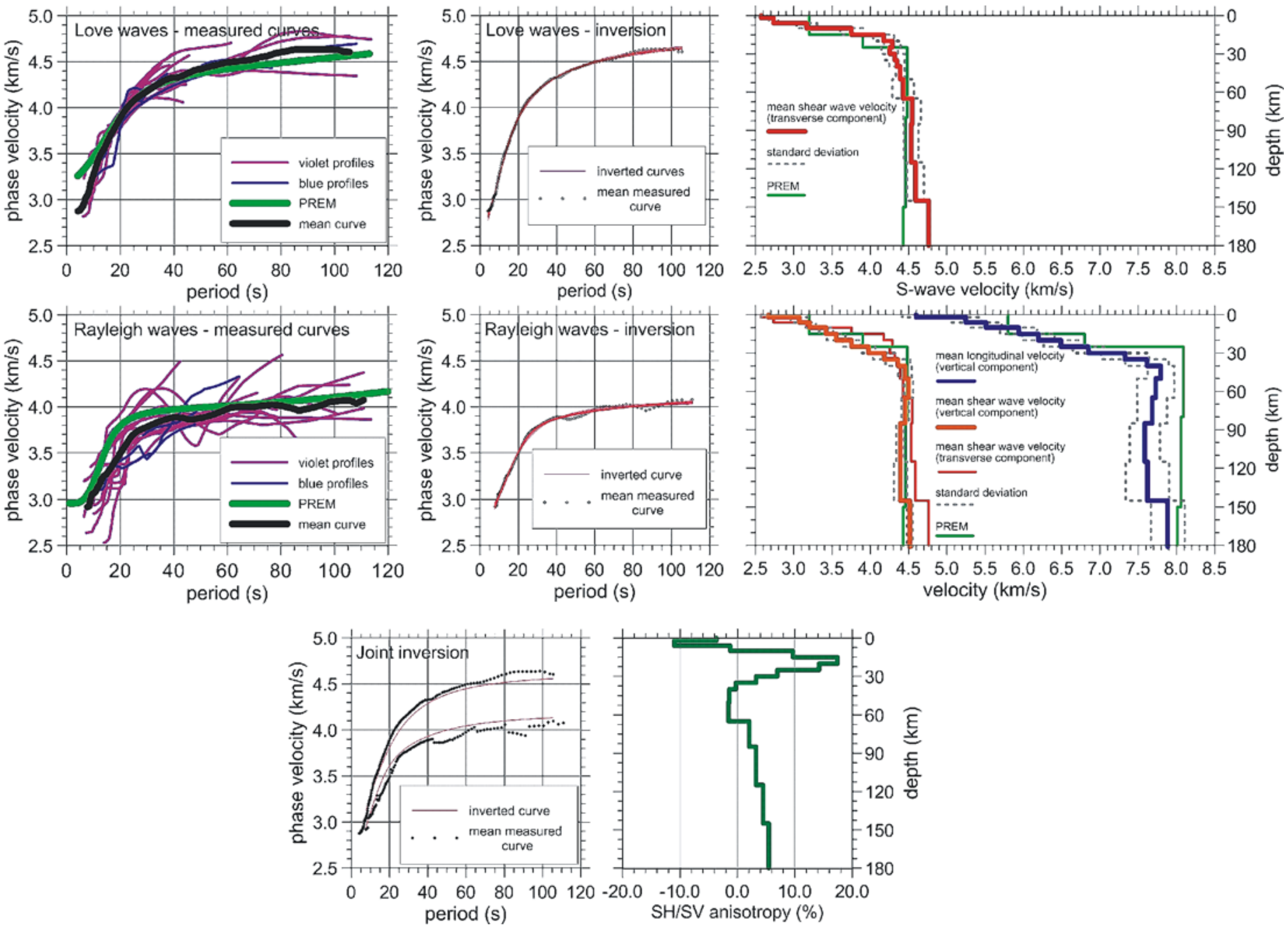

Fig. 3 Determined phase velocity dispersion curves for Love and Rayleigh waves and results of their inversions. Both determined and inverted curves are compared to the dispersion curve calculated for the PREM model. The lowest panel represents the fit of the joint inversion of the Love and Rayleigh wave dispersion curves. Right: Anisotropy estimate from a ration between the mean shear wave velocities determined from Love (T) and Rayleigh (Z) wave dispersion curves.

The result of inversion for the Love and Rayleigh waves are represented in Fig. 3. Inverted dispersion curves (red) are fitted to the measured mean dispersion (black dots). We provide 10 inversions for the same input parameters. Due to the uncertainty given by the non-uniqueness of the problem, each solution differs a little from the others. Then, mean velocity distribution with standard deviation is computed from these 10 solutions. In case of Love waves, only shear velocity is found. In case of Rayleigh waves, both shear and longitudinal velocities are found, however, the longitudinal velocity is constrained by the possible v_p/v_s ratio which is allowed to vary in the range 1.63 – 1.83. The dependence of Rayleigh wave dispersion on the longitudinal velocity is smaller than on the shear wave velocity and hence the longitudinal velocity is more constrained so that the problem is solved with an emphasis on the shear wave velocity distribution. Inversion of Love wave mean dispersion curve gives a very good fit to the measured data. Rayleigh wave mean dispersion curve is more complicated but inversion is still reliable. The resultant v_p/v_s ratio is in the range 1.68 – 1.80.

Shear wave velocity structures in Fig.3 show averaged crustal and upper mantle velocity distributions. Since the surface wave paths between both countries cross several geologically different units, the result cannot be assigned to any real structure. However, it can be considered as an effective filter converting the surface wave-groups measured in one country to the wave-groups measured in the other. The similarity of the dispersion curves measured from both sides and also the similarity of the curves for two different azimuths of propagations confirms that the averaged structural filter can be considered as stable and hence the shear velocity inversion has its significance.

Joint inversion of both Love and Rayleigh wave dispersion curves (the lowest panel of the Fig. 3) do not provide reasonable results for isotropic medium. Love waves require higher shear wave velocities than Rayleigh waves for longer periods. A comparison of resultant shear wave velocity distributions computed separately for Love and Rayleigh waves, allows to estimate the apparent ratio between SH (transverse component) and SV (vertical component). The discrepancy can be caused either by anisotropy or by heterogeneity and different ray-paths, or by both phenomena together. From the SH/SV ratio, the maximal anisotropy estimate can be deduced. For the upper mantle, where the results are most stable, the anisotropy estimate reaches 5 %, see Fig. 9, right panel. In the lower crust, the maximal anisotropy is estimated to be 10 – 18%.

4 Conclusions

Average phase velocity from transverse component (Love waves) and from vertical component (Rayleigh waves) is determined and inverted for mean shear and longitudinal wave velocity distribution in the crust and the upper mantle. The results are compared to the PREM model. Shear wave velocity determined jointly using Love and Rayleigh waves pronounces discrepancy that can be caused either by anisotropy or by divergent true ray-paths of the two respective wave types.

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