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6.5 Comparison of the Love-Rayleigh discrepancy in central Europe (GRSN) and southern Scandinavia (NORSAR)

6.5.1 Introduction

The lower crust and mantle are known to be laterally heterogeneous. Furthermore, they are supposed to be anisotropic. However, anisotropy in the upper mantle and the lower crust is a matter of debate, in particular in continental regions and in subduction zones. This question might be investigated by shear-wave splitting studies, but the depth resolution of this method is limited. Investigation of anisotropy by inversion of surface wave observations shows the advantage of a good resolution in depth.

Love-Rayleigh discrepancy denotes the observation that dispersion curves of fundamental Love and Rayleigh modes cannot be explained by the same isotropic one-dimensional model (McEvilly, 1964). It was repeatedly detected in oceanic regions, e.g. in the Pacific (Ekström and Dziewonski, 1998), while for continental regions the amount of the Love-Rayleigh discrepancy was discussed controversially (e.g., Montagner and Tanimoto, 1991). The Love-Rayleigh discrepancy might be explained by radial anisotropy, that means by different velocities for the horizontally polarized SH- and the vertically polarized SV-wave velocities. The fundamental Rayleigh mode is mainly sensitive to the velocity of transversal particle motion in vertical direction, as SV, whereas Love waves are sensitive for velocities in horizontal direction as SH. However, similar effects might be caused by thin isotropic layers of alternating high and low velocities, or by the different influence of lateral heterogeneity or higher modes on the measurements of the phase velocities of Love and Rayleigh waves (Levshin and Ratnikova, 1984; Maupin, 2002). Azimuthal variations in the Love-Rayleigh discrepancy point to azimuthal anisotropy (Maupin, 1985).

Here, we present examples of the investigation of the Love-Rayleigh discrepancy in two tectonically different continental regions: for the Phanerozoic asthenosphere and lithosphere in central Europe and at the border of the Precambrian Baltic Shield.

6.5.2 Method and Measurements

Dispersion curves of the fundamental modes were measured by a two-station method (Meier et al., 2004). One event is recorded at two stations. The cross correlation of the seismograms leads to phase differences and with the known distance between the stations the phase velocities can be calculated. This procedure is repeated for many events. Then, the inversion of averaged phase velocity curves of fundamental surface wave modes yields one-dimensional models of the *S*-wave velocity structure. These are interpreted as a average models describing the structure beneath the paths.

6.5.3 GRSN

Phase velocities of the fundamental Love and Rayleigh modes were determined for two paths between stations of the German Regional Seismic Network (GRSN). This network consists of 16 permanent broadband stations (STS-2) and was installed in the early 1990s. Here, dispersion curves for the two paths BUG-WET and BFO-CLZ were measured (Fig. 6.5.1). The angle between the two paths is about 90 degrees. The lengths of the paths are 473 and 417 km, respectively. For a minimum event magnitude Ms 5.0 and the given geometry and 36 and 72 events were found, respectively. Phase velocity curves for these events were averaged for each path. The maximum azimuthal deviation of the great-circle paths of wave propagation from the great-circle between the stations was limited to 7°.

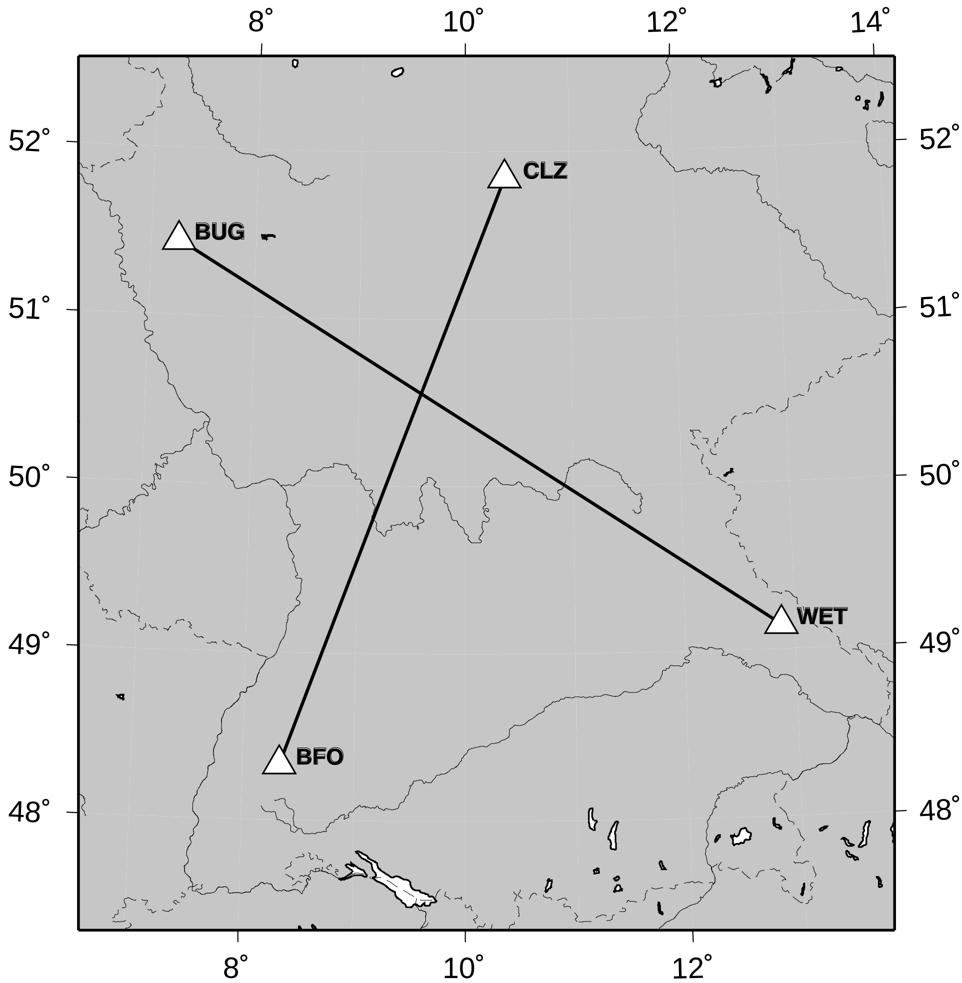

Fig. 6.5.1. Love and Rayleigh phase velocities are measured for the paths BUG-WET and BFO-CLZ using a two-station method (Meier et al., 2004). The inversion of the phase velocities yields 1D-models of the S-wave velocity structure that are interpreted as a average models of the paths. The angle between the two paths is about 90 degrees. The lengths of the paths are 473 and 417 km, respectively.

Phase velocities were determined between 5 and 100 mHz (Fig. 6.5.2, left). The 1D-*S*-wave velocity model that results from the inversion of the Rayleigh wave phase velocity shows an asthenosphere between 80 and 250 km depth. However, it does not show up in the inversion result of Love wave velocity curves (Fig. 6.5.2, right). For both models the theoretical Rayleigh wave phase velocities were calculated and compared to the observed curves (Fig. 6.5.2, left). Both paths show a Love-Rayleigh discrepancy in the frequency band between 5 and 30 mHz. This corresponds to depths between 80 and 250 km. This found discrepancy points to radial anisotropy in the asthenosphere and confirms results by Wielandt et al. (1988) and Friederich and Huang (1996). Remarkably, the amount of this Love-Rayleigh discrepancy in the asthenosphere is comparable to that of the Pacific around Hawaii (Ekström and Dziewonski, 1998).

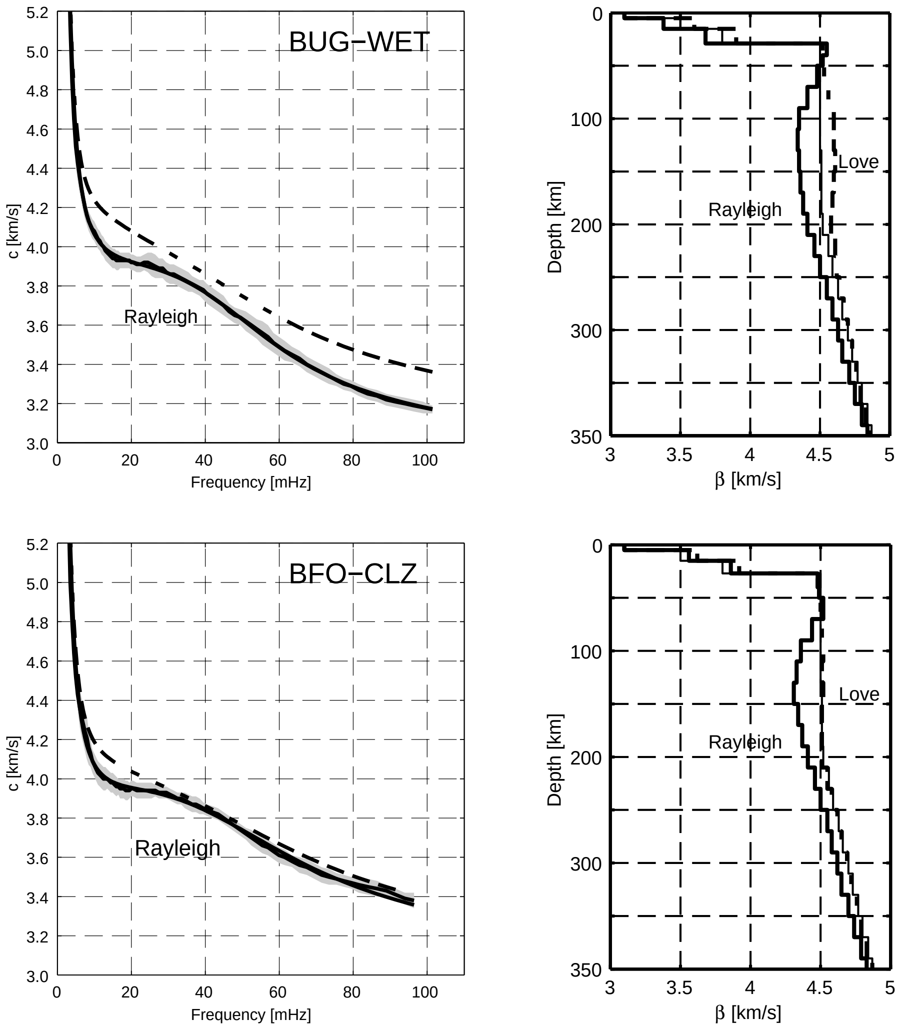

Fig. 6.5.2. The 1D-S-wave velocity model that results from the inversion of the Rayleigh wave phase velocity shows an asthenosphere between about 80 km and 250 km depth. It does not show up in the inversion result of the Love wave velocity curve (right). Theoretical Rayleigh wave phase velocities for both models are depicted on the left (dashed lines). The solid lines show the observed data and the grey area indicates the corresponding standard deviations. Both paths show a Love-Rayleigh discrepancy between 5 and 30 mHz. In addition, a Love-Rayleigh discrepancy is found between about 50 and 100 mHz.

In addition, a Love-Rayleigh discrepancy between 50 and 100 mHz is detected (Fig. 6.5.3). The Love-Rayleigh discrepancy in this frequency range corresponds to lower crustal levels and it differs for the two paths. The Rayleigh-wave phase velocity curves are different above 50 mHz pointing to azimuthal anisotropy in the crust with a fast axis oriented approximately in NE-SW direction. Studies of Pn-anisotropy yield similar results (e.g., Bamford, 1987; Song et al., 2004). Surprisingly, the dispersion curves of the Love waves are similar for both paths. It remains an open question if the behavior of the Love waves is due to finite-frequency effects or due to anisotropy of the lower crust. Finite-frequency effects of wave propagation result from lateral heterogeneity and are expected to be stronger for Love than for Rayleigh waves. On the other hand this new observation can be explained by models of an anisotropic lower crust.

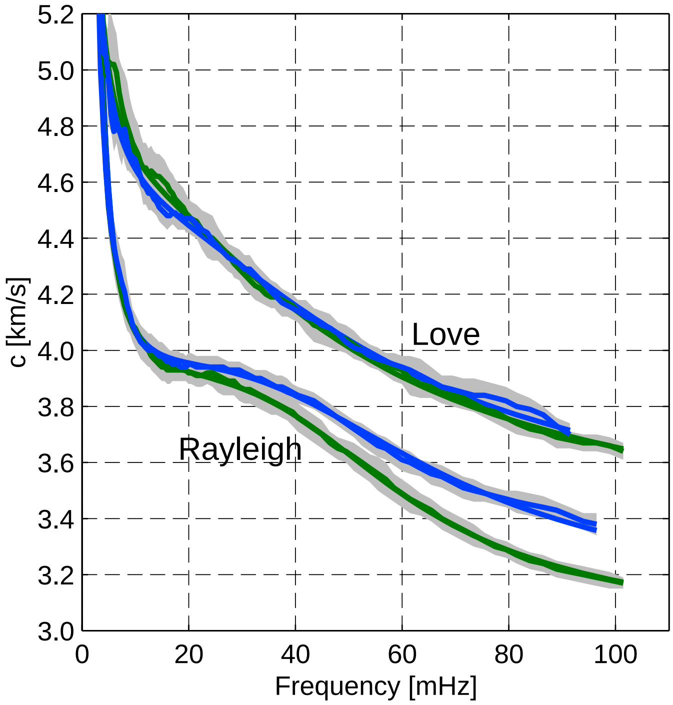

Fig. 6.5.3. Phase velocity curves for the paths BFO-CLZ (blue) and BUG-WET (green); the gray shaded area indicates the uncertainty range of the observations. The dispersion curves of the Love waves are similar for both paths. However, the Rayleigh wave phase velocity curves are different above 50 mHz. The azimuthal variation in the Love-Rayleigh discrepancy might be explained by azimuthal anisotropy in the crust with a NE-SW oriented fast polarization axis. Studies of Pn-anisotropy yield similar results (e.g., Bamford, 1987; Song et al., 2004).

6.5.4 NORSAR

Phase velocities of fundamental Love and Rayleigh modes were determined for 8 paths between six NORSAR broad-band stations (Fig. 6.5.4). The seventh broad-band station in the center of the array could not be used because the inter station distances will then become too short. The distances between the used stations vary between 48 and 72 km. Surface wave observations from altogether 227 events were investigated for the time period January 1996 to July 2003. The number of events evaluated for a single path varies for Rayleigh waves from 17 to 58. A total of 206 events were used for the determination of Love-wave phase velocities. Due to the smaller distances between the stations phase velocities could only be analyzed between about 20 and 100 mHz (Fig. 6.5.5, left).

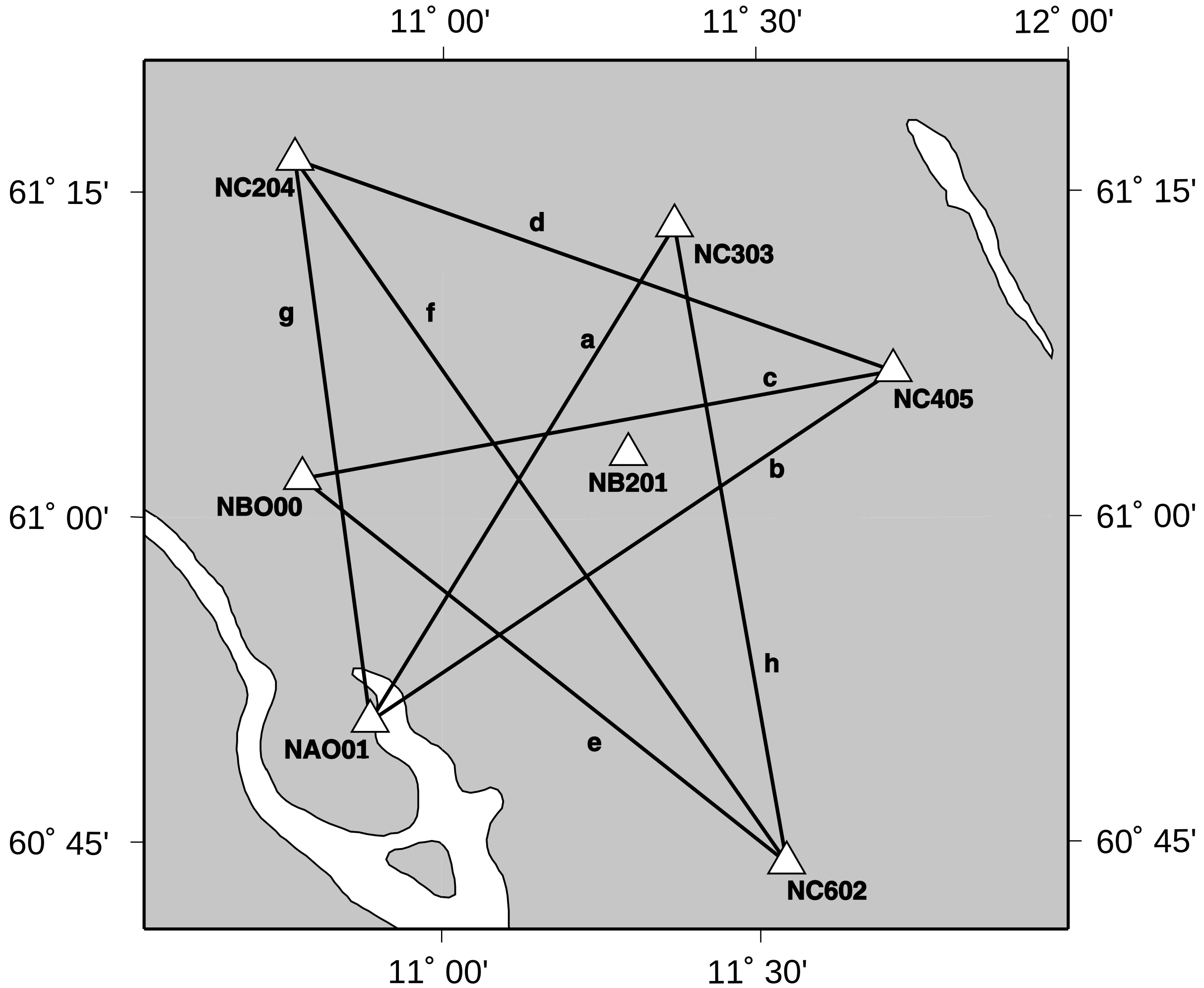

Fig. 6.5.4. Illustration of the eight different paths between six broad-band stations of the NORSAR array used in this study.

The Rayleigh-wave phase velocities of all paths were averaged and inverted to an average model of the structure beneath the NORSAR-array. The resulting 1D *S*-velocity model (Fig. 6.5.5, right) reaches only down to 100 km because of the limited frequency range. The *S*-wave velocity in the mantle lithosphere is lower than expected for stable cratonic regions. The mean depth to the Mohorovicic discontinuity is about 35 km.

Theoretical Love and Rayleigh phase velocity curves were calculated for this model (Fig. 6.5.5, left, red lines). Comparison with the averaged observed curves and their standard deviation shows no significant Love-Rayleigh discrepancy. This might be due to the large standard deviation (gray shaded areas) of the phase velocity curves mainly caused by the small distances between the stations.

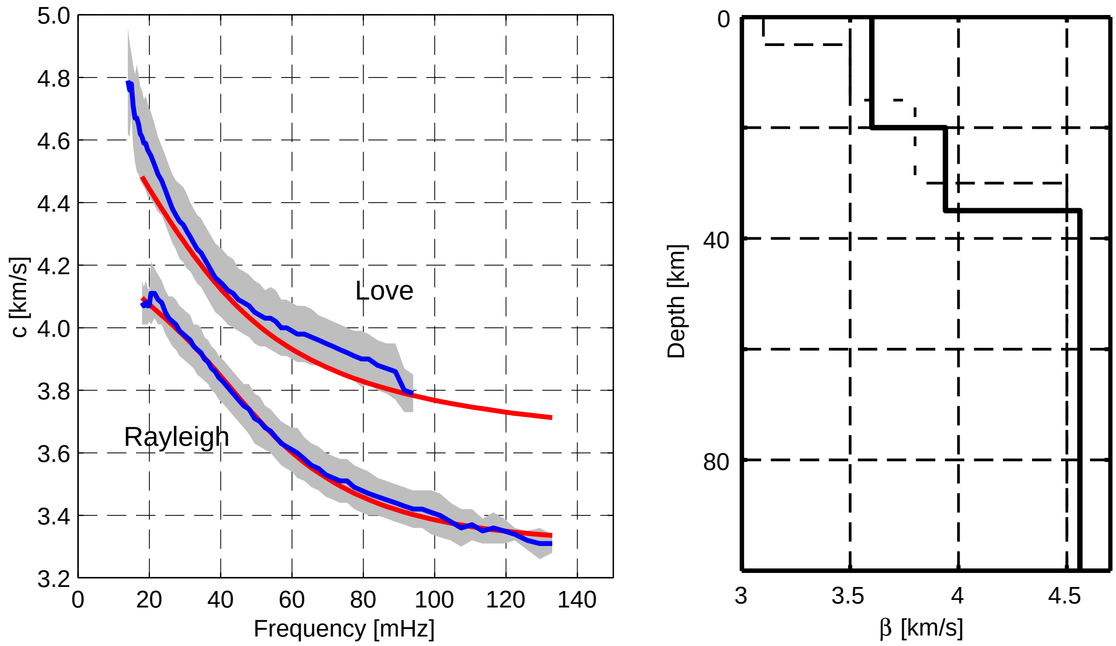

Fig. 6.5.5. Average Love and Rayleigh dispersion curves (left, blue). The inversion of the Rayleigh-wave phase velocity curves yields a 1D-model of the S-wave velocity (right, solid curve; the broken line shows the starting model). Theoretical Love and Rayleigh phase velocity curves for the models are shown on the left (red). Comparison with the averaged observed curves and their standard deviation (gray shaded areas) shows no significant Love-Rayleigh discrepancy.

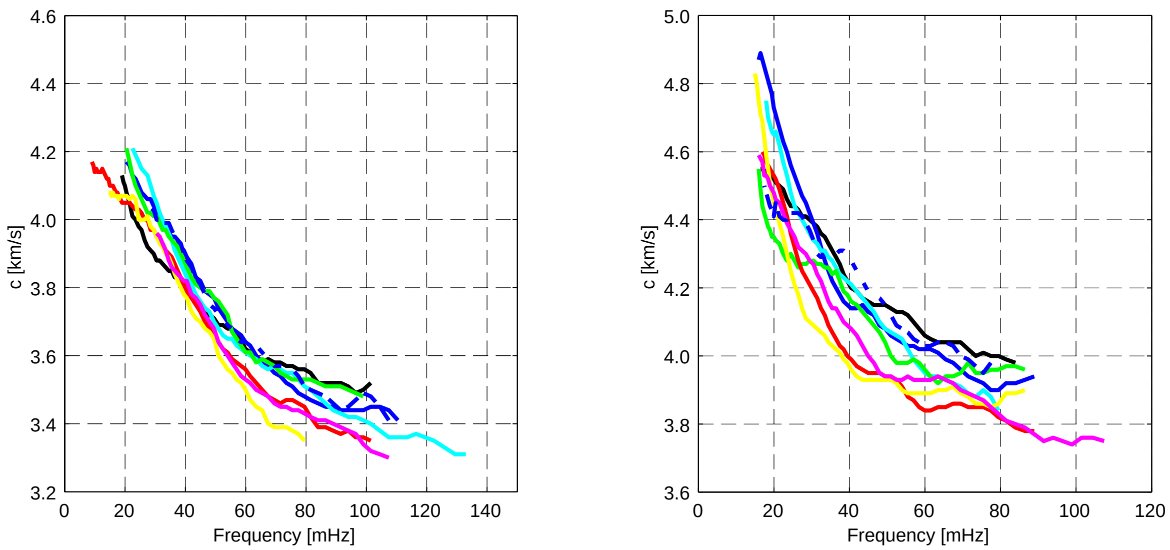

Fig. 6.5.6. Rayleigh (left) and Love wave (right) dispersion curves for the different raypaths crossing the NORSAR array (for path identification see text). Strong differences in the phase velocities are present above 50 mHz for Rayleigh waves and above 20 mHz for Love waves. The variations in phase velocities are similar for Love and Rayleigh waves: Paths with slow Rayleigh wave phase velocities show slow Love wave phase velocities as well. This observation can be explained by lateral heterogeneity in the crust but not by azimuthal anisotropy.

Comparing the phase velocities of the eight paths shows that strong differences are present above 50 mHz for Rayleigh waves and above 20 mHz for Love waves (Fig. 6.5.6). The different paths as labelled in Fig. 6.5.4 correspond with following colors used in Fig. 6.5.6: a (black), b (blue), c (cyan). d (green), e (blue, broken line), f (magenta), g (yellow), and h (red). The structure in a certain depth affects Love wave dispersion curves at lower frequencies than Rayleigh wave dispersion curves. Variations in phase velocities are similar for Love and Rayleigh waves: Paths with slow Rayleigh wave phase velocities show slow Love wave phase velocities as well. This observation can be explained by lateral heterogeneity in the crust.

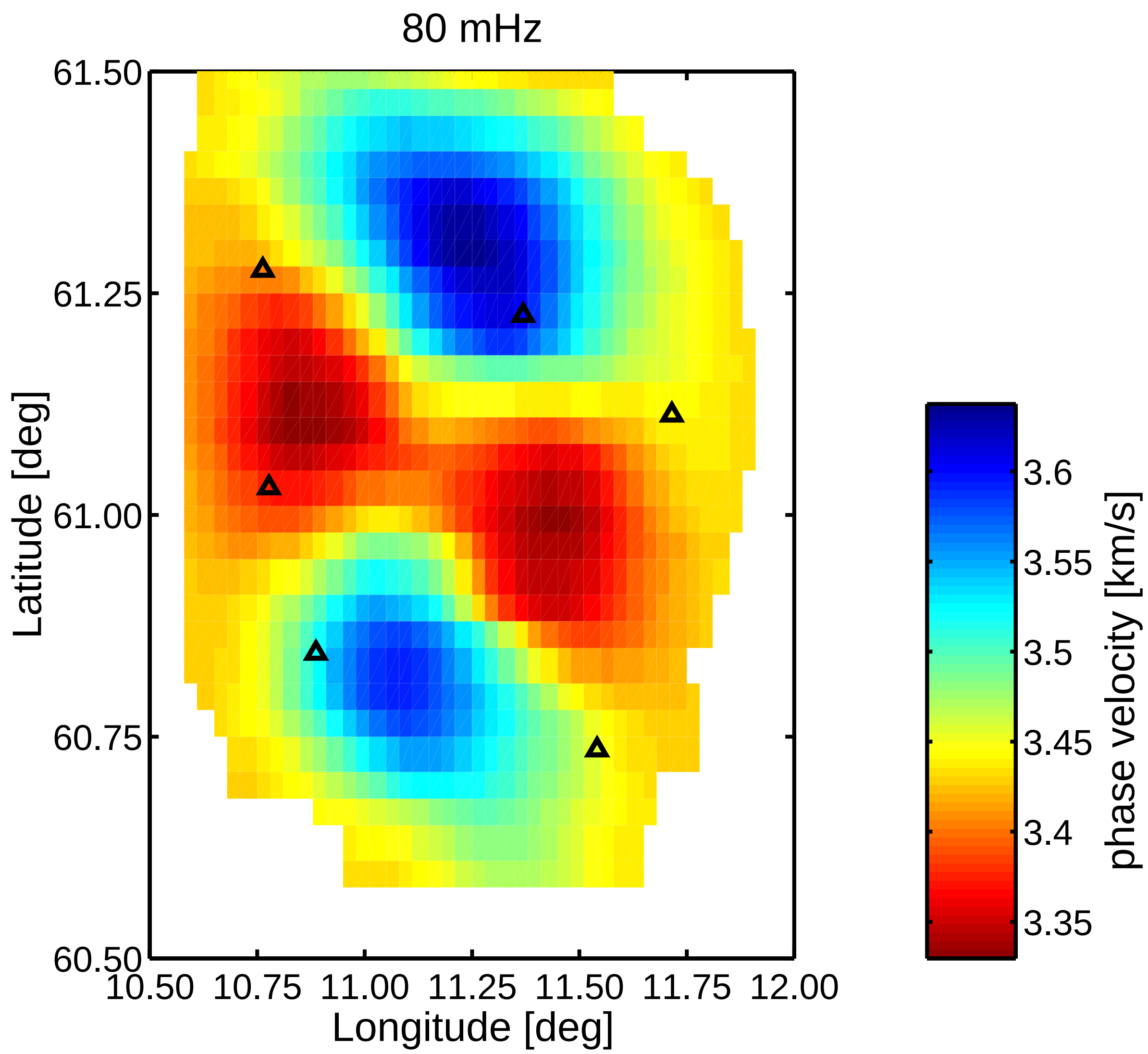

Fig. 6.5.7. Phase velocity map of the fundamental Rayleigh mode at 80 mHz. The strike of the low velocity anomaly in the crust is about NW-SE. It is similar to the strike of the Precambrian structures at the surface. A comparable result was obtained by the classical ACH-study using relative P-wave residuals observed at the NORSAR array (Aki et al., 1977).

To locate such lateral heterogeneities a phase velocity map of the fundamental Rayleigh mode at 80 mHz was calculated (Fig. 6.5.7). Rayleigh waves of about 80 mHz are mostly sensible for the middle crust at a depth range between 15 and 25 km. The strike of the low velocity anomaly in the crust is about NW-SE. It is similar to the strike of the Precambrian structures at the surface. For the crust, a comparable result was obtained by the classical ACH-tomography study using teleseismic P-phase observations at the single NORSAR sites (Aki et al., 1977).

6.5.5 Conclusions

GRSN

In Central Europe the asthenosphere is found between 80 km and 250 km depth. The Love-Rayleigh discrepancy in the asthenosphere amounts to about 5%. This is comparable to the degree of Love-Rayleigh discrepancy in the Pacific.

Azimuthal variations of the Rayleigh phase velocity point to azimuthal anisotropy in the lower crust. The orientation of the fast axis is approximately NE-SW.

In contrast to the Rayleigh wave phase velocities, Love waves do not show dependence on azimuth. Further studies should reveal if this discrepancy is caused by finite-frequency effects, or contamination of the Love-wave phase velocities by higher modes, or if this discrepancy might yield constraints on models of the anisotropy in the lower crust.

NORSAR

The *S*-wave velocity in the mantle lithosphere is lower than expected for stable cratonic regions. However, the NORSAR array is located at the border of the Precambrian Baltic Shield and this region was influenced by several tectonic processes. The depth of the Moho is about 35 km.

Variations in the phase velocity between the paths point to lateral heterogeneities with S velocity variations of up to +/- 3.5%. The strike of the observed velocity anomaly in the crust is NW-SE. It is similar to the strike of the Precambrian structures at the surface.

The amount of the Love-Rayleigh discrepancy in the lower crust is not significant, which might be partly due to the large standard deviation of the phase velocities.

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