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Tormod Kværna (Ed.)

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6.3   P-wave Polarization and FK Analysis of NORSAR Array Data to Investigate Local Anisotropy and Lateral Heterogeneity

6.3.1   Introduction

Three-component broad-band data from the NORSAR array are ideally suited to apply polarization (*e.g.*, Jurkevics, 1988; Schulte-Pelkum *et al.*, 2001) and fk-analysis (*e.g.*, Davies *et al.* 1971; Capon, 1973; Posmentier and Herrmann, 1971) to estimate anomalies of wave polarization and propagation vectors induced by local wave speed anisotropy and lateral heterogeneities. Long recording time and high quality data guarantee in fact a good azimuthal distribution of events with high signal-to-noise ratio (SNR).

Array techniques as fk-analysis are commonly applied for event location and to enhance the SNR by delaying and stacking of the traces (beamforming). Fk-analysis estimates together with the signal slowness and backazimuth provide also a measure of the coherence of the seismic wave crossing the array. Polarization analysis is mainly used as a single station method to investigate the characteristics of the particle motions.

6.3.2   Data and analysis

Fk- and polarization analysis have been applied to almost 20 years of NORSAR array data to investigate anisotropy of seismic velocities and lateral heterogeneities beneath the array.

We expect that polarization and propagation direction of P waves are both affected by seismic anisotropy, as well as by lateral heterogeneities, but with different sensitivities. Polarization parameters are finite frequency observables mostly related to structures up to about one wavelength from the receiver area. The propagation vector direction is also sensitive to distant heterogeneities and distant anisotropy. By polarization analysis we can estimate the deviation of the P-wave polarization vector and by fk-analysis the deviation of slowness and backazimuth. The dependence of those deviations on event backazimuth, epicentral distance and frequency is studied.

In this study, we used data from all seven three-component sites (NAO01, NBO00, NB201, NC204, NC303, NC405, and NC602) of the NORSAR array, which have recorded broadband data since 1996. The locations of these stations maintain the circular shape and aperture of the whole array. Altogether about 600 first arriving teleseismic P waves were analyzed. Events with high SNR have been selected and a good distribution in backazimuth and distance could be obtained (Fig. 6.3.1).
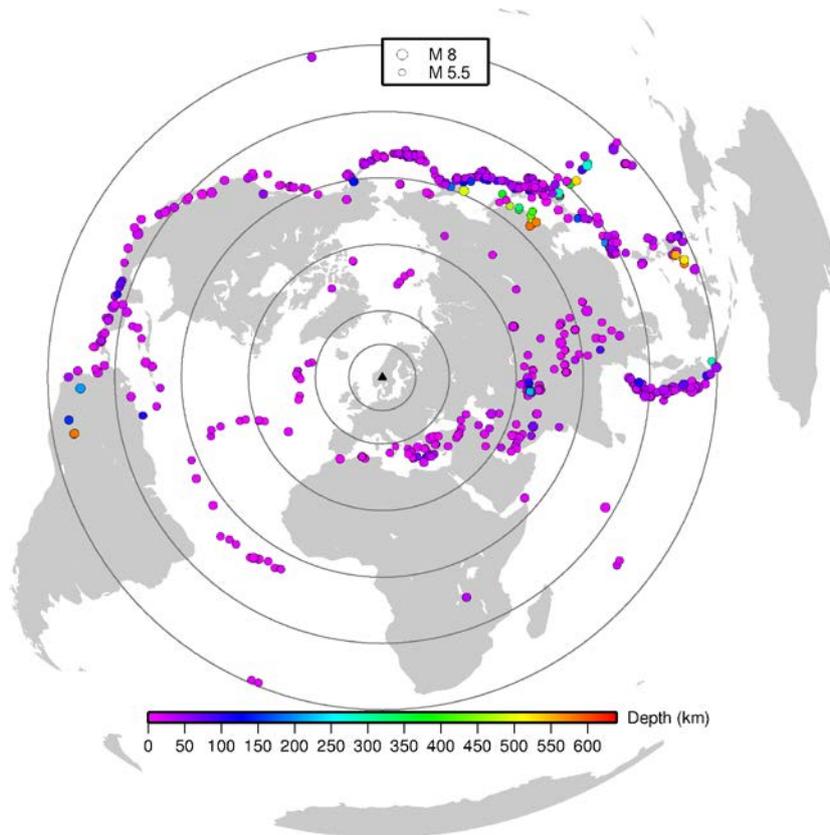
*Fig 6.3.1
Epicenter map (circles) of the seismic events used in this study. The map is centered at the location of the NORSAR array.*

6.3.3 Fk-analysis

A sliding window fk-analysis algorithm has been applied to estimate backazimuth and slowness of the first arriving P waves of the selected events in the following frequency bands (0.03 – 0.1 Hz, 0.1 – 0.5 Hz, 0.5 – 1 Hz, 1 – 4 Hz).

The effect of filtering (number of poles and values of corner frequencies) and length of time window have been investigated as well. The slowness and backazimuth estimates didn't show any dependence on the filtering nor on window length, whose maximum and minimum were limited by the array aperture and central frequency. Only measurements characterized by high coherence have been considered to study the deviation of P-wave propagation direction from the great circle path direction as a function of backazimuth, distance and frequency.

Fig. 6.3.2 shows the backazimuth anomalies (top) and slowness anomalies (bottom) as function of backazimuth for lower and higher frequencies. By fk-analysis changes in the horizontal slowness vector due to local and distant lateral heterogeneity and due to distant anisotropy may be detected. In case of local lateral homogeneous azimuthal anisotropy, we expect that by fk-analysis changes in the slowness but not in the backazimuth, are observed, as the slowness may change, but the wavefront is not deformed.
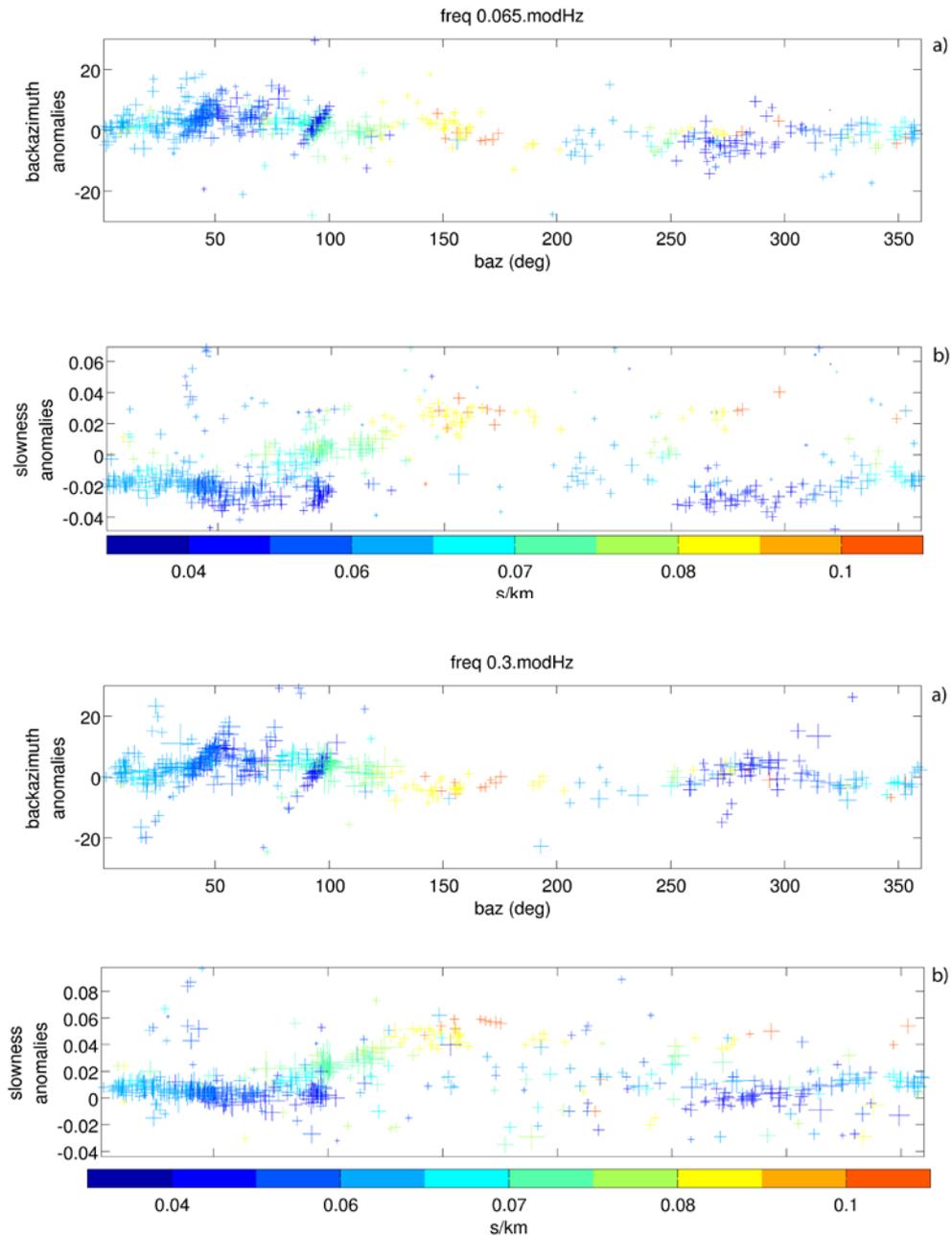
Fig. 6.3.2 *Backazimuth (a) and slowness (b) anomalies from fk-analysis plotted as function of the theoretical backazimuth, for low frequencies (up), high frequencies (down). Colors are used here to distinguish between events characterized by different theoretical slowness vectors (from IASPEI tables). We observe slightly negative slowness anomalies for events with small theoretical slowness and positive anomalies for events with large slowness for the backazimuth between 80 and 250°. Sign and amplitude of the deviations seem to have a weak dependence on frequency and a clear dependence on backazimuth. Different slownesses sense differently the structure characteristics. The observed deviations can be interpreted in terms of distant and local heterogeneities.*

6.3.4   Harmonic analysis of backazimuth anomalies

As can be seen in Fig. 6.3.2 (a) the azimuthal deviations are mainly a function of backazimuth and frequency. To investigate the characteristics of this dependence, we apply a harmonic analysis. We assume that the azimuthal deviations can be expressed as the sum of cosine functions of backazimuth with different periodicities. For each component it is possible to estimate amplitude (A_k) and phase (phi_k). The dominant periodicity estimated by fk-analysis for the observed azimuthal anomalies at NORSAR is clearly 360°.

This periodicity in the backazimuth anomalies can be generated by a velocity gradient *e.g.*, caused by a dipping interface (see *e.g.*, Niazi, 1966). From the phase of the 360° term it is possible to determine the strike of the structure showing the velocity gradient and the direction to the low velocities. The 180° periodicity term can be explained in terms of azimuthal anisotropy with a horizontal symmetry axis. From the phase of this harmonic it is possible to estimate the direction of the fast axis of anisotropy.

6.3.5   Polarization analysis

P-wave polarization parameters, namely azimuthal deviation and incidence angle, have been estimated by solving the eigenvalue problem of the 3-component signal covariance matrix in a moving window, following the algorithm proposed by Jurkevics (1988). The parameters have been calculated for each 3C-station of the NORSAR array in 3 frequency bands (0.03 – 0.1 Hz, 0.1 – 0.5 Hz and 0.5 – 1 Hz). The procedure has been automatized and an automated picking algorithm has been used to estimate the polarization parameters of the first P-wave onset including a measure for the quality of the estimate (Cristiano *et al.*, in preparation). Fig. 6.3.3 shows as example the results of the polarization analysis for the array sites NB201 and NC204. Also the azimuthal deviation of the P-wave polarization is mainly dependent on the backazimuth and the frequency. Therefore, we do not separate measurements related to events with different epicentral distances. This works as an averaging of deviations over epicentral distances and different source locations and characteristics, and results in a down weighting of the ray path contribution and source area effects.
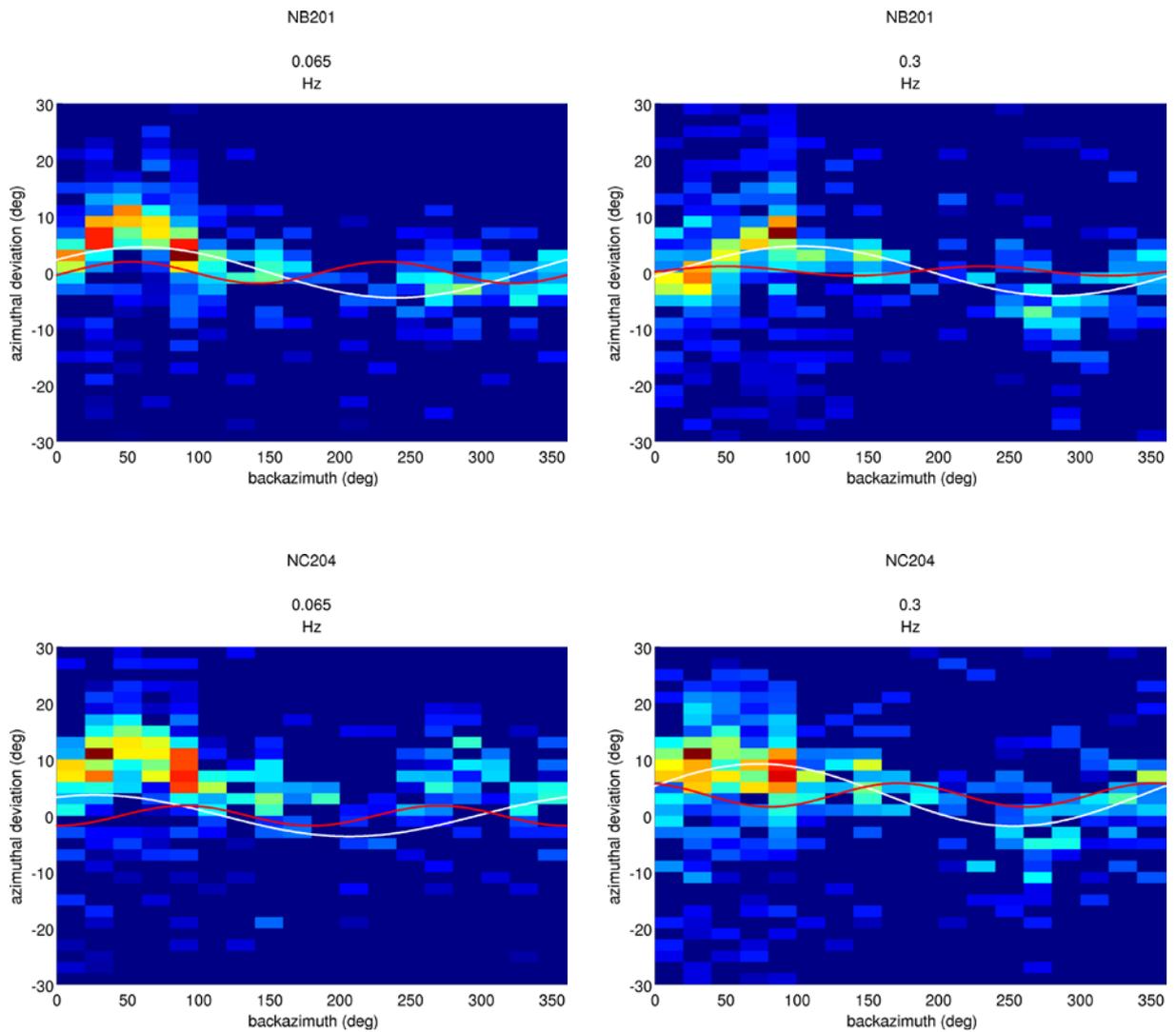
Fig. 6.3.3   2D histogram of the azimuthal deviations estimated by polarization analysis at the
NORSAR sites NB201 and NC204 in two frequency bands (0.03 – 0.1Hz, 0.1 – 0.5 Hz). The
measurements are distributed in bins of azimuthal deviation and backazimuth ranges.
Colors are used to show which bins have the higher number of high quality measurements.
Plotted as overlay are the cosine functions with 360° and 180° periodicity from the applied
harmonic analysis. Minimum and maximum of the color scale is in dark blue and red,
respectively.

6.3.6   Discussion of the results

Harmonic analysis has been applied on the azimuthal deviations estimated by polarization analysis. The dominant periodicities are 360° and 180° for each station of the NORSAR array, but the 180° term is only significant at sites NC204 (see Fig. 6.3.3) and NC303.

The directions to high velocity anomalies estimated by analysis of azimuthal deviations of the first arriving P-wave polarization are consistent on the whole NORSAR array and with the fk-analysis estimate. High velocity directions at low and high frequency point south-southeast (160±8°).

The high velocity directions show a dependence on frequency. High frequency measurements are more sensitive to the shallow structure beneath the array, while low frequency P-waves measurements are related to a deeper structure.

We observe a good agreement between the high velocity directions estimated by polarization analysis at high frequencies and the P-wave velocity anomalies estimated by Stratford (2011) in the upper crust along a profile crossing the Oslo Graben.

There is consistency between the high velocity directions at low frequencies and the Moho topography estimate by receiver functions of Svenningsen *et al.* (2007). So we suggest that the high velocity anomaly estimated by polarization and fk-analysis can be related to this Moho topography. The high frequency observables are related to the upper crust (wavelength of about 20 km).

The directions of fast axis of anisotropy, estimated by polarization analysis, are significant only at NC204 and NC303 and only for low frequency observations. The fast directions are 110° with an uncertainty of few degrees and fully consistent with fast directions estimated by Roy and Ritter (2013) applying the SKS/SKKS splitting method.

6.3.7   Summary

Fk-analysis and polarization analysis of the first-arriving P wave are used for the investigation of lateral heterogeneity and azimuthal anisotropy close to the NORSAR array. Due to the different sensitivities of these methods to local and distant structures, the results of the two methods complement each other.

The estimated azimuthal deviations by polarization analysis and fk-analysis show a clear dependence on the event backazimuth. The high velocity directions are consistent at each station of the NORSAR array and are in good agreement with observations made with different approaches in the array area. The anisotropic contribution to azimuthal deviations observed by polarization analysis is significant only at stations NC303 and NC204 and fast directions match the fast directions estimated at those stations with SKS splitting.

Polarization analysis has been applied for the investigation of anisotropy and lateral heterogeneity beneath the NORSAR array. The estimated deviations are robust for polarization analysis and fk-analysis. The polarization analysis has the advantage to be a single station approach and sensitive also to local anisotropy.

L. Cristiano, CAU
J. Schweitzer, NORSAR
T. Meier, CAU

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