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Proterozoic–Archean boundary in the mantle lithosphere of eastern Fennoscandia as seen by seismic anisotropy

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Abstract

Lateral variations of seismic anisotropy investigated by body waves allow us to detect the Archean–Proterozoic boundary in the upper mantle beneath the south-eastern Fennoscandia, though isotropic P-velocity perturbations in teleseismic P tomography or shear-velocity variations retrieved by inversion of surface waves by other authors do not noticeably differ in the Proterozoic and Archean mantle beneath the SVEKALAPKO array. The boundary seems to be inclined to the SW, in general, and very complex, forming a broad transition zone. This zone appears in the P residuals, which accumulate the velocity deviations along the ray path, as almost isotropic structure due to superposition of pieces of the mantle lithosphere with differently oriented anisotropy. The shear-wave splitting is consistent for groups of stations within the Archean and Proterozoic domains, and detects anisotropy even in the central transitional domain, which may reflect anisotropy of the thickest lithosphere wedge. In general, variations of the splitting parameters indicate a very complicated structure, which cannot be approximated by a single layer with horizontal symmetry axis or a simple contact of two mantle lithosphere blocks. We propose three potential candidates for a mantle lithosphere model around the Proterozoic–Archean contact.

Keywords: Mantle lithosphere anisotropy; Proterozoic–Archean boundary

1. Introduction

The main target of a deep seismic tomography experiment of the SVEKALAPKO project (SVEcofennian–KArelian–LAPland–KOla) of the EUROPROBE programme (1992–2000) was to investigate the lithosphere structure in the central part of Fennoscandia, a tectonically stable region since the Paleoproterozoic (Gee and Zeyen, 1996). The research focuses on detecting the upper mantle boundary between the Archean Karelian craton and the Paleoproterozoic Svecofennian orogen in southern Finland (Fig. 1). The central part of Fennoscandian Shield preserves

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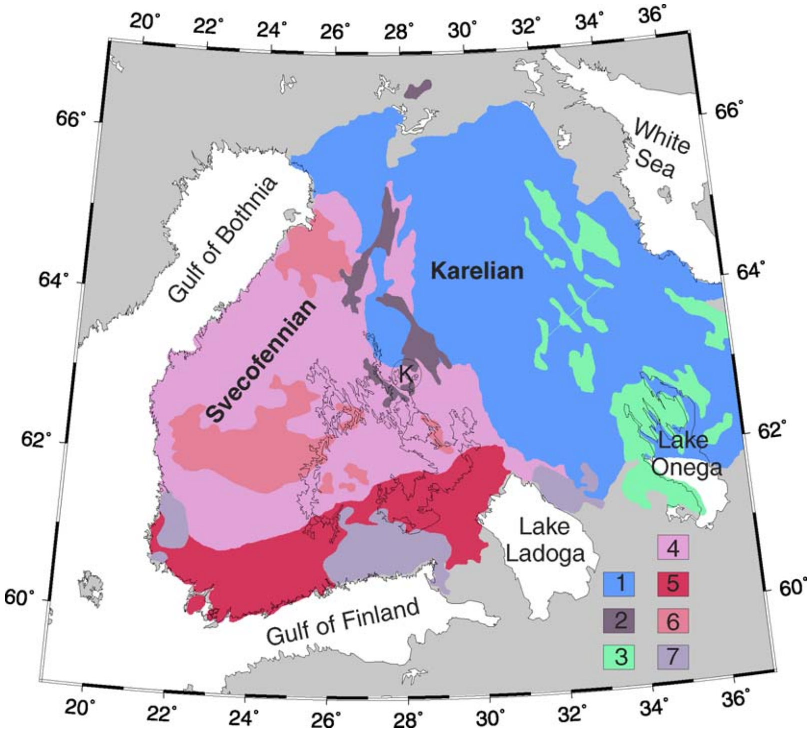

Fig. 1. Timing of major tectonic events in the eastern Fennoscandian Shield, modified from Koistinen et al. (2001) and Lehtinen et al. (1998): (1) Archean (>2.5 Ga); (2) Archean with Svecokarelian overprint; (3) Palaeoproterozoic rocks (ca. 2.5–1.96 Ga, even younger in the Lake Onega area), little affected or unaffected by Svecokarelian deformation and metamorphism; (4) Svecokarelian (phase 1, ca. 1.9–1.88 Ga); (5) Svecokarelian phase 1 and/or Svecokarelian phase 2 (ca. 1.89–1.75 Ga); (6) rocks of post- (ca. 1.77–1.70 Ga) and pre- (ca. 1.45 Ga) tectonic event with ca. 1.45–1.40 Ga metamorphic overprint; (7) post-Svecokarelian, Palaeo- and Mesoproterozoic rocks (including rapakivi granite); K: Eastern Finland Kimberlite Province.

unusually thick crust, which is comparable to that of Himalayas today, but lacking topographic expression. Numerous active seismic experiments conducted in the region provided us with good knowledge of crust structure (e.g. Grad and Luosto, 1987; Luosto, 1997), which is necessary for tomographic research of the upper mantle.

Several different methods were applied when processing seismic waveforms recorded during the SVEKALAPKO field measurements. Sandoval et al. (2003) compiled a detailed crustal model prior calculating a high-resolution teleseismic P-wave tomography beneath the SVEKALAPKO array down to 300 km. The tomography resulted in finding an anomalous upper mantle structure beneath the south-eastern Fennoscandia (Sandoval et al., 2004). The 3D image of isotropic seismic velocities shows positive up to 2% velocity perturbations in the central part of the model of the upper mantle. The high-velocity heterogeneity masks velocity differences between the Proterozoic and Archean domain of Fennoscandia, if any. This means that contrary to Proterozoic–Phanerozoic lithosphere contact in south-western limit of Fennoscandia (Arlitt, 1999; Cotte et al., 2002; Plomerová et al., 2002), the tomography does not 'see' the Proterozoic–Archean boundary in the upper mantle beneath Finland. Similarly to the P-velocity tomographic image, the lithosphere beneath the Archean and Proterozoic domains does not appear as noticeably different in shear-wave velocity maps derived by inverting Rayleigh waves (Bruneton et al., 2004b). Bruneton et al. (2004a) propose a stratified lithospheric mantle, in which a layer of anomalous and slow material overlies normal cratonic peridotites (Kukkonen and Peltonen, 1999). The stratifications are considered as a dominant feature in the region and possible effects of seismic anisotropy are assumed to be marginal.

Yliniemi et al. (2004) used refracted and reflected waves of local events and quarry blasts to model structure of the crust and uppermost mantle of southern Finland. They found gently dipping short segments of reflectors of a possible broader refractor interface at depth 65–85 km in south-central part of Finland and very short segments of reflectors at 100–130 km depth in areas up to about 200 km south-west of the surface trace of the contact of the Archean and Proterozoic domains. They attribute the shallower reflectors to possible relicts of ancient north-eastward subductions

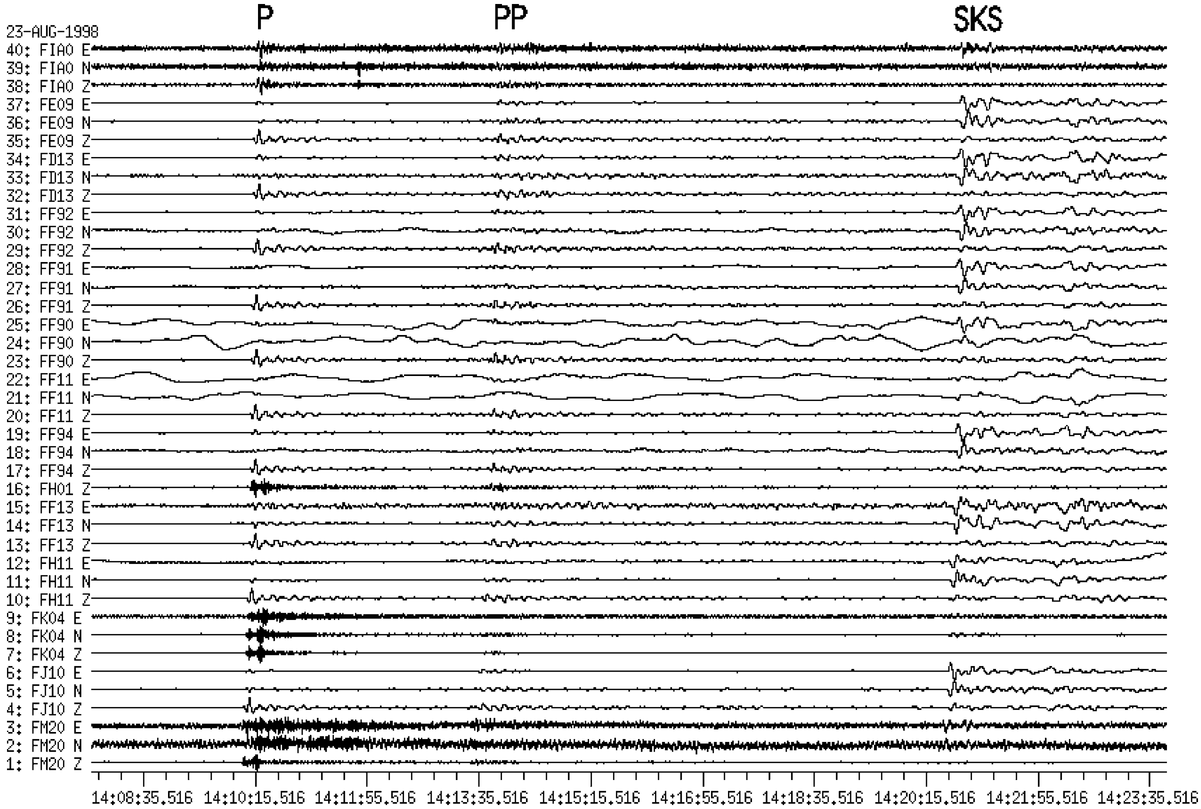

Fig. 2. Unfiltered three-component records of teleseismic event of 23 August 1998, at 13:57:15, located off coast of central America (11.66°N, 88.03°W) at depth 54 km, classified with MS = 6.3 (NEIC-EDR). The records show P and SKS phases at several stations of the array.

and collision processes (Snyder, 2002). On the other hand, no upper mantle boundary was found in a receiver function study (Alinaghi et al., 2003) above the 400 km and there are only small P and S velocity changes at those depths (Sandoval et al., 2004; Funke et al., 2003; Bruneton et al., 2004a). Yliniemi et al. (2004) associate the deeper sub-horizontal boundary either with a rheological boundary or compositional changes, which could be attributed it to the lithological contact between depleted Archean and less depleted Proterozoic mantle similarly to results of studies of mantle xenoliths from other Precambrian regions (e.g. Griffin et al., 1999). On the contrary, Bruneton et al. (2004b) did not find a link between the compositional stratification they proposed for the southern Finland mantle and location of the Proterozoic–Archean boundary.

A detailed study of spatial variations of relative P residuals and shear-wave splitting allows us to model anisotropic structure of mantle lithosphere domains and to identify their boundaries (Plomerová et al., 2002). Particularly in Northern Europe, anisotropic models of the southern edge of Baltica around the TESZ (Babuška and Plomerová, 2004) or of the mantle lithosphere around the Protogine zone in south-central Sweden (Plomerová et al., 2001) brought a new insight into understanding geodynamic development of Fennoscandia. This paper aims at demonstrating a usefulness of 3D study of seismic anisotropy and its ability to detect contact of two lithosphere domains with similar mean velocities in the mantle, but with different orientation of anisotropic structures. Results of anisotropic studies complement isotropic models by providing independent 3D self-consistent anisotropic images (Plomerová et al., 2002) and show domain boundaries, in case where isotropic modelling is not sufficient (Plomerová et al., 2001).

2. Body-wave anisotropy observations

To model anisotropic structure of the upper mantle of south-eastern Fennoscandia below the SVEKALAPKO array, we analysed carefully re-picked P arrivals of the same data set as it was used in isotropic teleseismic tomography (Sandoval et al., 2004). Fig. 2 shows examples of unfiltered records of an event with both P and SKS phases at several stations of the array. At some stations the signal is disturbed by a short- or long-period noise (e.g. M20, FIA0, FF90). Also reversed polarities and/or interchanged N–S and E–W components had to be deciphered (e.g. FF13, FH11). Basing on method of Babuška et al. (1984), we construct P-residual spheres at each station, where directional terms of relative P residuals are plotted in stereographic projection of lower hemisphere, showing their dependence on azimuth and angle of propagation within the mantle. The residuals were firstly corrected for variation in crustal thickness and velocities (Sandoval et al., 2003; Malaska and Hyvönen, 2000) and then relative residuals were calculated using a reference level formed by five stations: FB07, FF05, FF11, FJ06, FG14 (Fig. 3). Relative directional means calculated first in azimuth fans of 20° and then averaged across the all fan windows are subtracted in the directional terms plotted in the P-residual spheres. We relate major variations in the directional terms to velocity variations associated with large-scale anisotropic mantle structures below a station, though effects due to smaller-scale oriented crustal fabrics need not be eliminated by crustal corrections.

In general, the anisotropic signal is consistent over the SVEKALAPKO array and changes systematically. Two basic patterns dominate in the P spheres with a transitional region south-west of the surface trace of the Archean–Proterozoic boundary (Fig. 3). Waves arriving with relatively higher velocities from NE are typical for the whole Archean part south of latitude 66° (Domain I), while in the Proterozoic arc along the western rim of Finland, the fastest waves arrive from the SE and SW (Domain II). The residuals decrease to south-central Finland, being very small in a transition zone around the Archean–Proterozoic boundary (Domain III). This may indicate an oblique collision, i.e. a slanting transition between the two lithosphere domains with different anisotropic structure, rather than a steep suture between the domains, or their more complicated 'wedge-like' penetration. In case of the inclined boundary between the two domains, the teleseismic P waves propagating at incidence angles between 20° and 50° sample both overlying structures and create a broad zone with a gradual transition pattern of P residuals. The pattern of the P-spheres itself does not seem to be substantially affected by crustal or mantle heterogeneities found in the isotropic tomography. If it so, then the high-velocity body located below the central part of the SVEKALAPKO array (Sandoval et al., 2004) would reverse the P-sphere pattern of domains I and II, which is not the case. The P-sphere pattern of a solitaire station (SDF) north of 66° is reversed relative to other stations in the Archean, which indicates another mantle lithosphere domain of the Archean craton. Though this indication is based on the pattern of only one station in the SVEKALAPKO data, the observation is the same as the pattern of much larger data set comprising data of permanent observatories of entire Fennoscandia (Plomerová et al., 2005).

Though anisotropic signal in the P spheres used to be questioned sometimes and tend to be assigned solely to velocity heterogeneities, the shear wave splitting is generally accepted as doubtless diagnostics of velocity anisotropy within the mantle. Core–mantle refracted shear waves (SKS) would be recorded as vertically polarized SV with no energy on transverse component, if they propagated only through isotropic medium. We demonstrate that shear waves split beneath the SVEKALAPKO array, i.e. two shear waves with orthogonal polarization and with a time delay of the slower one are recorded (Fig. 4). Similarly to the P spheres, we observe a coherent orientation of the fast shear waves and split time delays (splitting parameters) at groups of nearby stations (Fig. 5). However, lateral variations of the splitting parameters across the array for a particular shear wave indicate variations of anisotropic structure of the upper mantle. We observe a distinct change of the shear wave polarizations around the Archean–Proterozoic boundary. Besides the domains delineated by the P spheres, the shear-wave splitting anisotropy seems to divide the Archean region of southern Finland (Domain I) into two parts, supporting thus the idea of complex structure of Archean cratons composed of several mantle lithosphere domains.

To delimit the anisotropic structures we invert at each station variations in the directional terms of relative P residuals, resulting in retrieving orientation of symmetry axes of anisotropic structure, leaving them free in 3D. We search for a minimum of a misfit function $f(\varphi, \theta, H)$:

$$f = \sum_{j=1}^{M} \left[\frac{|\Delta t_j^{\mathrm{obs}} - \Delta t_j|^2}{(\sigma_j^{\Delta t})^2} \right] \qquad (1)$$

where Δt^{obs} and Δt are observed travel times and those calculated in an anisotropic model for directions of propagations defined by azimuth φ and incidence angle i of the P waves, weighted by standard deviation σ of the jth observation. For modelling the large-scale anisotropy we assume two synthetic peridotite aggregates (Babuška et al., 1993) with hexagonal symmetry. The first one, with 'fast' symmetry axis (a), approximates the orthorhombic symmetry and the second one, with 'slow' symmetry axis (b), assuming hexagonal symmetry with the high-velocity foliation plane (a,

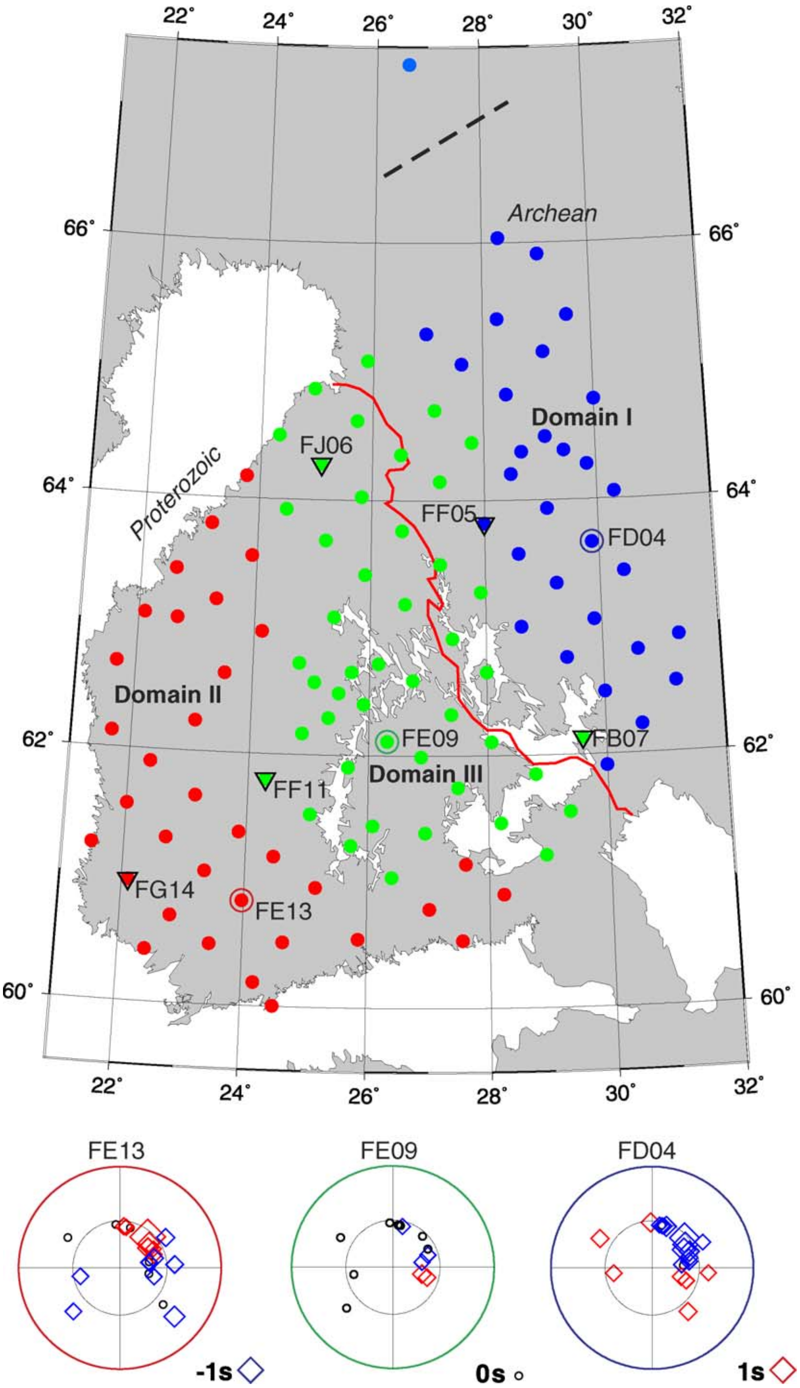

Fig. 3. The SVEKALAPKO array of seismic stations (dots), grouped according to the Archean (Domain I, blue), Proterozoic (Domain II, red) and transition (Domain III, green) pattern of the P-residual spheres, reflecting directional dependence of relative P velocities in the mantle lithosphere beneath stations. The directional terms of relative residuals (negative: blue, positive: red, zero: black), shown for stations FE13, FE09 and FD04, are plotted in dependence on direction of propagation within the mantle lithospheres given by azimuth and 'incidence' angle. Centre of the circle corresponds to vertical propagation, the thin circle to 30°, and the outer circle corresponds to an angle of 60°. Typical examples in individual domains are shown for three stations: FE13, FE09, FD04 (circled). Five stations used to calculate the reference level of relative residuals are marked by triangles. The red curve marks schematically the surface trace of the Proterozoic–Archean contact.

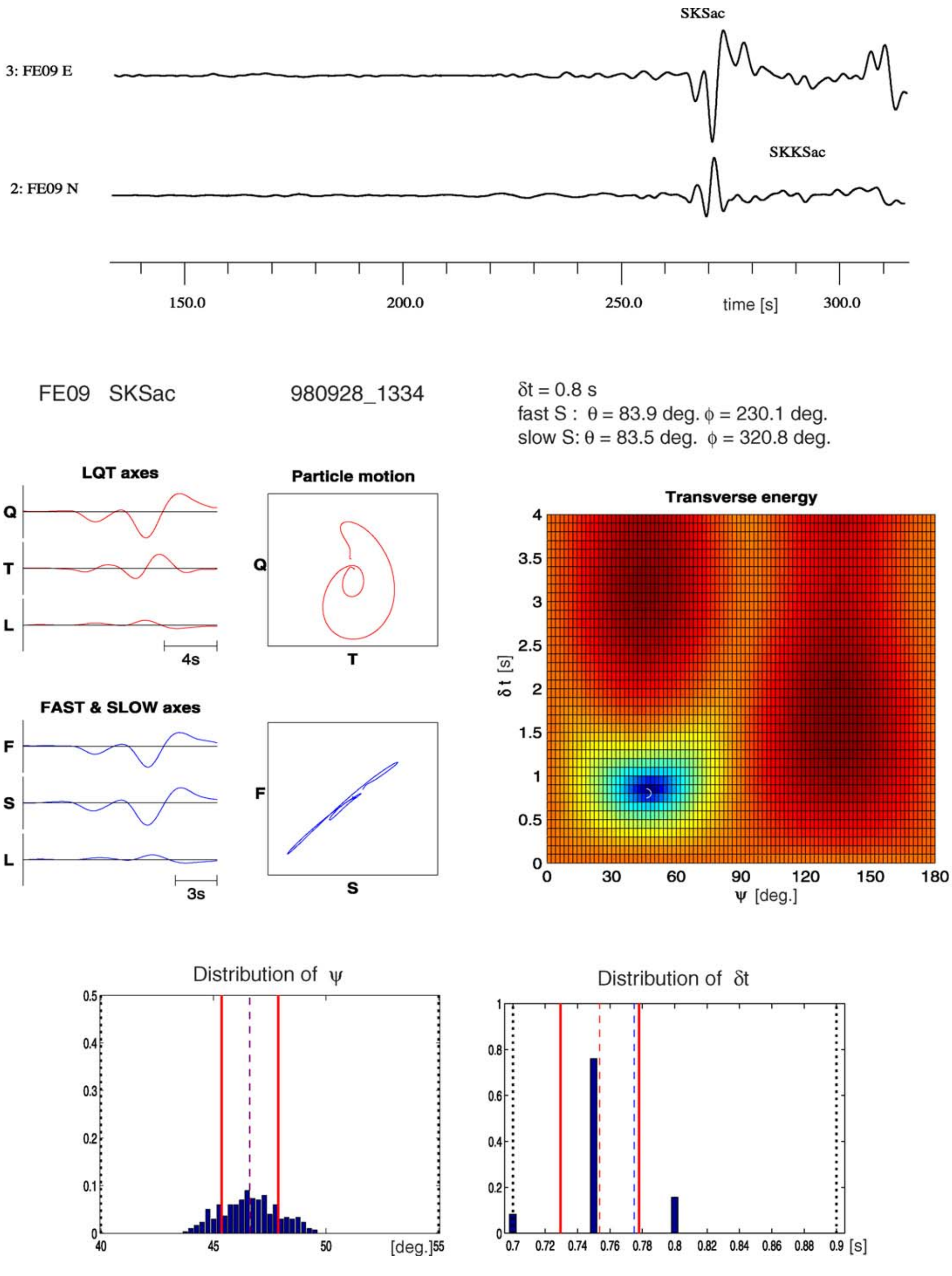

Fig. 4. Example of evaluating the shear-wave splitting parameters in 3D at station FE09 located in central part of the SVEKALAPKO array for an event from Java (8.19°S, 112.41°E, $h = 151$ km, $m = 6.4$) on 28 September 1998. Orientations of the fast split shear wave in the (*Q*–*T*) plane are given by the angle ψ and magnitude of the splitting by the time delay δt. Standard deviations of the splitting parameters (PSI stands here for ψ expressed in degrees and DT for δt in seconds) are determined by the bootstrap method (Sandvol and Hearn, 1994). The broadband velocity records were filtered by the 3rd order Butterworth band-pass filter. The linearly polarized signal (lower left) originated from the elliptically polarized signal in the LQT co-ordinate system (upper left) by a rotation in the *Q*–*T* plane and after a time shift δt. The lower left signal corresponds to the minimum (blue area with a half circle) of the misfit function (right). The polarization vector ψ of the fast shear wave is described by spherical angles θ (measured upward from the positive axis z oriented downward) and ϕ (azimuth from the north; this value is searched for if only horizontal components are analyzed). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

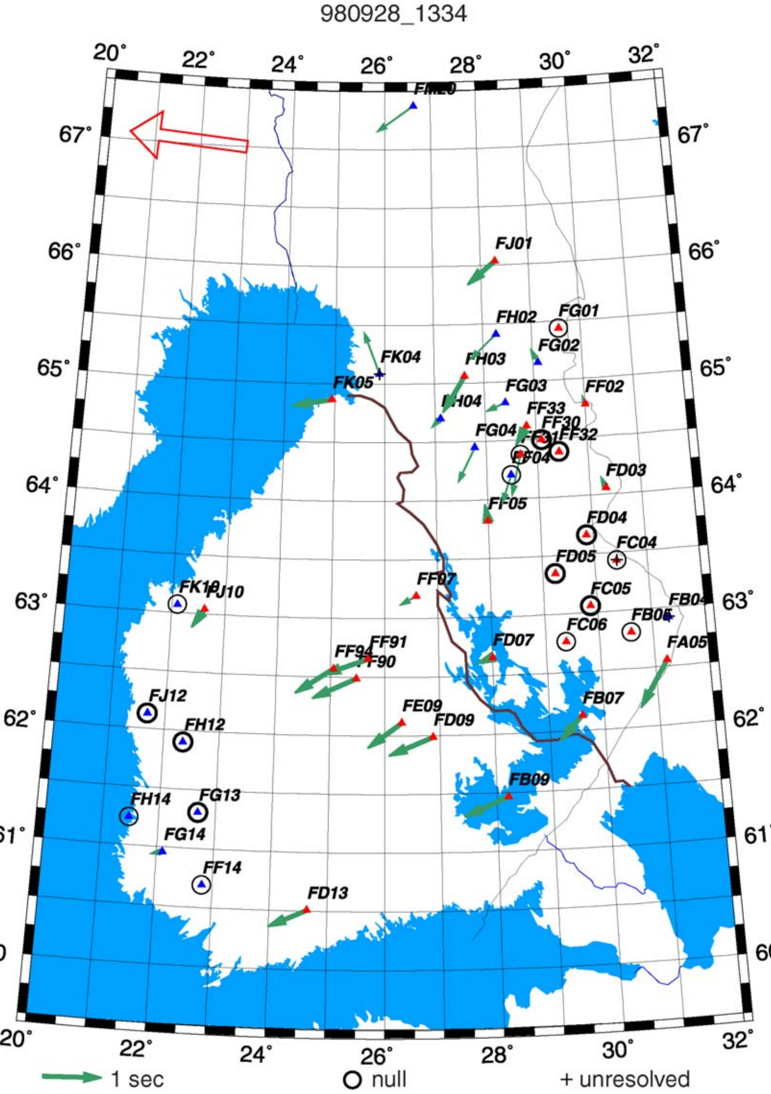

Fig. 5. Lateral variations of the shear-wave splitting parameters of the Java event, back-azimuth marked by big red arrow. There are four groups of basic splitting characteristics for this particular direction of propagation: (1) mostly null splits in SW Proterozoic (Domain II) and (2) the fast shear wave in the SW azimuth in the transition (Domain III); (3) the Archean divides into two parts: null splits in the south, while (4) the fast shear wave dips mostly to SSW in the northern part. The change in the fast split shear waves is linked with the Proterozoic–Archean contact. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

c). Elastic properties of the 'mixed' model of the mantle material we described as elasticity tensor:

$$C_{ij} = \alpha C_{ij}^{\text{fast}} + (1-\alpha)C_{ij}^{\text{slow}}, \quad 0 \le \alpha \le 1, \;\; i = 1, \ldots, 6, \;\; j = 1, \ldots, 6 \tag{2}$$

where C_{ij}^{fast} and C_{ij}^{slow} are elasticity tensors of peridotite aggregates with fast (*a*) and slow (*b*) symmetry axes, respectively (Kozlovskaya et al., 2005). The parameter α defines the degree of anisotropy and the tensor C_{ij} describes hexagonal, orthorhombic, or isotropic medium for $\alpha < 0.5$, $\alpha > 0.5$ or $\alpha = 0.5$, respectively. We invert for orientation of the symmetry axes defined by two Euler angles—azimuth φ and inclination θ (calculated upward from vertical axis), thickness of the anisotropic medium *H* and a parameter α using a 'mixed' anisotropic model assuming elastic constants as a-priori known in a model.

Fig. 6 shows azimuth of plunging symmetry axes, calculated at each station of the SVEKALAPKO array from its P-residual sphere and parameter α determining symmetry of anisotropy. The Archean Domain I is characterized by

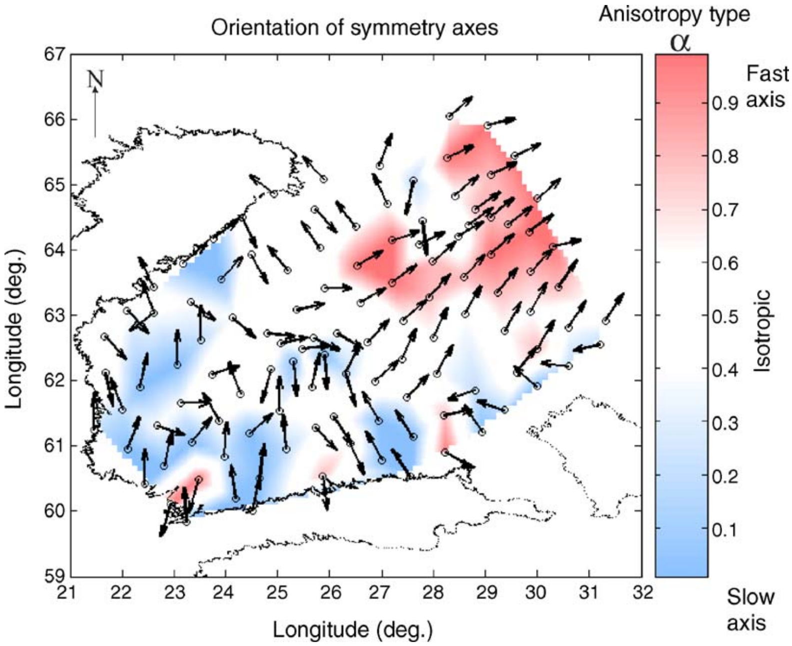

Fig. 6. Anisotropic model of mantle lithosphere resulting from inversion of the P-residual spheres at individual stations with the use of a 'mixed' model (2) (see also the text). Parameter α (in colours) defines whether the anisotropic symmetry is closer to hexagonal model with slow axis *b*, or, to orthorhombic symmetry, approximated by a hexagonal model with fast axis a. Arrows point in azimuths of dipping axes of hexagonal symmetry. 'The fast' axes a dominate in the Archean, while the 'slow' axes *b* in the Proterozoic. The central part of the array – the transition domain – appears mostly as isotropic.

mostly homogeneous orientation of the fast symmetry axes *a* dipping to NE. The Proterozoic part of the SVEKALAPKO region consists of two main domains. The Proterozoic Domain II is characterized by hexagonal symmetry with slow symmetry axis *b* slightly dipping approximately to the N or S, i.e. with the steep high velocity foliation planes (*a*, *c*) striking E–W on average. A broad transitional Domain III in the central part of the array, reflect only very week velocity variations in dependence on direction of propagation (see Fig. 3) and appear as mostly isotropic, with not well resolved and diffused orientation of the symmetry axes. Though the P anisotropy resolves the Archean–Proterozoic boundary in the mantle lithosphere, the longitudinal waves alone cannot resolve the symmetry of individual lithosphere domains reliably. Therefore, at present stage we are hunting for more shear-wave splitting parameters in surprisingly rather noisy SVEKALAPKO dataset (Vecsey et al., 2005). All anisotropic parameters evaluated in 3D, both the shear-wave splitting and the P-spheres, will input into joint inversion of multi-method geophysical data with the use of multi-objective optimisation (Kozlovskaya, 2001; Kozlovskaya et al., 2005).

3. Discussion and concluding remarks

Considering observed lateral changes of characteristics of anisotropic parameters of body waves we propose three potential candidates for a mantle lithosphere model around the Proterozoic–Archean (P–A) contact (Fig. 7). We search whether a model meets the low anisotropic signal of the P-spheres in the transition Domain III (Fig. 3), sharp changes in shear-wave splitting parameters at domain boundaries (Fig. 5) and location of mantle subhorizontal reflectors/refractors as determined by Yliniemi et al. (2004). The lithosphere thickness of about 220–250 km is estimated beneath Fennoscandia according to a global model, in which the lithosphere bottom is defined as a transition between the fossil and present-day flow related anisotropy (Plomerová et al., 2002), regional P-tomography (Sandoval et al., 2004), mantle xenoliths (Kukkonen and Peltonen, 1999) from the Eastern Finland Kimberlite Province (see Fig. 1), rheological studies (Kaikkonen et al., 2000) and magnetotellurics (Korja et al., 2002). Model A (a smooth P–A boundary) seems to be compatible with the upper mantle reflectors above 100 km, while the reflectors at greater depth could represent an internal boundary in the Archean domain at depth at about 150 km (a two layer Archean lithosphere, Griffin et al., 1999). However, this simple model does not support the sharp change of splitting parameters near the contact of

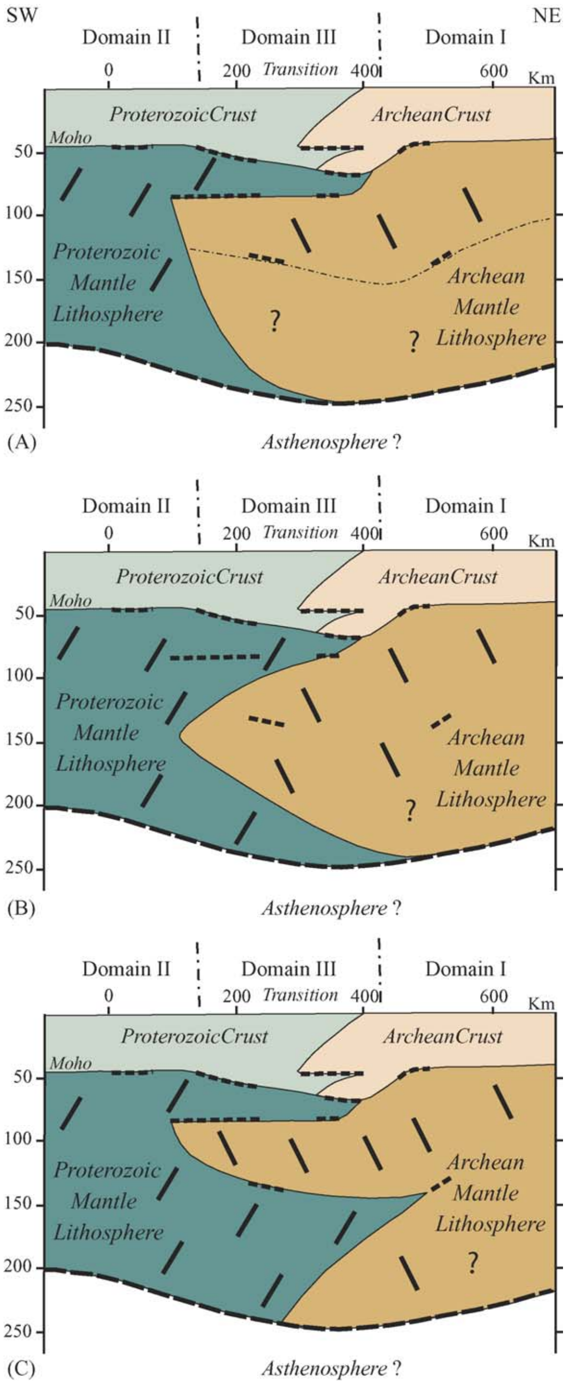

Fig. 7. Sketch of three possible candidates of a model of the mantle lithosphere: (A) a smooth Proterozoic–Archean contact and a two-layer Archean mantle lithosphere, (B) a single mantle wedge and (C) a multi-wedge mantle. The reflectors (thick dashed lines) and Moho depth are according to Yliniemi et al. (2004) based on Sandoval et al. (2003). Thick inclined lines within the mantle lithosphere show schematically dipping relative high velocities derived from the P residuals.

Domains I and III and a velocity pattern of the Archean mantle would dominate in the P pattern of Domain III. Model B (a single mantle wedge) allows us to explain the low P anisotropic signal in Domain III as a result of an integral effect of P-wave propagation through the Proterozoic and Archean segments of the mantle lithosphere with differently oriented anisotropic structure. On the other hand, such model fails to correlate its boundaries with the mantle reflectors and tends to exhibit a smoother lateral change in the splitting parameters. If there is an internal boundary within the thick Archean mantle lithosphere (e.g. at depths of about 150 km), it can represent a zone of weakening which would allow to form a multi-wedge Proterozoic–Archean transition (Model C). Such model is compatible both with the mantle reflectors and lateral changes of anisotropic characteristics of the body waves. A multi-layer model of the P–A transition can produce low anisotropic signal in P waves in the central part (Domain III) and distinct lateral changes in shear-wave splitting parameters. In any case, the P–A transition seems to be very complicated and not sharp. This is also reflected in lateral changes and mutual inter-growth of Proterozoic and Archean parts, both across and parallel to their meandering boundary on the surface.

Evaluation of lateral changes of seismic anisotropy of body waves appears as a powerful tool to detect the Archean–Proterozoic boundary in the upper mantle beneath the south-eastern Fennoscandia. The boundary seems to be inclined and complex. Inter-growing Proterozoic and Archean slivers of mantle lithosphere form a broad transition zone. This zone appears in the P residuals, which accumulate the velocity deviations along the ray path, as almost isotropic structure due to superposition of pieces of the mantle lithosphere with differently oriented anisotropy. On the other hand, the shear-wave splitting, consistent for groups of stations within individual domains, detects anisotropy even in the central transitional Domain III and may reflect anisotropy of the thickest lithosphere wedge. In general, variations of the splitting parameters indicate a very complicated structure, which cannot be approximated by a single layer with horizontal symmetry axis or a simple contact of two mantle lithosphere blocks.

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