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Variations of shear-wave splitting in Greenland: Mantle anisotropy and possible impact of the Iceland plume

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ABSTRACT

Seismic anisotropy was investigated by measuring shear-wave splitting at 19 broadband stations in Greenland. We examined mostly SKS and SKKS phases, but also some PKS and depth phases of SKS (e.g. pSKS, sSKS) for deep events. Splitting parameters (fast polarization and time delay) were determined for these phases. The fast polarizations at nine sites in southern Greenland are quite uniformly oriented about N–NE. Two sites in central northern Greenland show a similar geometry to southern Greenland. Similar fast polarizations in southern and central northern Greenland suggest continuity of structural fabric beneath large parts of Greenland. This coherent pattern extends across a number of geological provinces of varying age and suggests a common cause of anisotropy not related to the bitwise formation of the Greenland continental block. Four sites in an east–west oriented belt crossing central Greenland show varying fast polarizations and suggest a separate process causing the anisotropy there, which may indicate that these processes are not currently active. The overall pattern of anisotropy in our results, with the exception of variations across central Greenland, is similar to results obtained from Rayleigh waves. The irregular geometry of splitting across central Greenland may be related to the impact of the Iceland plume at ~60 Ma.

Reported splitting time delays range from 0.4 to 1.4 s with an average of 0.8 s, which can generally not be explained by crustal anisotropy alone. If confined to a lithosphere of thickness on the order of 100 km, time delays of up to 1.4 s indicate anisotropy of up to about 6%, assuming that the *a* crystallographic axis of olivine is preferentially contained in the horizontal plane. We suggest that the anisotropy beneath Greenland is located mainly in the upper mantle but some contributions from the crust and lower mantle may be present.

1. Introduction

Shear-wave splitting analysis is an important tool to characterize the strength and geometry of anisotropy beneath seismographs and thus deformation and flow if the anisotropy and its relationships between strain and tectonic processes are known (Silver, 1996; Park and Levin, 2002).

Anisotropy can be related to stress in the Earth's crust and past or present deformation in the mantle and therefore provides useful information about tectonic processes. Although the origin of anisotropy and its localization are enigmatic, the main source of anisotropy observed in vertically propagating shear waves is thought to be confined to the upper mantle. Azimuthal anisotropy is caused by the orientation of upper-mantle minerals (e.g. Nicolas and Christensen, 1987), mainly olivine, which is both highly anisotropic and develops strain-induced lattice-preferred orientation (LPO) (e.g., Hess, 1964; Vinnik et al., 1992; Silver, 1996 and references therein]. The a axis (fast velocity) of olivine aligns nearly parallel to the flow direction for large strains, but deviates from this for relatively small strains (Zhang and Karato, 1995) and aligns nearly parallel to the maximum, finite-strain direction (e.g., Christensen, 1984; Mainprice and Silver, 1993). These relationships between deformation and olivine alignment are complicated in the presence of significant amounts of water (Jung and Karato, 2001).

When a polarized shear-wave enters an anisotropic medium, it splits into two orthogonal quasi shear-waves (a fast and a slow shear wave). These phases travel with different wave speeds causing a time delay between them. Splitting parameters, the fast polarization, ϕ, and the time delay, δt, describe the polarization direction of the fast shear wave and the time difference between the fast and slow wave arrivals, respectively. The ϕ orientation is measured in the horizontal plane as azimuth (clockwise from north) and depends on the orientation of the

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anisotropic structure. The δt depends on both the path length and the strength of anisotropy in the medium (Plomerová et al., 1998). Core-refracted phases (e.g. SKS and SKKS) isolate receiver-side anisotropy due to P-to-S conversions at the core-mantle boundary (CMB). SKS and SKKS (hereafter SK*S) phases are radially (*SV*) polarized after the phase conversion at the CMB and therefore the energy on the transverse component and the elliptical particle motion are diagnostics of anisotropy or lateral heterogeneity beneath a receiver. These phases arrive nearly vertically with a steep incidence angle at the surface and thus provide good lateral resolution under the receiver. The splitting of teleseismic SK*S waves is, therefore, often used to study seismic anisotropy in the mantle beneath seismographs (Savage, 1999).

Splitting parameters can be determined from several methods developed in the last two decades. For instance, cross correlation methods have been used by Ando et al. (1983), Fukao (1984), Vinnik et al. (1984), Tong et al. (1994), Levin et al. (1999) and others. Inversion methods have been developed by Vinnik et al. (1988, 1989), Silver and Chan (1988, 1991), Šílený and Plomerová (1996), Plomerová et al. (1996), Wolfe and Silver (1998), Rümpker and Silver (1998) and Chevrot (2000). Vinnik et al. (1984) were the first to use shear-wave splitting observations on the continents from teleseismic core-refracted phases (see also Kind et al., 1985).

Here we use the inversion methods of Silver and Chan (1991) and Wolfe and Silver (1998). Firstly, north and east components of the original seismograms have been rotated to radial and transverse components. The aim is to minimize the energy on the transverse component since there would be no energy on the transverse component if the medium was isotropic or transversely isotropic with a vertical symmetry axis (i.e. a special case of anisotropy) beneath a seismograph. The method searches over a grid of possible splitting parameters in order to find the best parameters that minimize the energy on the transverse component. The advantage of the methods of Silver and Chan (1991) and Wolfe and Silver (1998), which is based on the Silver and Chan (1991) method, is that they give information on the accuracy of the splitting parameters determined for each single measurement by using *F*-test statistics. Sandvol and Hearn (1994) introduced a bootstrap technique for estimating uncertainty in shear-wave splitting measurements instead of using the *F*-test statistics to estimate the 95% confidence region.

Our objective in this study is to constrain seismic anisotropy in the upper mantle beneath Greenland, investigate possible variations of splitting parameters in the region, examine implications of seismic anisotropy for flow and deformation processes and observe if there is shear-wave splitting evidence related to the impact of the Iceland plume.

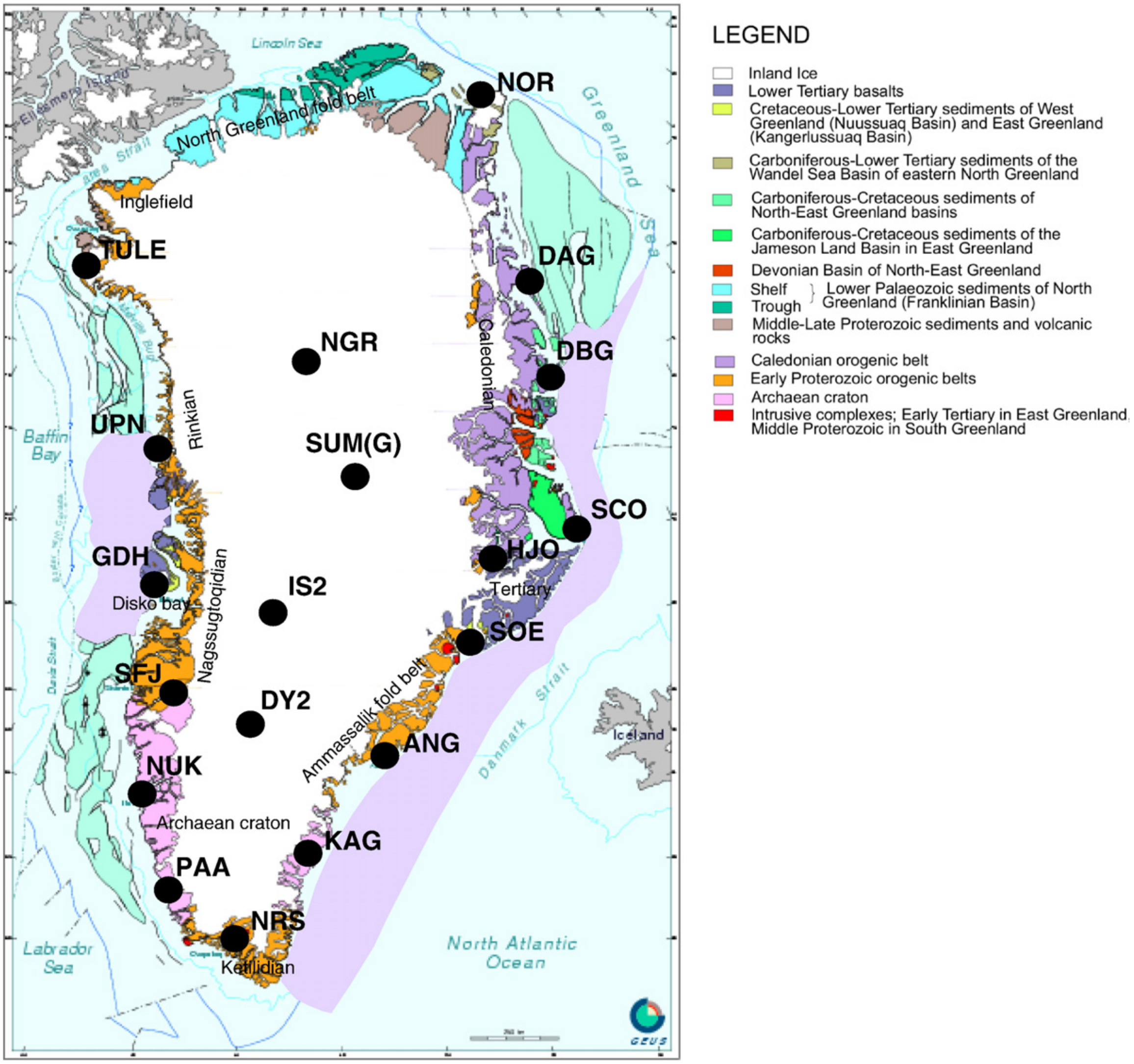

Fig. 1. Geological map of Greenland and the distribution of seismographs. Adapted after Dahl-Jensen et al. (2003) which is based on Henriksen et al. (2000). Volcanic margins (light purple area) adapted from Eldholm and Grue (1994).