Upper mantle seismic anisotropy of South Victoria Land/Ross Island, Antarctica from SKS and SKKS splitting analysis

Mitchell Barklage,[1] Douglas A. Wiens,[1] Andrew Nyblade,[2] and Sridhar Anandakrishnan[2]

[1]Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130 (mitchb@seismo.wustl.edu, doug@seismo.wustl.edu)
[2]Department of Geosciences, Penn State University, University Park, PA (andy@geosc.wustl.edu, sak@geosc.wustl.edu)

Summary We determine shear wave splitting parameters of teleseismic SKS/SKKS phases at stations in Antarctica as part of the TAMSEIS experiment. Our data indicate that the anisotropy is fairly uniform from the Transantarctic Mountains into the interior of East Antarctica with a slight change of fast direction near the Vostok Highlands. The data show fairly consistent fast direction of anisotropy oriented approximately N60E with splitting times of about 1 second for stations in the vicinity of the Transantarctic Mountains, along the coast, and into East Antarctica. However, stations in the vicinity of the Vostok Highlands show a small rotation of approximately 20 degrees of the fast direction of anisotropy as well as a decrease in magnitude of the splitting time of about 0.5 second.

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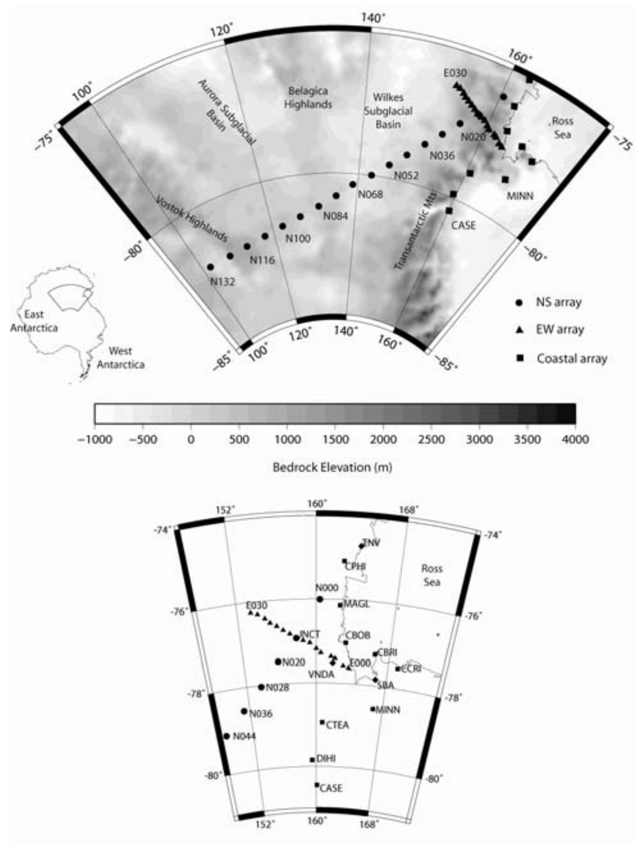

Figure 1. TAMSEIS array and subglacial bedrock topography (Lythe and Vaughan, 2001).

Introduction

Teleseismic shear wave splitting measurements have emerged as a powerful tool for studying the structure and dynamics of the upper mantle because the anisotropic parameters are closely related to upper mantle fabrics due to past and present deformation (Savage, 1999; Silver, 1996). In many cases the splitting observations can be correlated to the surface geologic fabric suggesting the crust and mantle deform coherently during orogeny as part of the plate (Barruol et al., 1997; Bormann et al., 1993; Helffrich, 1995). Thus splitting observations can be used to identify major tectonic boundaries, and are a powerful tool for studying lithospheric deformation especially in ice covered Antarctica where surface outcrops are minimal.

Due to the harsh conditions of working in Antarctica, only a limited amount of seismological data has been collected that is suitable for anisotropy analysis. Additionally, splitting observations reported to date (Helffrich et al., 2002; Muller, 2001; Pondrelli and Azzara, 1998; Pondrelli et al., 2004) consist of stations mainly along the coast or at the south pole. This study uses data from the Transantarctic Mountain Seismic Experiment (TAMSEIS), the first large-scale broadband seismic experiment to reach the interior of the Antarctic continent (Figure 1), to analyze the seismic anisotropy of the Antarctic lithosphere.

Data

This study employs horizontal-component, broadband seismic data recorded at 44 seismic stations in South Victoria Land/Ross Island Antarctica. This includes 41 temporary stations deployed as part of the Transantarctic Mountain Seismic Experiment (TAMSEIS) and 3 permanent stations of the Global Seismographic Network (VNDA, SBA, and TNV). The TAMSEIS network was in place from November 2000 through December 2003 and recorded data during the austral summer because stations were powered by solar panels. The TAMSEIS array consists of three elements (Figure 1): 1) the NS array is a 1400 km linear array of 17 broadband seismic stations with 80 km interstation spacing extending from the high central regions of the East Antarctic craton to the Transantarctic Mountains (TAM), 2) the EW array is an 400 km linear array of 16 broadband seismic stations with interstation spacing of 20 km crossing the TAM nearly perpendicular to the first array, and 3) the Coastal array is 11 broadband stations in the coastal regions along the TAM and on Ross Island.

The events used for this study were required to have a magnitude greater than 5.8 Mw and an epicentral distance between 90º and 140º. SKS/SKKS phases were carefully evaluated and those with a sufficient signal-to-noise ratio (SNR) that were clearly separated from other phases were chosen for analysis. Filtering has been applied to most of the data and when used, the filter was a pass-band with lower limit equal to 0.02 Hz and upper limit varying from 0.2 to 0.5 Hz.

Method

We determine shear wave splitting parameters of teleseismic SKS/SKKS phases in Antarctica using the technique of (Silver and Chan, 1991). Individual shear wave splitting measurements have been qualitatively rated A,B,C, and null based on: 1) SNR greater than four, 2) linearization of the particle motion, and 3) the waveform coherence between the two horizontal components rotated into fast and slow directions. Measurements that satisfy all three criteria are rated A. Measurements that satisfy two of the above criteria are rated B and measurements that satisfy only one criterion are rated C. A null measurement is one that does not show energy on the transverse component in the raw records. This may be due to an absence of anisotropy, an initial polarization of the incoming wave that is parallel or orthogonal to the fast anisotropic direction, or low SNR.

To increase the robustness of the results compared to the analysis of single events, we use a stacking method (Wolfe and Silver, 1998) to produce a weighted sum of the individual misfit surfaces and compute an average or global solution for each station. We use the (Restivo and Helffrich, 1999) implementation in which individual measurements are weighted in the stack based on the SNR and the back-azimuth to generate the stacked or global solutions.
The global solutions have been categorized A, B, or C based on: 1) the back-azimuth sampling and 2) single event rating. Global solutions with three or more back-azimuth quadrants sampled with single event ratings of A or B are considered robust. These are plotted as thick vectors in figures 2 and 3. Global solutions with two or more back-azimuth quadrants sampled by single events rated A or B are considered marginally robust. These are plotted as thin vectors in figures 2 and 3. Additionally, to achieve an A rating, the global solution must consist of at least four individual measurements with one of these four having fast direction greater than 20º away from the back azimuth. This non-nodal measurement must also contain the global solution in the 95% confidence interval. We find that this method of rating is in good agreement with the formal errors reported here. The formal error measurements are determined according to (Silver and Chan, 1991).

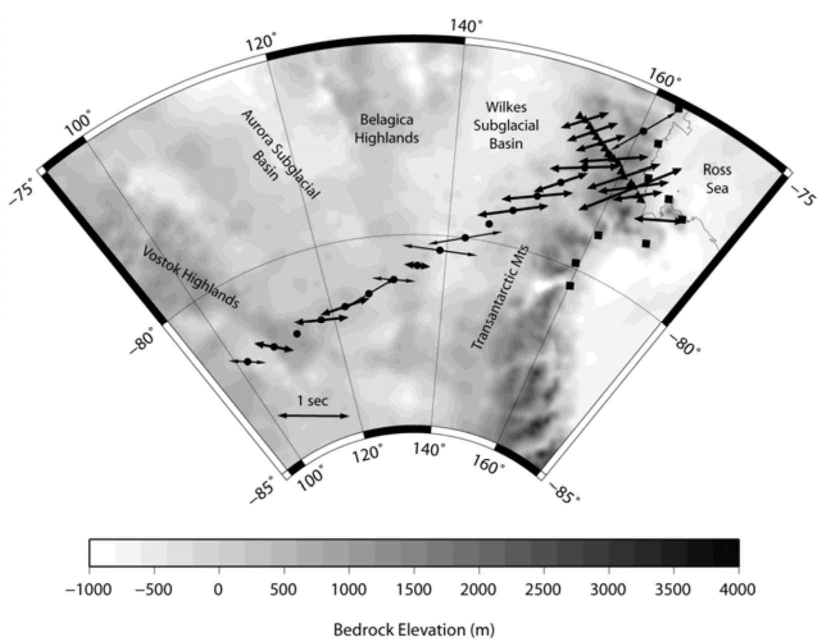

Figure 2. Splitting vectors across the TAMSEIS array plotted on subglacial bedrock topography. Thick vectors represent A quality stacks, thin vectors represent B quality stacks. C quality stacks are not shown.

Discussion & Conclusions

Comparisons with surface wave results and inferred depth of anisotropic layer

The anisotropy within East Antarctica just west of the TAM near the junction of the NS and EW arrays has an average fast direction of approximately N60E with splitting times of about 1 second as determined from SKS/SKKS splitting analysis. Azimuthal variations of Rayleigh wave phase velocities at the intersection of the N-S and E-W arrays reported by (Lawrence et al., 2006) show a fast axis of anisotropy oriented N65E ±15º with 3% ±1% anisotropy. These results are consistent with the SKS splitting results presented here. The Rayleigh wave anisotropy is strongest at periods of 40 seconds, but is also detectable at periods ranging from 20-120s suggesting the anisotropy is strongest in the uppermost mantle. Additionally, we find there is no systematic variation in the fast direction with the back azimuth. These observations suggest the anisotropy is distributed in a single layer over a broad range of depths in the uppermost mantle. This suggests that the anisotropy must result from lattice-preferred orientation (LPO) of olivine within the continental lithosphere (Zhang et al., 2000). Furthermore, a single anisotropic layer with 3% anisotropy that is 150 km thick with an isotropic shear velocity of 4.4 km/s produces splitting times of about 1 second. Therefore, the splitting observations reported in this study at the intersection of the EW and NS arrays of about one second establish an anisotropic layer due to LPO of olivine in the uppermost mantle of approximately 150 km.

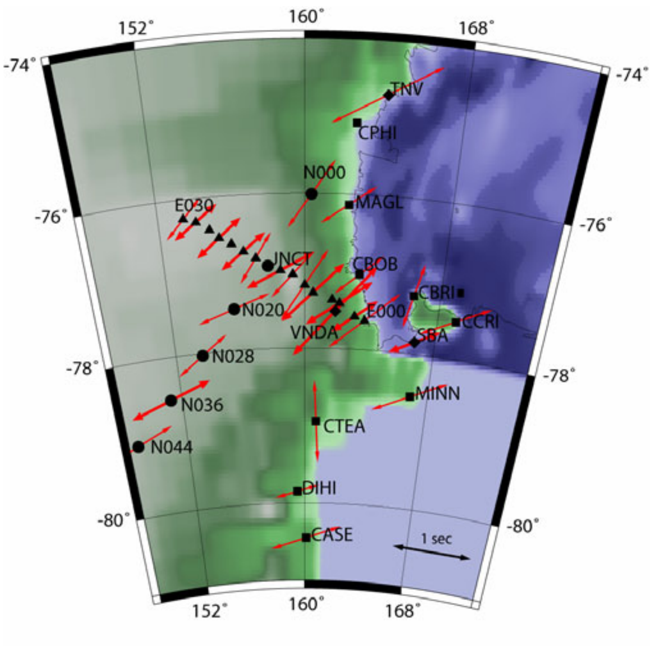

Figure 3. Close-up view of splitting vectors in the Ross Island region. Thick vectors represent A quality stacks, thin vectors represent B quality stacks. C quality stacks are not shown.

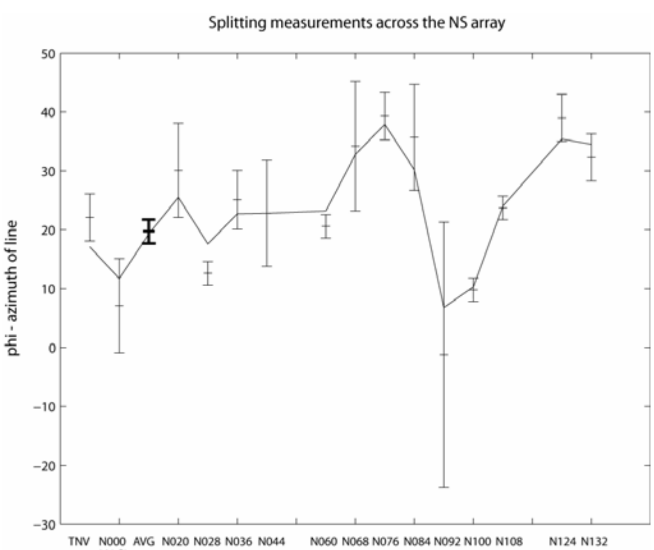

Figure 4. Fast direction of anisotropy plotted relative to the azimuth of the NS array. The data point in bold represents an average of stations taken near the intersection of the NS and EW arrays. Note the change in direction at station N092.

Relationship of anisotropy to geological history of the TAM

No obvious correlation exists between the TAMSEIS splitting results and structures at the surface in the vicinity of the TAM. Surface exposures of rock outcrops in the TAM record a widespread strong ductile tectonic fabric oriented roughly NW-SE suggesting a NE-SW vergence direction for the Paleozoic Ross Orogeny (Stump, 1995). This compressional tectonic event was sufficiently strong to overprint the structural grain from any earlier tectonic event (Goodge et al., 2001). Additionally, this tectonic event should have produced internal coherent deformation of the lithosphere that would have produced a lattice preferred orientation of olivine with the fast axis of olivine oriented perpendicular to the vergence direction (parallel to the minimum strain axis). However, the fast axis of anisotropy is oriented roughly NE-SW, parallel to the vergence direction for stations in the TAM. Therefore, these data suggest the seismic anisotropy present in the Antarctic lithosphere beneath the TAM is not related to the Ross Orogeny.

Basal stresses associated with absolute plate motion (APM) can also cause LPO of olivine in the upper mantle (Wolfe and Silver, 1998). This hypothesis predicts that the absolute plate motion vector is parallel to the fast axis. However, an absolute plate motion in the direction of N11W (Gripp and Gordon, 2002) is inconsistent with the observed splitting results. Additionally, LPO of olivine associated with APM usually only occurs for fast moving plates with a low viscosity zone at the base of the lithosphere (Bokelmann and Silver, 2002). The absolute plate motion vector calculated for the McMurdo Sound region in Antarctica (Gripp and Gordon, 2002) has a magnitude of only 1.3 cm/yr making it one of the slowest plates on the planet. Additionally, fast velocities between 80 and 220 km depth reported by (Lawrence et al., 2006) suggest the lithosphere beneath East Antarctica is rigid and would resist deformation and not be prone to basal shear. Therefore, APM cannot explain the splitting observations for East Antarctica.

Interpretation of splitting in the Ross Sea Region

Tectonic activity since the Ross Orogeny has primarily involved extension and continental breakup (Wilson, 1995). They show that the extension direction between East and West Antarctica is oriented roughly east-west. Splitting parameters at stations along the coast (with the exception of CTEA and CBRI) record a roughly east-northeast fast axis. This suggests that the observations along the coast may record some component of an extensional fabric oriented east-west, parallel to the minimum strain axes.

Splitting directions and possible terranes in East Antarctica

We observe a slight rotation of the fast direction of anisotropy near the end of the NS array. Figure 4 shows the fast direction of anisotropy plotted relative to the azimuth of the NS array. The results are plotted relative to the azimuth of the NS array because azimuths change rapidly with longitude near the poles. This figure shows that the splitting results are fairly consistent from the coast (TNV) through the TAM and into East Antarctica (N092). However, starting at station N092 there is a slight rotation in the fast direction of anisotropy towards a small angle (parallel with the line) at the extension of the Aurora subglacial basin, and then a rotation to a large angle (away from the line) after crossing the Vostok highlands. We characterize this region from N092 to N132 near the Vostok Highlands as a separate anisotropic domain. This separate domain could represent a major tectonic boundary as suggested by (Studinger et al., 2003).

Summary

We find evidence for an anisotropic layer in the uppermost mantle of approximately 150 km beneath East Antarctica just west of the TAM. We associate this layer to LPO of olivine in the upper mantle related to an orogeny that pre-dates the Ross Orogeny. We also observe a slight rotation of the fast direction of anisotropy near that Vostok Highlands that may represent a previously unidentified tectonic boundary.

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