

RESEARCH ARTICLE

Seismic anisotropy and mantle dynamics beneath Maitri Station in central Dronning Maud Land, East Antarctica: new insights from shear wave splitting analysis of core-refracted and direct S-phases

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Abstract

To elucidate the Gondwana supercontinent, we investigate mantle dynamics in Dronning Maud Land, Antarctica, using shear wave splitting analysis. This involves 12 S-phase teleseismic events and 38 core refracted phase (SKS, SKKS, PKKS and PKS) events, hereafter collectively referred to as XKS, recorded in the period 2013–17 (excluding noisy periods), at the broadband seismic station at Maitri, the Indian research station. The splitting parameters Φ (fast polarization direction) and δt (delay time) were estimated by cluster analysis and minimization of eigenvalues from covariance matrix of Φ and δt . Our XKS analysis, assuming a single layer of anisotropy, shows an average Φ of 62° and δt of 1.1 sec. The S-wave analysis shows an average Φ of 50° and δt of 0.97 sec. The Φ values of the fast XKS and S-wave phases, having a north-east–south-west direction, are sub-parallel to the geological boundary of Schirmacher Oasis and the continental margin of East Antarctica. The observed margin-parallel XKS and seismic anisotropy at Maitri, which are also aligned to magnetic anomalies, correlate well with frozen lithospheric anisotropy, due to the major tectonic events, lineations and/or transtensional rifting at the breakup of Gondwana.

To access the supplementary material, please visit the article landing page

Introduction

Seismic anisotropy is a study that explores how seismic wave velocities vary with direction, offering insights into past and current deformation and flow within the mantle. This phenomenon is regarded as an indicator of the dynamic processes shaping our planet's interior. Among the minerals present in the mantle, olivine is the most prevalent and exhibits significant intrinsic anisotropy, that is, transmitting energy more rapidly along specific

crystallographic axes, which happens during mantle-deformation or flow. While passing through such anisotropic media, the shear waves experience the phenomenon of 'splitting,' a seismological analogue of optical birefringence, through which researchers detect and quantify the change in the velocity of shear waves beneath the seismological recording station. Valuable information of the regional tectonic history and current mantle flow can be gleaned from the direction in which olivine crystallographic axes are aligned. This is assessed through SWS

Keywords

Gondwana; supercontinent; shear waves; mantle anisotropy; olivine; Schirmacher Oasis

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Abbreviations

CSIR: Council of Scientific & Industrial Research, India
DML: Dronning Maud Land
MAL: Maitri Station, DML
NOVO: Novolazarevskaya Station
PKKS: seismic phase in which a P-wave passes through the mantle, refracts twice within the liquid outer core and emerges as an S-wave.
PKS: seismic phase in which a P-wave travels through the mantle, then the liquid outer core, and converts to an S-wave upon re-entry into the mantle.
S-wave: shear/secondary wave
SWS: shear wave splitting
SKKS: seismic phase in which an S-wave travels through the mantle, refracts twice to a P-wave (K) in the outer core, and re-emerges as an S-wave in the mantle
SKS: seismic phase in which an S-wave travels through the mantle, refracts to a P-wave (K) in the outer core, and re-emerges as an S-wave in the mantle
XKS: core-refracted phases (including PKKS, PKS, SKKS, SKS)

analysis performed to determine two important parameters: Φ , which stands for fast polarization direction of the polarization plane of the fastest S-wave, and δt , which represents the delay between the arrival time of the fast and slow shear waves. The strain-induced lattice-preferred orientation of mainly olivine is the prominent cause for upper-mantle-anisotropy. The type of olivine's principal axes alignment in relation to the shear direction is differentiated by specific crystallographic orientations—A-type, B-type and so on (see Karato et al. 2008 for details). In continental regions, it is predominantly A-type fabric that facilitates the alignment of the olivine fast axis with the direction of maximum shear and is the primary contributor to seismic anisotropy. The SWS of XKS phases enables the study of the seismic anisotropy at the receiver side, whereas the SWS of S-phase facilitates the study at the source side.

Studies of seismic anisotropy in Antarctica have provided useful information pertaining to different regions of Antarctica (e.g., Müller 2001; Reading & Heintz 2008; Barklage et al. 2009; Salimbeni et al. 2010; Accardo et al. 2014; Lucas et al. 2022). Bayer et al. (2007) have investigated the crust and upper mantle beneath DML and found that the observed anisotropy can, in most cases, be related to major tectonic events that formed the geological features of the present-day Antarctic continent. Lucas et al. (2022) provided SWS measurements showing a north-east–south-west-oriented fast polarization direction in Antarctica. Lucas et al. (2022) interpreted them as regional contributions of both lithospheric and sub-lithospheric mantle anisotropy, whereas they attributed splitting measurements observed in the interior of East Antarctica to relict fabrics associated with Precambrian tectonism. Gupta et al. (2017) believe that the crust beneath the DML represents a volcanic passive continental margin originating in the Precambrian and responsible for the Gondwana supercontinent break-up.

We report 38 new XKS (SKS, SKKS, PKKS and PKS) measurements and 12 new S-phase measurements, obtained between 2013 and 2017 at MAI, India's broadband seismic station in DML, East Antarctica. Our goal is to correlate seismic anisotropy in DML with past or current geodynamic processes and build on insights gained from previous studies.

Geological setting

MAI is situated in Schirmacher Oasis, central DML, East Antarctica (70°45'S, 11°43'E; Fig. 1). Geologically, the eastern and western provinces of Antarctica are dissimilar (Boger 2011; Harley et al. 2013; Lamarque et al. 2015; Golynsky et al. 2018; Lloyd et al. 2020). East Antarctica

is recognized as a Precambrian craton and as the central part of the Palaeozoic Gondwana supercontinent. It is underlain by a crust that is about 55 km thick (e.g., Hansen et al. 2010; Graw et al. 2017; Lucas et al. 2022). The coastal terranes of the continental regions of East Antarctica are well-associated with conjugate terranes in India, Africa and Australia (Phillips & Laufer 2009; Boger 2011; Loewy et al. 2011). West Antarctica is understood to comprise the assemblage of Meso–Cenozoic crustal blocks (Dalziel 1992) or microplates with metamorphic and volcanic terranes (Torsvik et al. 2008; Boger 2011). It is characterized by a spatially variable crust (e.g., Dunham et al. 2020; Baranov et al. 2021) and by a heterogeneous upper mantle (e.g., Lloyd et al. 2020; Lucas et al. 2022).

Data and methodology

Following an upgrade in 2011, the MAI station features a 24-bit Reftek digitizer (RT-130-01) having 135 dB dynamic range and a Guralp CMG-3T seismometer with a dynamic range of 167 dB, a sensitivity of 1500 V/m/s and a frequency range from 0.0083 to 50 Hz. Our data is in the period from 2013 to 2017. Although the data-acquisition quality control was improved during the expeditions, extreme climatic conditions resulted in noisy waveforms during some periods. This reduced XKS and S-phase SWS data during 2013–17. We first discuss the XKS phases followed by the direct S-wave data and methodology. The distribution of these teleseismic events is shown in Supplementary Fig. S1. To get a window into the crustal architecture and tectonic evolution of the region through these magnetic anomalies, we used the Antarctic Digital Magnetic Anomaly Project (ADMAPP2) data, which comprises detailed and integrated magnetic anomaly data from various surveys (Golynsky et al. 2018).

XKS SWS

For XKS-phases, the presence of an anisotropy layer along the core–mantle boundary and recording station at the surface is expressed by the existence of the energy on the transverse component and elliptical particle motion. To quantify the anisotropy with SWS, we used the semi-automated method of Teanby et al. (2004), which is based on the approach of Silver & Chan (1991). Using the eigenvalue method, the splitting parameters Φ and δt were estimated through a grid search procedure, wherein the horizontal seismogram components were rotated and time-shifted to minimize transverse component energy and linearize XKS particle motion. We performed SWS analysis on a number of windows, wherein the algorithm uses cluster analysis to find stable measurements over

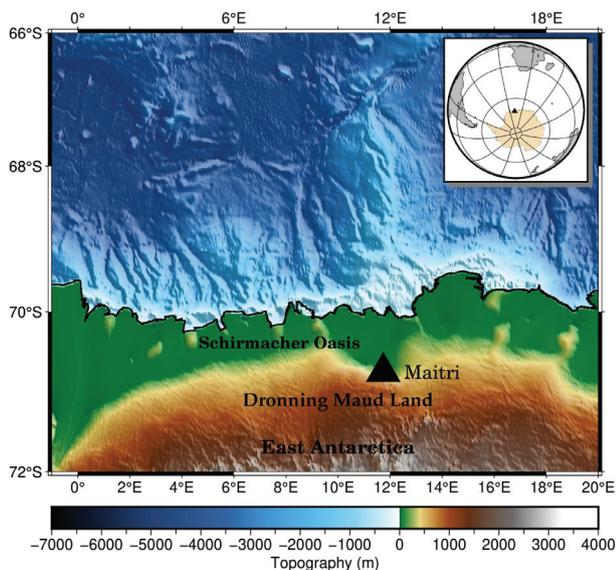


Fig. 1 The topography in the region of Maitri Station in Schirmacher Oasis, DML, East Antarctica.

many windows. The algorithm selects the window with the smallest errors in Φ and δt , which are fixed as 20° for Φ , and 0.5 sec. for δt . We also carefully checked each measurement manually and sorted all the measurements, based on their quality, as good, fair or null (Supplementary Table S1). For a robust analysis, we used only the good SWS measurements. An example analysis of good SWS data and result is shown in Supplementary Fig. S2.

S-wave SWS

We obtained a total of 12 waveforms with good signal-to-noise (>2) of the direct S-wave events with magnitudes ≥ 5.5 within epicentral distances from 30° to 90° . The signals with possible contamination with noise and other phases (e.g., SKKS and SKS) were removed from the analysis. The waveforms on transverse and radial components were processed for further analysis. As in the XKS analysis, we used the code of Teanby et al. (2004) for SWS analysis of direct S-phases. As in XKS, any measurement with an error $>20^\circ$ for Φ and 0.5 s for δt was discarded. An example showing a ‘good’ S-phase measurement is shown in Supplementary Fig. S3 and an example of null measurement is shown in Supplementary Fig. S4.

Results and discussion

The good SWS results of XKS data are shown in Fig. 2a and of S-phases in Fig. 2b. Supplementary Table S2 shows the good SWS results of both the XKS and S-phase

analyses. Supplementary Table S3 shows the good, fair and null SWS results of both the XKS and S-phase analyses. The results of null anisotropy are shown in Supplementary Fig. S4. Because of the lack of adequate back-azimuthal splitting data, we were unable to investigate multiple layers of anisotropy, and we assumed a single anisotropy layer with hexagonal symmetry and horizontal symmetry axis. With additional data, we may be able to analyse this aspect in future.

Our SWS measurements of upper mantle anisotropy beneath MAI (Fig. 2) are characterized by north-east–south-west Φ directions and δt of about one second (Silver 1996; Savage 1999). For comparison, we plot the SWS results of earlier studies in Fig. 2a. Bayer et al. (2007) reported two-layer anisotropy at the nearby Russian station NOVO, where the Φ of the upper layer is oriented parallel to Lithospheric Archean fabrics, whereas the anisotropy of the lower layer is correlated to the break-up of Gondwana in Jurassic times. For such stations like NOVO, showing two-layer anisotropy, we considered the upper layer values. Interestingly, this comparison demonstrates that the place where Bayer et al. (2007) collected data, and the locations of other studies, such as Müller et al. (2001) and Usui et al. (2007), which are located to the east and west of MAI in eastern Antarctica, also show a predominantly north-east–south-west Φ orientation (Fig. 2a). Lucas et al. (2022) also reported a north-east–south-west oriented Φ in eastern Antarctica. This highlights the qualitative similarities between the splitting results in our study and other studies in eastern Antarctica. Similarly, other studies in southern regions (not shown in Fig. 2a), such as Barklage et al. (2009), also report azimuthal anisotropy with Φ directions at approximately $N60^\circ E$ and a δt of about one second. in southern Victoria Land and the Ross Sea coast (which are south of MAI). In the Victoria Land region (south of MAI), Salimbeni et al. (2010) report Φ directions as north-east–south-west oriented. The comparison between our results and previous results in DML is shown in Supplementary Table S4.

Predominantly covered by the Antarctic Ice Sheet, the DML has complex geological structures that have been shaped by multiple tectonic events, including the amalgamation of East and West Gondwana during the Pan-African orogeny and subsequent rifting events leading to the break-up of Gondwana. Our study also makes use of magnetic anomalies, providing insights into the crustal geological structures—influenced by factors such as mineral composition, temperature and tectonic deformation—beneath the thick ice cover.

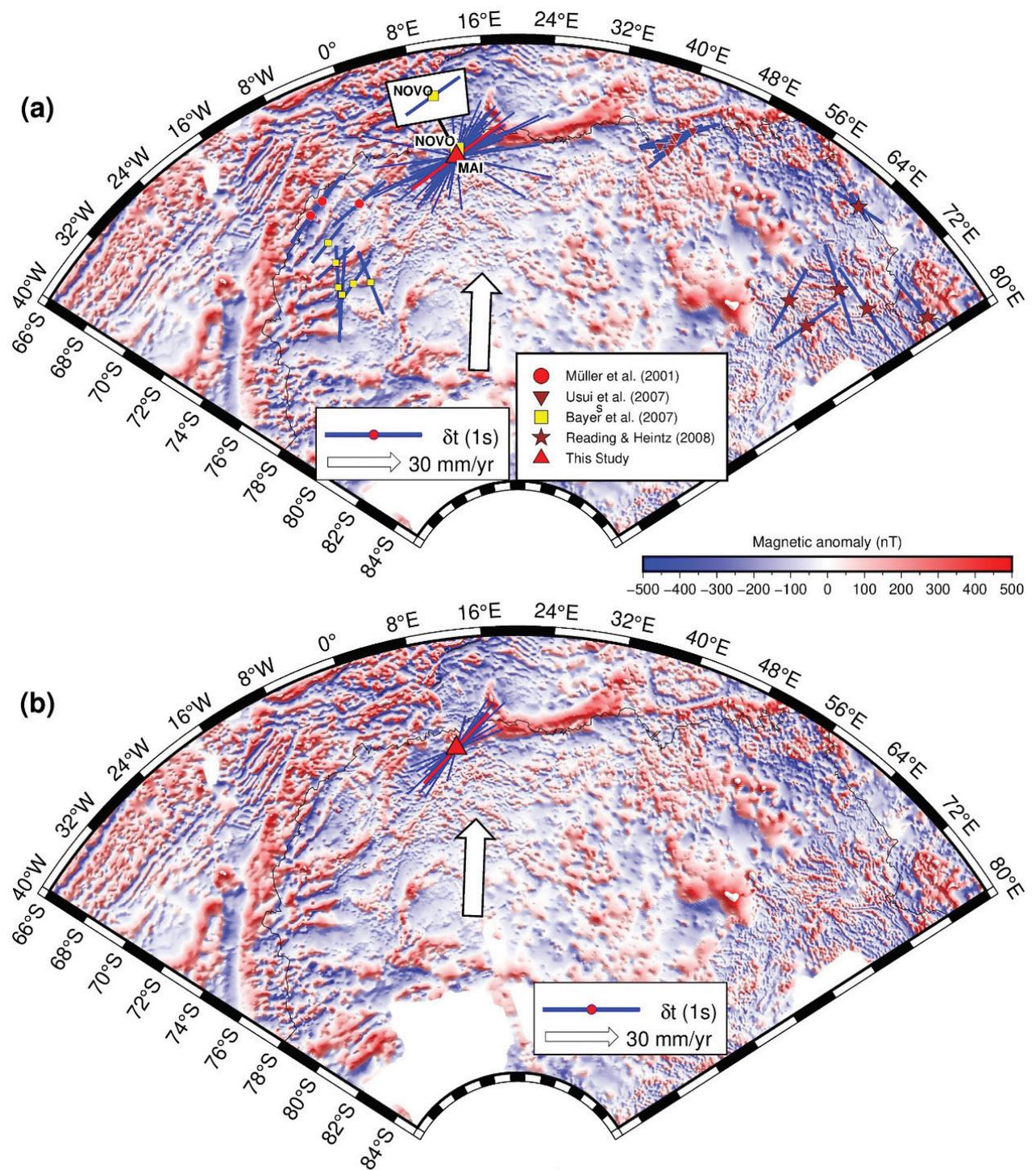


Fig. 2 (a) The observations of the individual (blue) and mean (red) SWS results (Φ and δt), plotted over magnetic anomaly grids (Golynsky et al. 2018), at MAI for the KKS-phases. Also shown are the SWS results of earlier studies around this region (see Supplementary Table S4). The nearby Russian station NOVO (Bayer et al. 2007) is also shown, along with places where data were collected by Müller et al. (2001), Usui et al. (2007) and Reading et al. (2008). (b) The S-phase results. The absolute plate motion direction (shown as white arrow) is derived from HS3-NUVEL1-A model (Gripp & Gordon 2002); the delay time δt (one second) is provided for reference.

Conclusion

This study has shown a coherence between the XKS and S-phase anisotropy at MAI (and NOVO). It follows the strike of the magnetic anomalies (Fig. 2a), which implies an alignment of crustal anomalies with mantle fabrics and crust-mantle coupling during the major orogenic events that formed the Antarctic continent. The margin-parallel XKS and S-phase anisotropy aligned to Schirmacher Oasis and the continental margin of East Antarctica correlates well with frozen lithospheric anisotropy, possibly caused by the lattice-preferred orientation of olivine from the major palaeo-tectonic events of Precambrian periods and the break-up of the Gondwana supercontinent, as suggested by Bayer et al. (2007). These results highlight the persistence of inherited anisotropy within the Antarctic lithosphere, linking present-day seismic observations to the continent's Precambrian tectonic architecture.

Acknowledgements

We sincerely thank the Section Editor, Dr Robert Spielhagen, and three anonymous reviewers who helped us to improve the manuscript significantly. We acknowledge the contributions of many scientists and technicians of the National Geophysical Research Institute, CSIR, Hyderabad, India. We thank Amit Bansal (now at the Central Scientific Instruments Organisation, CSIR, Chandigarh, India) for upgrading and acquiring digital data from the seismological station at MAI. We thank the director of the National Geophysical Research Institute, CSIR for permission to publish this work (vide ref. no. NGRI/Lib/2024/Pub-113).

Disclosure statement

The authors report no conflict of interest.

Funding

We acknowledge the National Centre for Polar and Ocean Research (NCPOR), Ministry of Earth Sciences, Government of India, for its support of the Indian Antarctic Programme and other scientific initiatives. The first author also acknowledges the support of the National Geophysical Research Institute, CSIR, from project MLP-7009-28.

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