Crust and upper mantle in Dronning Maud Land, Antarctica, retrieved from shear-wave splitting, receiver functions, seismic refraction and 3-D gravity modelling

B. Bayer,[1] Ch. Müller,[2] W. H. Geissler,[1] D. W. Eaton,[3] A. Eckstaller,[1] and W. Jokat[1]

[1]Alfred-Wegener-Institute for Polar-and Marine Research, Am alten Hafen 26, D-27568 Bremerhaven, Germany (bbayer@awi.de)
[2]FIELAX GmbH, Schifferstrasse 14, D-27568 Bremerhaven, Germany (mueller@fielax.de)
[3]Department of Earth Sciences, University of Western Ontario, London, ON, N6A 5B7, Canada (deaton@uwo.de)

Summary The crust and upper mantle of Dronning Maud Land (DML), Antarctica, have been investigated using teleseismic data from broadband seismograph stations deployed at temporary and permanent locations and recordings from a seismic refraction experiment. For shear-wave splitting analyses the observed anisotropy can in most cases be related to major tectonic events that formed the geological features of the present-day Antarctic continent. We rule out an anisotropic contribution from recent asthenospheric flow. An abrupt change in fast axis direction of the shear-waves and a remarkable Moho jump beneath the Kottas mountains appears to mark a suture between the Grunehogna craton, a fragment of the Kalahari-Kaapvaal craton in southern Africa, and the Mesoproterozoic Namaqua-Natal belt. In general, the Moho depth increases from the coast towards the mountain ranges of Wohlthatmassif and Kottas, where thick crust between 45-53 km is found. The Vp/Vs ratio are similar within geological units but different throughout DML.

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Introduction

The objective of the study was to probe the crustal depth and upper mantle structures in some locations of Dronning Maud Land (DML), East Antarctica. The study area covers the area between 20°W and 20°E and ranges from the continental margin at about 70°S to 75°S. At a smaller scale, DML is subdivided into three parts: the western, central and eastern DML. Their tectonic and geological evolution are similar. Several major geological and tectonic events during Earth's history formed the present-day Antarctic continent. Within the DML geological units were formed during several phases: (1) The Grenville event, at 1.1 Ga, forming the supercontinent Rodinia; (2) The Ross/Pan-African event at 500 Ma, forming the supercontinent Gondwana due to the collision between West and East Gondwana; (3) The break-up of Gondwana 160 Ma ago, which started in the Lazarev Sea (oceanic basin off DML), and which was accompanied by voluminous volcanism, and major outpourings of continental flood basalts (Jacobs et al., 2003). In western DML, an Archean cratonic fragment named Grunehogna craton (GRU) is exposed. It consists of Archean granitic gneisses and Mesoproterozoic sedimentary rocks of similar ages to the Kalahari-Kaapvaal craton in southern Africa. GRU is most likely a piece of the Kalahari-Kaapvaal craton dispersed during fragmentation of Gondwana (Groenewald et al., 1991). The entire southern side of GRU is rimmed by the Maudheim province (MP) comprised of Proterozoic high-grade metamorphic rocks of Grenvillian age (1163-850 Ma). The MP is likely continued as the Namaqua-Natal belt in southern Africa.

Experimental set-up

Seismological recordings

During several experiments, portable broadband seismometers (Lennartz with 5 and 20 s eigenfrequency) with Reftek recording systems were deployed in Dronning Maud Land (DML), Antarctica. These experiments were carried out across the Heimefront shear zone (HSZ) during the polar summer of 2003 and along the Kottas mountain range during the polar summer of 2004, both in western DML (Figures 1 and 2). The duration of recordings varied and depended strongly on weather conditions and technical robustness of the equipment. In most cases, less than 5 weeks of recording led to some detectable teleseismic events.

Temporary deployed stations across HSZ (KOH1-KOH5, see Figure 2) were placed on ice with increasing thickness towards the south. The continental ice has a maximum thickness of 3 km underneath summer drilling station Kohnen (KOH6). Stations in the Kottas mountain range (Weigel, KOT1, KOT4, see Figure 2) were deployed directly on exposed rocks. In addition, permanent broadband recordings from 2002 to 2005 of the South African base Sanae IV (SNAA) were investigated and yielded the greatest number of observations. We also used recordings of seismographs, operated during the polar winter 2005 at the Russian base Novolazarevskaya (NOVO) in central DML and at Weigel nunatak in the Kottas mountains.

Seismic refraction data

During the polar expedition ANT-VIII/5 in 1989/90, a refraction profile (named KOTTAS in Figure 1b) across the south western part of HSZ was shot (Miller & Oerter, 1991). The largest offset between shot points and seismic stations were 200 km (see Figure 1). The profile was aligned perpendicular to the NE-SW oriented mountain strike. It crosses the entire transition zone between the foreland, escarpment and the adjacent plateau. The major questions to be answered by the experiment were addressed to the crustal structures and its composition. For data acquisition and storage nine PCM (type Serie 5800) stations were used. Two stations with 4 seismic channels were equipped with vertical seismometers, seven stations had up to 8 channels and were equipped with three component seismometers of type Geosource PE-6 and one Lippmann 3-K seismometer. A total of 9 shots with a maximum charge of 800 kg dynamite were fired. At the northern end of the profile four shots were performed. Distances to the closest station AWI1 were 3, 8, 13 and 18 km. Three shots were carried out at the southern end in 3, 8 and 18 km distance from the closest southern station MUC10. Two middle shots between station AWI4 and MUC7 completed the seismic experiment.

First results and tectonic implications

Crustal depth and Vp/Vs ratio

Within the area of investigation, mapping of the crustal depths were carried out by using passive and active seismic methods. With the calculations of receiver functions and an interpretation of a seismic refraction experiment (see Figure 1) it is obvious that the depth to Moho increases from the coast towards the southern mountain range.

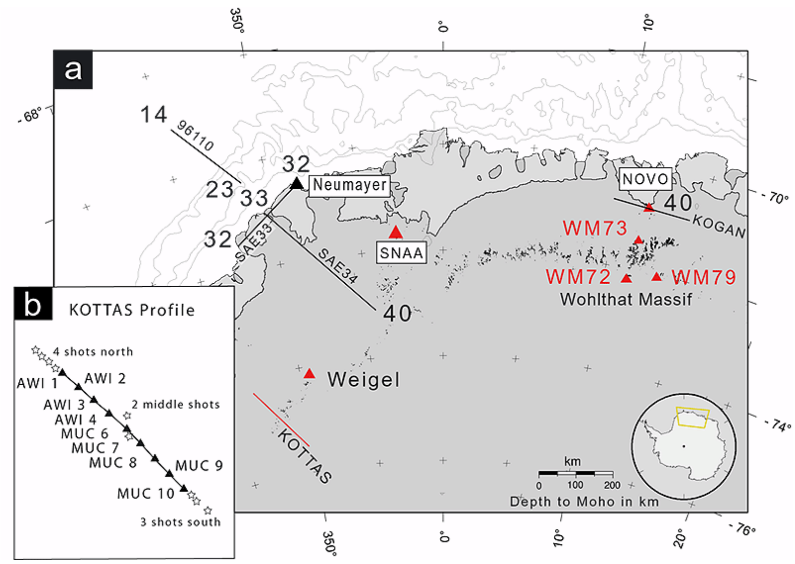

Figure 1a. Seismic stations and seismic refraction experiments within DML. Red triangles mark stations for which the crustal depth were retrieved by calculations of receiver functions. Black depth values are from previous refraction seismic experiments (Kogan, 1972, Kudryavtzek et al., 1991). Figure 1b shows the experimental set-up of the seismic refraction experiment performed in the Kottas mountains.

The crustal thickness ranges between 45 and 53 km below the mountain range. We explain this thickened crust as a mountain root. Such values were also found for mobile belts, which flank the Kaapvaal craton in southern Afrika (Nguuri et al., 2001). The depth variaton of 35-40 km found for undisturbed crust in southern Africa is comparable with our findings (Nguuri et al., 2001).

For all stations, a sharp converted signal (Ps) at the Moho is observed. This indicates a strong impedance contrast at the crust and upper mantle boundary. In most cases we are able to identify the multiples, which allows an estimation of the Vp/Vs ratio.

The western part of DML shows a higher Vp/Vs ratio than the central DML. For the Kottas mountains, a well constrained Vp/Vs ratio of 1.72 is calculated. This value agrees with the averaged global value for a continental shield. At Station SNAA, the receiver function method provided an ambiguous result which indicates a more complex crustal structure. Considering the location of the recording site and its relation to southern Africa, we prefer the values for the crustal thickness of 39 km and a Vp/Vs ratio of 1.80 as similar values were found in southern Africa (Nguuri et al., 2001). For the central DML, the seismic compressional and shear velocities can be described by a Vp/Vs ratio of 1.67. Such low values indicate a predominantly quartz-rich, felsic bulk composition of the crust (Zandt & Ammon, 1995).

Upper mantle structure

Investigations of shear-wave splitting from core refracted S-waves in a poorly accessible region reveals new insights into the deeper geological structure and tectonic evolution of DML. In general, anisotropic structures are rather complex and reflect fossil fabrics of multiple tectonic events that formed the area of investigation. In detail, we draw the following conclusions from the shear-wave splitting analyses regarding mantle structures and geodynamic evolution of Dronning Maud Land:

(1) Anisotropic features are not caused by asthenospheric flow since present-day absolute plate motion is slow and anisotropic patterns are rather complex and too inconsistent across the network to be explained by simple asthenospheric flow.

(2) In general, upper lithospheric anisotropic features follow the strike of major mountain belts (see Figure 2). On a smaller scale, fast anisotropy directions follow the strike of magnetic anomalies. This implies that crustal anomalies extend to the deeper lithospheric mantle caused by vertical coherent deformation and that both crust and mantle were strongly coupled during major orogenic episodes. As the orientations of the fast axes within Heimefront shear zone change very abruptly, we are able to provide stress evidence for a pronounced suture zone between the Archean Grunehogna craton and the Mesoproterozoic Maudheim province. This suture zone cuts through the entire lithosphere.

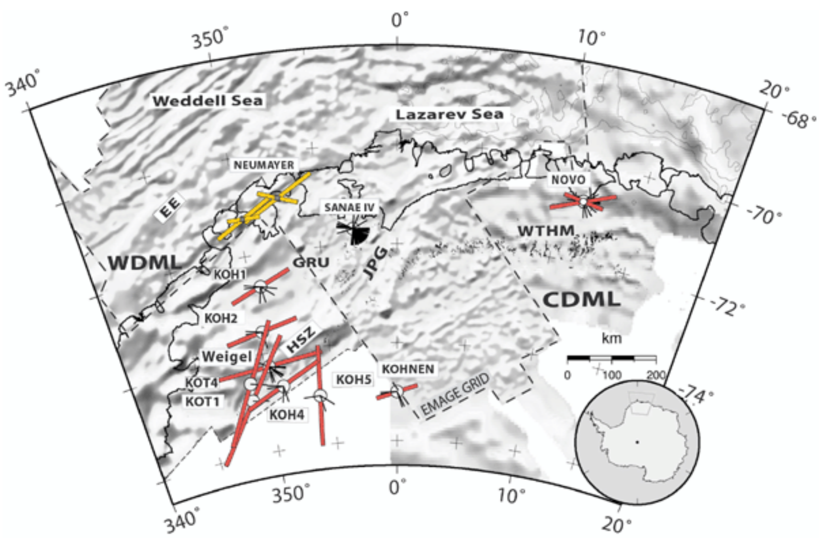

Figure 2. Estimated splitting parameters with grey scaled high resolution aero-magnetic anomaly grids of DML (EMAGE grid (Jokat et al., 2003) and ADMAP grid (Golynsky et al., 2001)). Thick red bars indicate anisotropy fast axis with length proportional to time delay.

(3) Where resolvable, lower anisotropic layers reflect fossil mantle most possibly created during first rifting stages of Gondwana break-up. Coastal stations like NOVO and results from the study of Mueller (2001) for the Neumayer station reveal exactly the same patterns for upper and lower layers, whereas stations further inland do not show evidence for a two-layer splitting.

(4) Inconsistent results regarding the azimuthal distribution of isotropic and anisotropic measurements were retrieved at SNAA. The observation of signal fractions on the vertical component suggests large-scale lateral heterogenic structures. These complex lithospheric structures beneath SNAA, situated at the southeastern flank of the Grunehogna craton, are explained by transition from cratonic to Grenvillian/Pan-African orogeny and possibly also affected by deformation processes, which accompanied the Gondwana fragmentation.

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