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Shear-wave velocities under the Transantarctic Mountains and Terror Rift from surface wave inversion

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Abstract. Rayleigh wave data between 20 and 120s period recorded in the western Ross Sea region of Antarctica are inverted using the waveform inversion technique described in *Passier and Snieder* [1995]. From the data we extract estimates of local S velocity structure beneath the Transantarctic Mountains and the Terror Rift. The shear wave velocities found are up to 6 % slower than the PREM model at between 40 and 160 km depth, depending on the propagation path, providing evidence of an anomalously warm upper mantle beneath the Terror Rift and, to a lesser extent, beneath the front of the Transantarctic Mountains.

Introduction

The Transantarctic Mountains (TAM) (Fig. 1), with a length of 3500 km and elevations of up to 4500 m [*Robinson and Splettstoesser*, 1984], are one of the major Cenozoic mountain ranges in the world. They define the morphological and lithospheric boundary between the East Antarctic craton and West Antarctica [*Bentley*, 1983,].

The eastern side of the TAM, termed the Transantarctic Mountain Front, borders the Ross Embayment, a vast submerged region of extended continental crust [*Davey*, 1981,]. Within the Ross Embayment multichannel seismic reflection data have revealed three major subsurface rift structures (e.g. [*Cooper et al.*, 1991]); the Victoria Land basin (VLB), the Central trough and the Eastern basin [*Davey et al.*, 1982]. Seismic data indicate that the basins are infilled with up to 14 km of sediment [*Davey et al.*, 1982], and are underlain by rifted continental crust [*Cooper et al.*, 1987; *Trehu et al.*, 1989], with crustal thicknesses between 17 and 25 km. Present-day rifting is thought to be represented by the Terror Rift, a 70 km wide axial rift zone [*Cooper et al.*, 1987] which lies on the western side of the VLB, 50-100 km east of the TAM Front in the western Ross Sea (Fig.1).

Although there is some limited information on the physical properties of the crust beneath the western Ross Sea and TAM, there is very little known on the upper mantle beneath the region. Most of the key process-oriented questions on the development of this rift system and the uplift of the TAM still require fundamental information about first-order characteristics of the lithosphere, including thickness, velocity and thermal structure, and the nature of major lithospheric and crustal boundaries across the rift system and its margins.

Past seismological studies of the lithosphere structure include that of *Evison et al* [1960] and *Adams* [1972] who used surface wave dispersion analysis to infer crustal thicknesses for the Antarctic craton as a whole. More recently *Roult et al.,* [1994] carried out surface wave tomography for periods greater than 70 s, using Antarctic station data, involving about 400 travel paths. However, these studies do not specifically target the western Ross Sea and TAM region.

In this paper we study the upper mantle structure beneath the western Ross Sea region by applying the waveform inversion technique of *Passier and Snieder,* [1995] (PS95) to surface wave data recorded in the region. Comparisons are made between observations of seismic waves with travel paths beneath the Terror Rift (TNV-SBA path, Fig.1) and beneath the TAM (TNV-VNDA path, Fig.1). Using these data, we extract information on the local S-wave velocity structure of the upper mantle beneath the Terror Rift and the TAM.

Method and data

The surface wave inversion technique presented by PS95 is used here to obtain relative S velocity perturbations as a function of depth along various short interstation paths. The technique uses the complex spectra of surface wave recordings as data for the inversion, and is an extension of the algorithm originally described by *Kushnir et al* [1988]. Source excitation and source to station parameters are estimated using a least-squares determination while an estimate of the interstation velocity structure is subsequently determined using a method of nonlinear optimisation. The technique differs from the classical two-station approach in that the construction of a dispersion curve is not necessary, thus avoiding error propagation via the mapping from the dispersion curve to S velocity. In this study we apply the PS95 technique to observed fundamental-mode Rayleigh wave data recorded in Antarctica.

In the western Ross Sea region in Antarctica there are only 3 broadband stations which can provide data relevant to this study : VNDA, a USGS supported digital 3 component borehole seismometer situated in the Transantarctic Mountains; SBA, a New Zealand operated system at Scott

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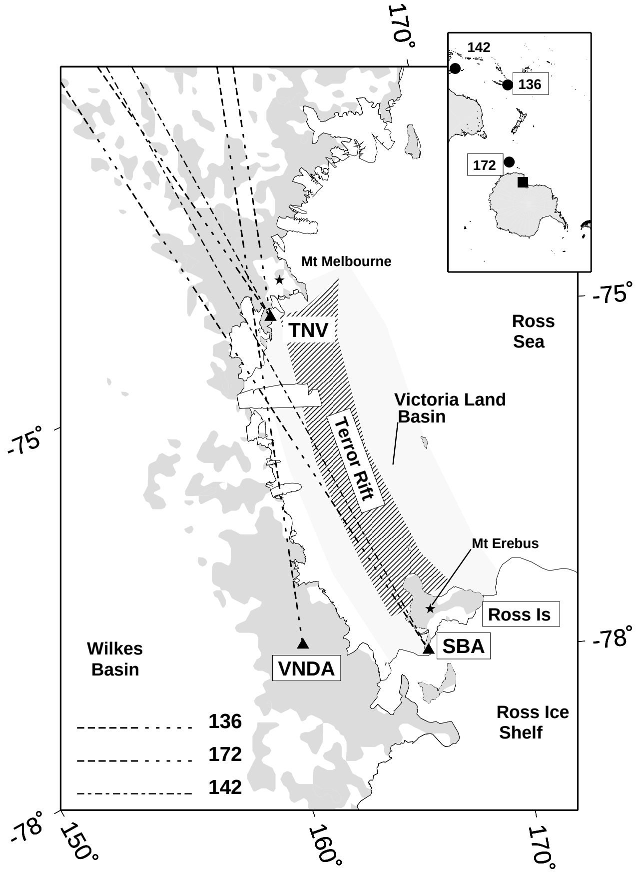

Figure 1. The western Ross Sea region, Antarctica, showing the Terror Rift (stripes), Transantarctic Mountains (TAM, dark grey shade) and Victoria Land Basin. Seismograph stations TNV, VNDA and SBA are marked as solid triangles. The light grey shade represents floating shelf ice and glaciers. Active volcanoes are shown as stars. Great circle paths for the travel paths from events 136, 142 and 172 are also marked, following the key (b) Inset shows the location of the earthquakes (solid circles) and the study region (solid square)

Base, Ross Island; and TNV, a very broadband system operated by the Italian Antarctic Group [*Morelli et al.*, 1994]. The station locations are shown in Fig.1.

Suitable earthquakes were selected by searching the IRIS-DMC catalogues on the basis of epicentral distance ($\Delta < 85°$), magnitude (greater than 6) and source-receiver back-azimuth. Although the VNDA, SBA, and TNV stations have common records for only a few suitable events, these events have excellent signal to noise ratio and are adequate for this study. Event locations are detailed in Table 1.

During pre-processing the waveforms were decimated to 0.8 samples per second and corrected for instrument response. After a multiple filter analysis the data then underwent time-variant filtering [*Landisman et al.*, 1969] in order to isolate the fundamental mode from the rest of the signal in the period band 20s to 120s. Waveform inversions were performed using the vertical component displacement recordings.

Results

We will discuss the results for the travel paths beneath the Terror Rift and the TAM margin separately. In some inversions, regularization was applied by adding the weighted depth integral of the squared velocity perturbations to the function to be minimized in the inversion. However this regularization was usually relatively small and did not significantly affect the estimates of the velocity perturbation.

Beneath the Terror Rift

The first data we examine are from the May 22, 1995, event in D'Entrecasteaux Islands, (event 142, Table 1). The calculated great-circle travel path to station SBA for this event passes roughly beneath the surface expression of the Terror Rift (Fig.1). The inversion of this data is assisted by the fact that this is a shallow event (30 km) so that almost all of the energy is contained within the fundamental mode.

The vertical component of the displacement recordings for this event are shown for stations TNV and SBA in Fig.2 along with the synthetic waveforms calculated using the velocity model obtained from the inversion. The fit of the synthetic waveforms to the observed waveforms is excellent, both for phase and amplitude.

Fig.2c shows the velocity perturbation calculated in the inversion for the path between TNV and SBA, relative to the PREM velocity model [*Dziewonski and Anderson*, 1981]. A negative perturbation represents slower velocities along the TNV-SBA path relative to the PREM model. The derived velocity perturbations are up to -6% at 40 to 100 km depth, and are around -4% below that, down to a depth of around 160 km. Synthetic tests show that the lower depth bound of this contrast is not particularly well defined; the data fit is not that sensitive to perturbations in the velocity model below 160 km depth, probably because of the decreasing resolving power with depth of the fundamental mode energy.

For the second event (June21 1995, event 172, Table 1), the path from this event to station SBA also passes beneath the surface expression of the Terror Rift, although the calculated travel path lies slightly to the west of the path for event 142. The velocity perturbation between TNV and SBA derived from the inversion, shown in Fig.2d, is very similar to

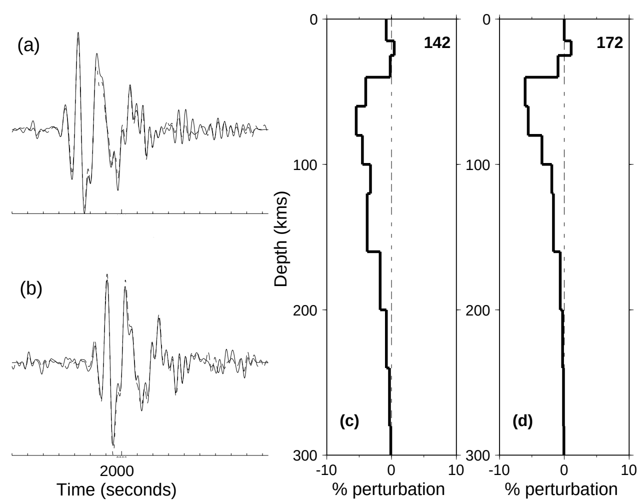

Figure 2. (a) The vertical component of station TNV (solid line), event 142, which was used as data for the inversion, and the fit (dashed line) after inversion. (b) As for (a) but for station SBA (c) Velocity perturbations for the TNV-SBA path, event 142 (d) Velocity perturbations for the TNV-SBA path, event 172

Table 1. Earthquake events used in this study

Event	Date	Time	Lat	Lon	Depth	Region
136	16/05/95	20:12:44	23.0 S	169.9 E	20 km	Loyalty Islands
142	22/05/95	04:02:55	9.7 S	151.5 E	30 km	D'Entrecasteaux Islands
172	21/06/95	15:28:52	61.7 S	154.8 E	10 km	Balleny Islands

that derived for event 142, with a velocity perturbation of up to -6% at 40-80 km depth.

Beneath the TAM margin

The calculated travel path from event 136 (Table 1) to station VNDA (Fig.1) lies well to the west of the surface expression of the Terror Rift, instead passing roughly beneath the front of the TAM, which is inferred to represent the easternmost edge of the East Antarctic craton [*Bentley*, 1983,].

Data from this event were inverted using recordings from stations TNV and VNDA (Fig. 3). The synthetic waveforms calculated using the velocity model obtained from the inversion are shown in Fig. 3, along with the relative velocity perturbation calculated in the inversion for the path between TNV and VNDA (Fig.3c).

The fit of the synthetic waveforms to the observed waveforms is quite good, especially for the phase, while there are some small discrepancies in amplitude. The calculated velocity perturbations are up to 2 % lower than the PREM reference model between 60 and 160 km depth. Below 160 km there is little perturbation away from PREM velocities which, as noted above, probably reflects the limitations of the fundamental mode data.

Seismic refraction studies indicate thickening of the crust beneath the TAM, from 20-22 km beneath the Ross Sea to around 35 km beneath the TAM. The influence of such changes in crustal thickness on the inversion results, as well as the vertical resolving power of the inversion technique, is examined in PS95 using synthetic models. They show that contamination of the inversion solution below the Moho is small for 30 km changes in crustal thickness. We infer that the deeper parts of our model are unlikely to be greatly affected by the changes in crustal thickness expected beneath the TAM.

Discussion

Using Rayleigh wave data recorded in the western Ross Sea region we have obtained localized estimates of the S velocity structure beneath key structures.

The shear wave velocities found beneath the Terror Rift are up to 6% slower than the PREM velocity model. These lower-than-average velocities persist from 40 km down to a depth of at least 160 km (Fig.2), indicating an anomalously slow upper mantle beneath the Terror Rift.

These results are consistent with other observations and measurements in the western Ross Sea region. There is present-day active volcanism [*LeMasurier*, 1990] at Mt Melbourne, at the northern extent of the Terror Rift (Fig.1), and Mt Erebus, at the southern extent. Separately, unusually high heat flows are observed in the Terror Rift and VLB (83-126 mWm^{-2}, *Blackman et al.,* [1987]; 80-100 mWm^{-2}, *Della Vedova et al.,* [1992]), which suggests unusually high conductive heat transfer through anomalously thin lithosphere.

An estimate of the maximum temperature anomaly for the upper mantle beneath the Terror Rift can be made using the S velocity anomalies obtained in this study and an approximate temperature-velocity relation such as that of *Karato* [1993], which assumes high attenuation (Q=50). Given the *Karato* relation, and a S velocity anomaly of 0.3 km/s (event 172, 50 km depth), then a temperature anomaly of around 300K is implied, assuming that no partial melt is present.

To the west of the Terror Rift, inversion of data from the TNV-VNDA station pair (Fig.3) indicate slower than average S velocities along the TNV-VNDA travel path; S velocities up to 2% slower than the PREM reference model extend between 60 and 160 km depth, indicating that the upper mantle beneath the TAM Front is anomalously warm.

Various uplift mechanisms have been suggested for the TAM, including simple shear extension [*Fitzgerald et al.*,

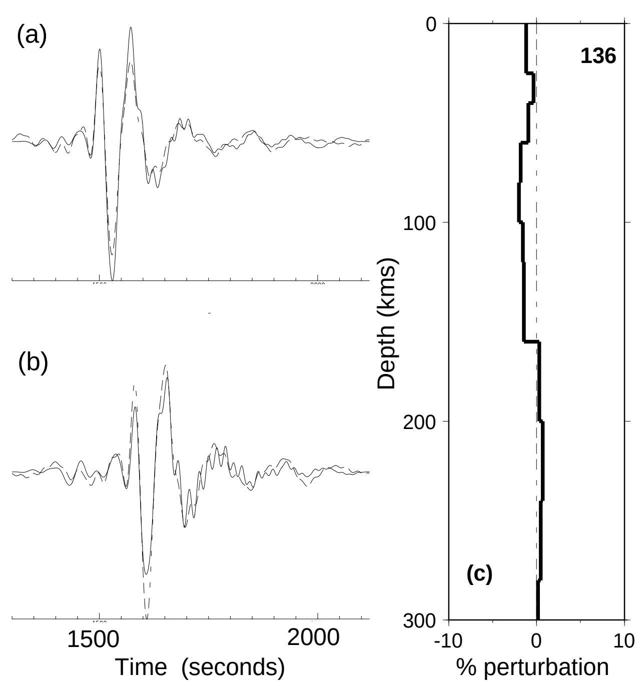

Figure 3. (a) The vertical component of station TNV (solid line), event 136, which was used as data for the inversion, and the fit (dashed line) after inversion. (b) As for (a), but for station VNDA. (c) Velocity perturbations for the TNV-VNDA path, event 136

1986] and models involving thermal conduction or advection [*Stern and ten Brink*, 1989; *ten Brink and Stern*, 1992]. In the latter models the uplift of the TAM scarp is assisted by thermal conduction of heat from the Ross Embayment to the cold, old, much thicker lithosphere west of the TAM Front, which requires that regional thermal anomalies are present in the upper mantle immediately beneath the TAM mountain front (e.g. [*Bott et al.*, 1992,]). Our results as described above appear to be in agreement with these models, at least for depths shallower than 160 km.

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