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Tectonophysics 416 (2006) 187 – 207
TECTONOPHYSICS
www.elsevier.com/locate/tecto

An investigation of upper mantle heterogeneity beneath the Archaean and Proterozoic crust of western Canada from Lithoprobe controlled-source seismic experiments

Andrew R. Gorman [a,*], Balázs Németh [b], Ron M. Clowes [c], Zoltan Hajnal [d]

[a] *Department of Geology, University of Otago, PO Box 56, Dunedin 9015, New Zealand*
[b] *PotashCorp, 500-122 1st Avenue South, Saskatoon Canada SK S7K 7G3*
[c] *University of British Columbia, Department of Earth and Ocean Sciences, 6339 Stores Road, Vancouver Canada BC V6T 1Z4*
[d] *University of Saskatchewan, Department of Geological Sciences, 114 Science Place, Saskatoon Canada SK S7N 5E2*

Accepted 28 November 2005
Available online 17 February 2006

Abstract

Observations of upper mantle reflectivity at numerous locations around the world have been linked to the presence of a heterogeneous distribution of rock types within a broad layer of the upper mantle. This phenomenon is observed in wide-angle reflection data from Lithoprobe's Alberta Basement Transect [the SAREX and Deep Probe experiments of 1995] and Trans-Hudson Orogen Transect [the THoRE experiment of 1993]. SAREX and Deep Probe image the Archaean lithosphere of the Hearne and Wyoming Provinces, whereas THoRE images the Archaean and Proterozoic lithosphere of the Trans-Hudson Orogen and neighbouring areas.

Finite-difference synthetic seismograms are used to constrain the position and physical properties of the reflective layer. SAREX/Deep Probe modelling uses a 2-D visco-elastic finite-difference routine; THoRE modelling uses a pseudospectral algorithm. In both cases, the upper mantle is parameterized in terms of two media. One medium is the background matrix; the other is statistically distributed within the first as a series of elliptical bodies. Such a scheme is suitable for modelling: (1) variations in lithology (e.g., a peridotite matrix with eclogite lenses) or (2) variations in rheology (e.g., lenses of increased strain within a less strained background).

The synthetic seismograms show that the properties of heterogeneities in the upper mantle do not change significantly between the two Lithoprobe transects. Beneath the Trans-Hudson Orogen in Saskatchewan, the layer is best modelled to lie at depths between 80 and 150 km. Based on observations from perpendicular profiles, anisotropy of the heterogeneities is inferred. Beneath the Precambrian domains of Alberta, 400 km to the west, upper mantle heterogeneities are modelled to occur between depths of 90 and 140 km. In both cases the heterogeneous bodies within the model have cross-sectional lengths of tens of kilometers, vertical thicknesses less than 1 km, and velocity contrasts from the background of −0.3 to −0.4 km/s. Based on consistency with complementary data and other results, the heterogeneous layer is inferred to be part of the continental lithosphere and may have formed through lateral flow or deformation within the upper mantle.

Keywords: Upper mantle heterogeneity; Western Canada; Finite-difference modelling; Controlled-source seismology

* Corresponding author. Fax: +64 3 479 7527.
E-mail addresses: andrew.gorman@otago.ac.nz (A.R. Gorman), binemeth@potashcorp.com (B. Németh), clowes@eos.ubc.ca (R.M. Clowes), zoltan.hajnal@usask.ca (Z. Hajnal).

0040-1951/$ - see front matter
doi:10.1016/j.tecto.2005.11.023

1. Teleseismic Pn and the Pn coda

Long-range (greater than ~600 km) observations of refractions travelling at upper mantle velocities (8.1–8.3 km/s) are not predicted by most homogeneous or smoothly varying models of the upper mantle. However, seismic energy with these velocities has been observed since the 1960s in earthquake seismograms (Bath, 1967) and is often seen in controlled-source refraction/wide-angle reflection (R/WAR) data sets at offsets as great as 3000 km (Pavlenkova, 1996). This teleseismic Pn phase (Bath, 1966), is distinct from the deeper higher-velocity P phase (Fig. 1). At offset distances beyond 600–800 km, the teleseismic Pn phase generally has a greater amplitude than the P phase that precedes it. R/WAR surveys have recorded the teleseismic Pn phase beneath several different cratonic regions of the Earth including: much of northern Eurasia through the Soviet-era Peaceful Nuclear Explosion (PNE) programme (Egorkin and Pavlenkova, 1981; Egorkin et al., 1987); the Baltic Shield and its margins from the FENNOLORA (Guggisberg and Berthelsen, 1987), EUGENO-S (EUGENO-S Working Group, 1988) and BABEL (BABEL Working Group, 1990, 1993) projects; and North America through such Lithoprobe investigations as SNORE in the Slave and Northern Cordilleran Lithospheric Evolution Transect (Fernandez Viejo et al., 1999). Other experiments have recorded the same phase beneath the southwestern European margin and the south Atlantic Ocean (Pavlenkova, 1996) suggesting that the phenomenon is not restricted to continental lithosphere.

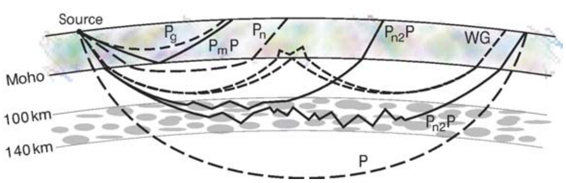

Fig. 1. Schematic summary of lower crust and upper mantle phases (not drawn to scale) identified in controlled-source seismic data sets. Identified phases are represented by raypaths travelling from left to right. Pg—crustal refractions, PmP—reflections from the Moho, Pn—refractions from the uppermost mantle, P—general phase name for refractions from the mantle, WG—whispering gallery phase [any inhomogeneities present in the lower crust add to the complexity of WG (e.g., Morozov et al., 1998; e.g., Nielsen and Thybo, 2003); an example of one such raypath is shown here], Pn_2P—teleseismic Pn that propagates to much greater offsets than Pn; it is similar to Pn except that the near-horizontal portion of the raypath is characterised by multiple reflections and scattering within a distinct layer of heterogeneities in the upper mantle between depths of ~90 and 140 km; two such examples are shown in the figure.

The source of the teleseismic Pn phase can be attributed to either of two scenarios: the whispering gallery phenomenon (e.g., Menke and Richards, 1980; e.g., Morozov et al., 1998; Nielsen and Thybo, 2003; Nielsen et al., 2003), or channelling of energy through multiple reflections and scattering within a heterogeneous region of the upper mantle (e.g., Fuchs and Schulz, 1976; Nielsen et al., 2002; e.g., Perchuc and Thybo, 1996; Ryberg et al., 1995; Thybo and Perchuc, 1997; Tittgemeyer et al., 2000, 1996, 1999) (Fig. 1). A common feature of both of these schemes is a coherent coda of reflected and scattered arrivals that coalesce at far offsets into a discernible teleseismic Pn phase. Interpretations of older R/WAR data sets are limited by the surface sampling interval (often 10s of km), whereas more recent surveys benefit from a station spacing on the order of a kilometer. This enables more subtle waveform characteristics of the upper mantle phases—and in particular the Pn coda at offset distances as low as 200 to 300 km—to be utilised in the interpretation. These upper mantle arrivals are clear on the Lithoprobe R/WAR data sets recorded in the Trans-Hudson Orogen and Alberta Basement transects of western Canada (Clowes et al., 1999).

Whispering gallery models involve multiple reflections of the Pn wave off the underside of the Moho (Fig. 1); the Pn coda is explained by invoking lower crustal heterogeneities (Morozov et al., 1998; Morozov and Smithson, 2000; Nielsen and Thybo, 2003). Morozov (2001) presents strong evidence that the whispering gallery phase is often overlooked in the analysis of R/WAR data sets. However, in specific cases, the modelling of whispering gallery events cannot successfully reproduce either the amplitude characteristics of the teleseismic Pn and Pn coda or the coherent energy in the Pn coda while simultaneously preserving the lower crustal characteristics observed in real data (Nielsen et al., 2003; Tittgemeyer et al., 2000). In the Lithoprobe data sets collected in western Canada (discussed in detail later), the offsets recorded are not optimal for observing the whispering gallery phase and any associated crustal heterogeneities.

Models of upper mantle heterogeneity usually involve the development of a distinct layer of statistically defined reflective bodies bounded above and below by regions that are comparatively transparent seismically. The observation of a large number of spatially continuous seismic reflections within the teleseismic Pn coda implies that heterogeneity in the mantle is the result of thin layering. Ray-trace synthetics indicate that these reflections are near or beyond the critical angle. A variety of modelling methods