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A comparison of cratonic roots through consistent analysis of seismic surface waves

H.A. Pedersen [a,*], S. Fishwick [b,c], D.B Snyder [d]

[a] Laboratoire de Géophysique Interne et Tectonophysique, Université Joseph Fourier, CNRS, BP 53, F-38041 Grenoble Cedex 9, France
[b] Bullard Laboratories, Department of Earth Sciences, University of Cambridge, Madingley Road, Cambridge, CB3 0EZ, United Kingdom
[c] Now at: Department of Geology, University of Leicester, University Road, Leicester, LE1 7RH, United Kingdom
[d] Geological Survey of Canada, 615 Booth Street, Ottawa, Canada K1A 0E

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Four cratonic regions are compared using existing dispersion curves and inverting these curves with an identical inversion method and parametrization. The four areas are the Archaean Kaapvaal Craton (southern Africa), Slave Province (central Canada) and Yilgarn Craton (western Australia), and the predominately Proterozoic region of South-Central Finland. The aim of this study is to identify the reliably resolved differences, and similarities, between the four study areas rather than obtaining a 'best' model for each area. Alongside the inversion, we also compare the observed dispersion curves with predicted ones using models with either constant shear velocities or constant composition in the lithosphere. The three main conclusions of this study are that 1) models of constant composition within the lithosphere do not explain the dispersion curves, in fact the less physically-based models of constant shear velocity provide a better fit to the data for all of the areas; 2) a low velocity zone in the deep lithosphere or below the lithosphere is resolved beneath the Kaapvaal while the three other areas have no such low velocity zone; 3) in spite of age differences, the shear velocities in the Kaapvaal, Slave and South-Central Finland are similar while the Yilgarn has significantly faster velocities. We also suggest that in order to understand the creation and evolution of the lithosphere a model driven approach to the analysis of surface wave dispersion is a valuable complement to classical inversion of dispersion curves, which suffer from the problem of non-unique solutions.

1. Introduction

Our knowledge of the continental lithosphere has progressed rapidly over the last two decades. Analysis of xenoliths and xenocrysts has yielded information on the composition of the lithospheric mantle while geophysical imaging methods have provided further constraints on its structure. We are still, however, in the process of translating this information into constraints on large-scale composition and models of the creation and evolution of the lithospheric mantle during the Earth's history.

Shield areas are key to a better understanding of the Earth's lithosphere, as they provide clues to the creation of the first continents, and how the process of lithosphere creation has evolved over time. A popular model (Jordan, 1975) which is supported by geochemical (Boyd, 1989), geodynamical (Forte and Perry, 2000), and combined interpretation of seismic and gravity data (Deschamps et al., 2002), suggests that the degree of crustal material melt extraction was higher in the early Earth than at present due to a decrease of mantle temperatures over time. The high degree of melt extraction in the early Earth would result in a dry and iron depleted lithospheric mantle which is characterized by high viscosity and low density and which can resist erosion from small scale mantle convection. Even though this model provides concepts which explain the overall geochemical and geophysical observations, it is still uncertain precisely when the change in lithospheric mantle composition took place and how the thick cratonic lithosphere was created (e.g. review by Lee, 2006).

Global Earth models show that the shield areas have high seismic velocities down to at least 200 km depth (e.g., Grand, 2002; Megnin and Romanowicz, 2000), but the lateral resolution in these studies is generally too low to determine the structure of individual tectonic units within the shield. Regional analyses of surface waves recorded by temporary arrays of closely spaced broadband seismometers can provide detailed data from selected areas. Two main approaches are used in such regional studies, both aim at calculating absolute shear wave velocities in the lithosphere.

The first method is based on the waveform inversion of regional events. One style of waveform inversion is to compute a 1D path-averaged model for the shear wavespeed structure between the source and receiver, by modelling aspects of the waveform (e.g., Nolet, 1990; Cara and Leveque, 1987). The set of 1D models can then be combined within a tomographic inversion to obtain the regional velocity structure (e.g., Simons et al., 2002, Priestley et al., 2006). Alternatively a full 3D waveform inversion can be directly performed incorporating mode coupling and multiple forward scattering (Friederich, 2003). An advantage of the waveform inversion methods is that they have

* Corresponding author. Tel.: +33 4 76 63 52 59.
E-mail address: Helle.Pedersen@obs.ujf-grenoble.fr (H.A. Pedersen).

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relatively good depth resolution due to the use of higher mode surface waves; a limitation is that in most cases the lateral resolution is insufficient to determine the structure of relatively small tectonic units.

The second approach, on which this study is mainly based, analyzes local propagation velocities — 'dispersion curves' — of fundamental mode surface waves within the array. It is possible to correct for diffraction effects outside the array through the use of array analysis (e.g. Friederich, 1998; Bruneton et al., 2001; Li et al., 2003; Chevrot and Zhao, 2007; for a short discussion see also Pedersen, 2006). The subsequent inversion of the observed dispersion curves for a model of shear-wave velocities in the lithosphere is strongly non-unique, due largely to the use of only the fundamental mode surface waves. Comparisons between different areas is therefore inconsistent: in principle the different methods should result in similar phase velocity dispersion curves, however, the inverse problem to obtain Vs(z) is generally solved differently and rarely with similar parameterizations. In practice this means that inversions carried out by different research groups using the same dispersion curves are likely to yield very different Vs(z) models, with all of the results equally probable.

We focus on the comparison between four different shield areas for which high-quality data is available from temporary arrays of broadband seismometers. We use existing dispersion measurements and invert them with the same inversion procedure and parameterization, except for the crustal part of the model which is adapted to each study area. Rather than providing a single model for each area, we explore which similarities and differences between the areas are stable for different parameterizations. Forward modeling is also used to test whether particularly simple structures will fit the dispersion characteristics for each region. The aim is not to find the 'best' model for each area but to determine which are the reliably resolved similarities and differences between them.

Three of the areas, the Slave Province (Canada), the Yilgarn (Australia) and the Kaapvaal (South Africa) are of Archean age, while the last one in Finland is dominated by Proterozoic (Svecofennian) rocks at the surface. After a short presentation of each area, we discuss the inversion procedure. We finally present comparisons between the four areas for different model parameterizations using both the inversion results and forward calculations.

2. Study areas

Our ideal criteria for the choice of study areas are: a 2D broadband array within a single tectonic unit, identical data processing and detailed knowledge of the crust. In practice, the four regions do not combine all these criteria. Due to the influence of surface wave diffraction, great-circle deviations (e.g., Cotte et al., 2000) and non-planar wavefronts (e.g. Friederich, 1998) which cannot be removed using two-station measurements, we consider that a 2D broadband array (as opposed to a linear deployment) is the minimum requirement, while we were more flexible on the other criteria.

2.1. Kaapvaal, southern Africa

The Kaapvaal craton (see Fig. 1) forms the southern continental nucleus of southern Africa, and is composed of the western Kimberley block and the eastern Witwatersrand block, separated by the Colesberg Lineament. North of the craton lies the Limpopo belt which formed during the Archean collision between the Kaapvaal and Zimbabwe Cratons, and to the south the Proterozoic (1100–1900 Ma) Namaqua-Natal mobile belt. The intracratonic Bushveld Complex (2050 Ma), the largest layered mafic intrusion in the world, is located in the northern part of the Kaapvaal Craton.

Between 1997 and 1999 a large array of broad band seismometers was deployed for the Southern Africa Seismic Experiment (SASE) as part of the multidisciplinary Kaapvaal Project (Carlson et al., 1996). The array followed a 2000 km long SW–NE trend from the Cape Fold Belt through to the southern part of the Zimbabwe Craton, and covered an area of approximately 1000 × 600 km over the majority of the Kaapvaal Craton. Prior to the SASE experiment, studies of the upper mantle beneath southern Africa used paths that crossed a number of different terranes, results using these regional paths suggested that a low velocity zone (LVZ) is required below about 160 km depth (e.g., Priestley, 1999). Since the SASE experiment a number of different studies have been undertaken using the available data, with a focus on the LVZ. Results from body wave tomography suggest that the Kaapvaal Craton has fast velocities relative to the surroundings down to at least 250 km depth (e.g., Fouch et al., 2004), however as absolute velocities are not calculated it is not possible to assess whether there is a LVZ within the vertical profile. Results from surface wave studies using the SASE data have had varying interpretations. Li and Burke (2006) use a two plane wave inversion technique to obtain phase velocities. Their second step of inverting the phase velocities to obtain the shear wave structure of the crust and upper mantle suggests that a modest LVZ is required at depths of 160–260 km. Using a two-station method, Larson et al. (2006) calculate phase velocities which are then inverted for the shear wave structure, they find that there is a slight decrease in S-wave velocities with depth, but do not observe a strong LVZ that is seen in the other studies. Priestley et al. (2006) incorporate the data from the SASE array into a regional study that uses a waveform inversion technique to obtain the shear wavespeed structure, they show fast velocities relative to the standard reference Earth model PREM (Dziewonski and Anderson, 1981) down to depths of 200 km, with an LVZ at about 150–225 km depth. A recent study incorporating 3D sensitivity kernels (Chevrot and Zhao, 2007) suggests that relatively high velocity roots extend to at least 250 km, however without reference velocities it is again not possible to recognize any LVZ. The questions of whether an LVZ is present, whether it is related to the base of the lithosphere, or if it is indicative of strong vertical variations in temperature, composition and/or fluids, remain an area of debate.

Analysis of garnet xenocrysts from kimberlites suggest that there are spatial variations in lithospheric structure beneath southern Africa, with much of the variability thought to be caused by metasomatic refertilisation (e.g., Griffin et al., 2003). Body wave studies (e.g., Fouch et al., 2004) and high resolution surface wave studies (e.g., Li and Burke, 2006; Chevrot and Zhao, 2007) both show variations in wavespeed across the craton. Detailed structure in these models differs, suggesting a significant level of uncertainty, and thus frustrating robust conclusions concerning the intracratonic structure.

In this study we focus on the average structure of the Kaapvaal Craton within the SASE array. In order to produce an *a priori* crustal model (see Table 1) we use the many studies that have used the receiver function technique to investigate the crustal structure of the region (e.g., Nguuri et al., 2001; Niu and James, 2002; Nair et al., 2006). We use an average crustal thickness of 38 km; throughout the majority of the Kaapvaal Craton the variation is about +/−4 km. Lower crustal velocities are generally quite slow, average Vs is about 3.9 km/s. In the region of the Bushveld Complex the crustal structure is quite different, however as this is only a relatively small part of our study area we have not incorporated it into the average crustal model. The transition from upper to lower crust is placed at 15 km depth and Vp values are also based on a refraction study across part of the craton (Durrheim and Green, 1992).

2.2. Slave Province, Canada

The exposed Archean crust of the Slave craton covers an area 500 km (E–W) by 700 km (N–S), surrounded by orogens which are Paleoproterozoic or younger in age (Fig. 2). A POLARIS seismic array occupied an area about 400 km (E–W) by 200 km (N–S) near the centre of the craton. The Slave Province is relatively complex, with ages of surface rocks being some of the oldest on Earth (the ca. 4030 Ma Acasta gneisses, Bowring and Williams 1989). The younger rocks in the area (2730–2580 Ma) bear witness to a complex evolution through that period, after which it is