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The state of the upper mantle beneath southern Africa

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Abstract

We present a new upper mantle seismic model for southern Africa based on the fitting of a large (3622 waveforms) multi-mode surface wave data set with propagation paths significantly shorter (≤6000 km) than those in globally-derived surface wave models. The seismic lithosphere beneath the cratonic region of southern Africa in this model is about 175±25 km thick, consistent with other recent surface wave models, but significantly thinner than indicated by teleseismic body-wave tomography. We determine the in situ geotherm from kimberlite nodules from beneath the same region and find the thermal lithosphere model that best fits the nodule data has a mechanical boundary layer thickness of 186 km and a thermal lithosphere thickness of 204 km, in very good agreement with the seismic measurement. The shear wave velocity determined from analyzes of the kimberlite nodule compositions agree with the seismic shear wave velocity to a depth of ~150 km. However, the shear wave velocity decrease at the base of the lid seen in the seismic model does not correspond to a change in mineralogy. Recent experimental studies of the shear wave velocity in olivine as a function of temperature and period of oscillation demonstrate that this wave speed decrease can result from grain boundary relaxation at high temperatures at the period of seismic waves. This decrease in velocity occurs where the mantle temperature is close to the melting temperature (within ~100 °C).

Keywords: Southern Africa; Surface waves; Kimberlite nodules; Upper mantle; Lithosphere

1. Introduction

Archean and Proterozoic shields form the oldest parts of the crust and lithosphere and are therefore of particular importance in understanding the early evolution of the Earth and the stabilization of the continents. They are also the only regions where we have samples of mantle material from depths greater than about 70 km whose physical properties can be measured directly and compared with in situ velocities determined from seismic studies. These samples come from kimberlite eruptions that bring mantle nodules to the surface. Because the lithosphere beneath the shields is thick and the magmas that transport the nodules to the surface are generated at the base of the lithosphere, kimberlites bring up nodules from greater depths than do alkali basalts that constitute the typical magma-type of eruptions found throughout the younger parts of continents. Since these nodules contain garnet, clinopyroxene and orthopyroxene, the pressures and temperatures at which they last equilibrate can be estimated from their mineral compositions.

The depth extent of the continents has been in question for over four decades (MacDonald, 1963). Jordan (1975) proposed that the oldest parts of the

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continents – the shields – are underlain by a layer about 400 km thick composed of high-velocity, low density material which he termed the “tectosphere.” Since the shields must carry these high velocity roots with them as the continents drift, the question of the depth extent of the continents is also of major geodynamic significance. The first seismic tomography models which were derived from body waves and long-period surface wave data supported the tectosphere model with high-velocity continental roots extending to over 400 km depth (e.g. Woodhouse and Dziewonski, 1984; Montagner and Tantimoto, 1991). However, more recent work which includes both long and short period surface wave data (e.g. Debayle and Kennett, 2000a; Priestley and Debayle, 2003; Ritsema et al., 2004) shows the high velocity roots beneath the oldest parts of the continents extend no deeper than ~200 km, in agreement with the petrological estimates (e.g. Boyd et al., 1985) which do not support cratonic roots extending deeper than ~200 km.

The Kalahari craton (Ashwal and Burke, 1989) of Southern Africa, consisting of the Kaapvaal and Zimbabwe cratons, the Limpopo mobile belt, and the Namaqua Belt (Fig. 1), has formed a stable unit for the past 2.3 Ga (McElhinny and McWilliams, 1977). In the discussion below, we are principally concerned with the Kalahari craton because its seismic structure has been recently intensively studied and because a great deal of petrological and geochemical work has been carried out on the mantle nodules from the kimberlite pipes of southern Africa. Qiu et al. (1996) used both multi-mode high frequency surface wave data whose propagation paths were largely confined to the Kalahari craton and petrologic data from kimberlite pipes on the Kalahari craton, to show that a relatively thin, high-velocity lid exists in the upper mantle beneath southern Africa with lower shear wave velocities at deeper depths in the upper mantle. Priestley (1999) and Priestley and McKenzie (2002) found from a re-examination of the data studied by Qiu et al. (1996) and the analysis of additional data, that the seismic lithosphere, which we equate to the high velocity upper mantle lid, beneath southern Africa extended at least to a depth of ~160 km. Ritsema and van Heijst (2000) used 40–200 s

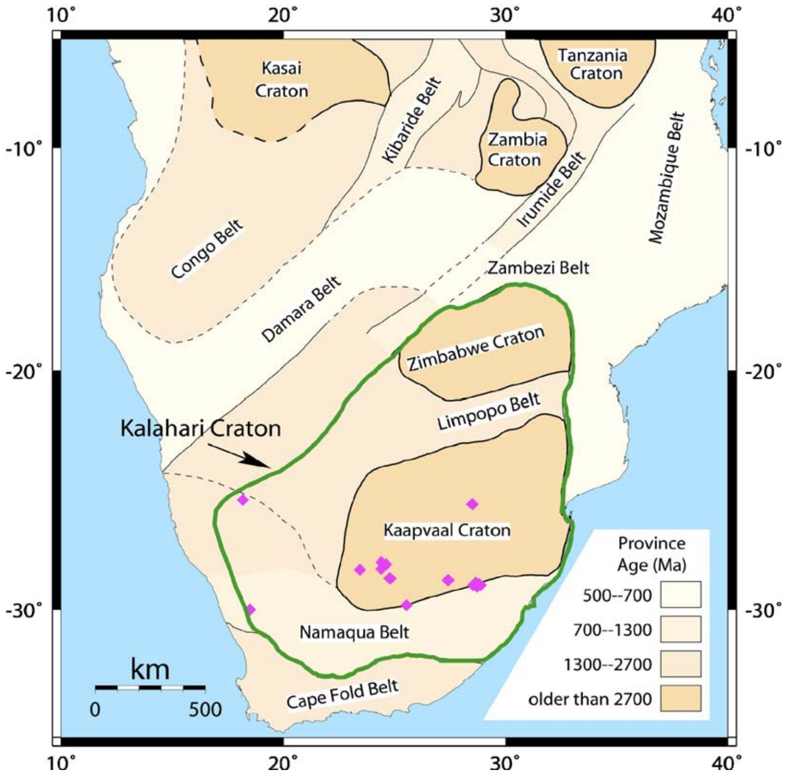

Fig. 1. Tectonic map of southern Africa. Most of southern Africa consists of Archean blocks and intervening mobile belts. The Kalahari craton (Ashwal and Burke, 1989) is composed of the Kaapvaal and Zimbabwe cratons, the Limpopo mobile belt and the Namaqua Belt. The Kalahari craton has been a stable unit for the past 2.3 Ga (McElhinny and McWilliams, 1977). Diamonds denote the locations of the kimberlite pipes of southern Africa.