WHAT DO CURRENT GEOPHYSICAL MODELS OF ARCHEAN LITHOSPHERE REALLY TELL US? - AN EXAMPLE FROM SOUTHERN AFRICA

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Introduction

Modern geophysical methods can be used to characterise the compositional and thermal state of Archean lithospheric mantle with increasing precision. However, these models are snapshots of the current lithospheric conditions, and may not adequately reflect the recent evolutionary history of the lithosphere. The common practice of interpreting geophysical models of Archean lithosphere in a uniformitarianist fashion may therefore not properly account for previous thermal or tectonic activity beneath a region.

Kaapvaal cratonic lithosphere samples

The Kaapvaal Craton in southern Africa is undoubtedly the most studied of the Archean-age cratons. Hundreds of occurrences of kimberlites and related rocks provide geographically extensive suites of mantle xenoliths and xenocrysts that have been actively studied for decades. In addition, there have been a number of detailed seismic and magnetotelluric surveys of the craton and surrounding regions. Comparisons of these data provide a method for tracking the evolution of the lithospheric mantle from the time of the kimberlite eruption to the present. The Kaapvaal cratonic lithosphere samples used for this study were brought to the surface during two episodes of kimberlite magmatism approximately 119 and 90 Ma (Figure 1).

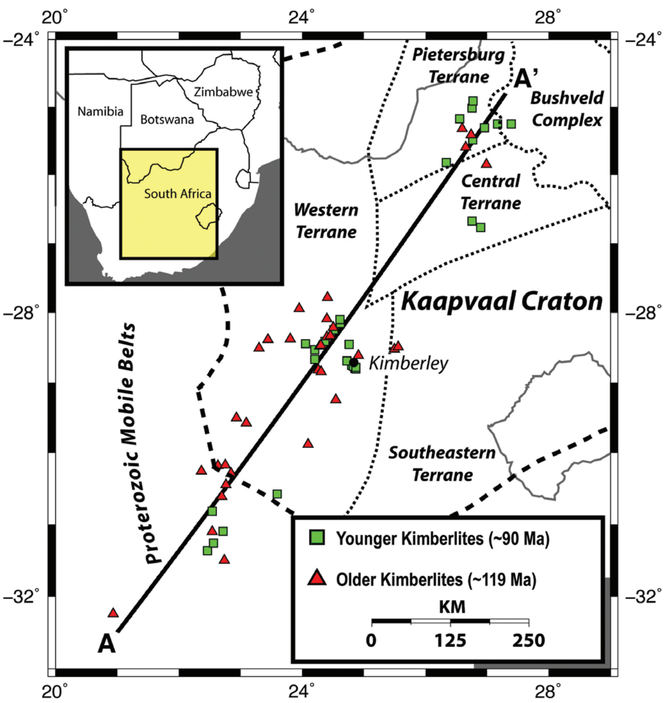

Figure 1. A simplified tectonic map of southern Africa showing the locations of kimberlite hosts used in this study. Section line A-A' refers the vertical sections shown in Figures 2 and 3.

Transforming garnet data into seismic data

Garnet xenocrysts collected from these kimberlite occurrences in the course of diamond exploration provide a geographically extensive sample of mantle material from each time period. Using the garnet geotherm method (Ryan et al. 1996), a pressure and temperature (P-T) is calculated for each garnet. Combining P-T data with whole-rock compositional estimates derived from garnet chemistry (Griffin et al. 1999, O'Reilly & Griffin 2006) supplies the information required to directly calculate seismic velocities.

Seismic velocities for the upper mantle are calculated from the garnet data using components of the LitMod - Perple_X computer codes (Afonso et al. 2008, Connolly 2009). The stable mineral assemblage at a given depth is estimated using a Gibbs free-energy minimization algorithm (Connolly 2005, 2009) within the system CaO-FeO-MgO-Al_2O_3-SiO_2 (CFMAS). The elastic moduli of the bulk rocks are computed using the elastic moduli of each end-member mineral, the pressure, and the temperature. The mole fraction of each end member (e.g. forsterite) present in each stable phase (e.g. olivine) is calculated as part of the Gibbs free-energy minimization algorithm mentioned above. The resulting elastic moduli of each stable mineral phase are then calculated as the mean values of the end-member moduli weighted by their respective mole proportions. Finally, the elastic moduli of the bulk rock are calculated using the Voigt-Reuss-Hill averaging scheme. Anharmonic seismic velocities obtained in this way are then corrected for anelastic effects due to grain size and seismic wave frequency. The shear-wave seismic velocities derived from the older and the younger set of garnet xenocrysts are shown in Figure 2.

Modern vs. ancient seismic signals

There are significant reductions in upper mantle seismic velocities between the eruption of the older and younger set of kimberlites, particularly below 175 km in the southwestern half of the profile. These reductions are largely expected in light of large-scale changes to the composition and thermal state of the lithospheric mantle recorded in xenoliths and xenocrysts during the same period (Bell et al. 2003, Kobussen et al. 2009). The very low velocities derived from the younger garnet xenocrysts indicate a strong seismic low-velocity zone beneath the southwestern and northeastern corner, but not the central part of the profile.

Modern tomographic models of the same region indicate a slightly different picture. Figure 3 is a section through

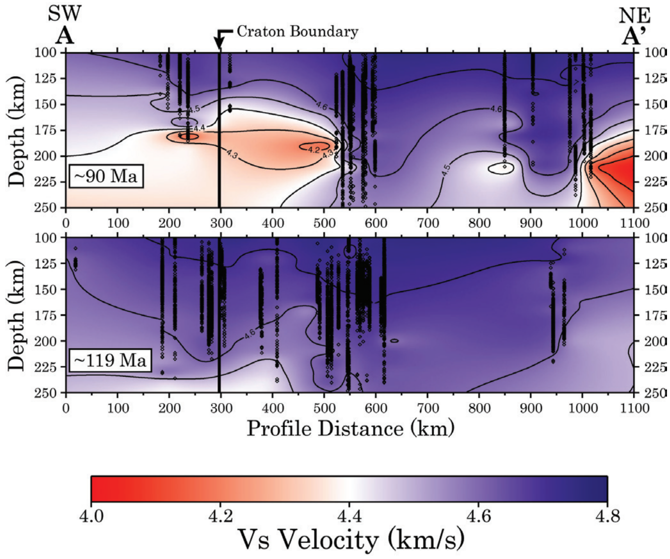

Figure 2. Garnet-derived S-wave velocities for the older (bottom) and younger set of garnet xenocrysts along profile A-A' in Figure 1. The heavy vertical black line shows the craton boundary as mapped at the surface. Individual garnet xenocrysts are shown as open symbols at the points where they project onto the cross-section. For contouring methods, see Kobussen et al. (2009).

the Kaapvaal Craton along the same profile shown in Figure 2. In comparison to the younger garnet-derived model, velocities in the modern tomographic model are higher at depths below 175 km in the southwestern and extreme northeastern corner of the profile. However, the velocities from the tomography are lower in the central parts of the section at depth.

The changes in seismic velocity among these three profiles suggest a consistent evolutionary trend in the thermal and chemical state of the lithospheric mantle beneath southern Africa. In the oldest image, the garnet-derived S-wave velocities are consistent with a thick lithosphere in a state of near thermal equilibrium. Conversely, S-wave velocities derived from the younger set of garnet xenocrysts suggest extreme local thermal disequilibrium, as evidenced by the very irregular pattern of seismic velocities and anomalously low velocities at ~175-220 km depth in the southwestern half and northeastern corner of the profile. Directly adjacent to the very low velocities are relatively high velocities in the centre of the profile. In the modern tomographic image, the thermal disequilibrium recorded in the younger garnets has dissipated into a broad low-velocity zone beneath the entire craton. Independent thermal modelling (Nyblade & Sleep 2003) confirms that relatively warm lithosphere

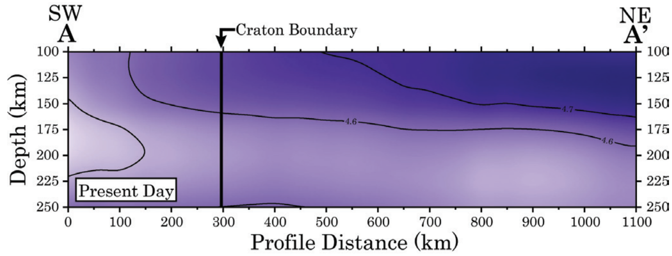

Figure 3. A section through a modern tomographic surface-wave model (S. Fishwick, pers. comm.) along profile A-A' in Figure 1. The colour scale is the same as Figure 2.

must remain beneath southern Africa to explain the anomalously high topography of the Southern African Plateau. Our own preliminary thermal modelling also indicates that the irregular thermal anomaly recorded by the younger set of garnets would dissipate into a broad zone of relatively higher temperatures at 175-250 km, consistent with the tomographic model.

Conclusions

Modern geophysical models of cratonic lithosphere provide only a snapshot of the current compositional and thermal conditions of a region. Without greater context on the recent tectonothermal history of the lithosphere, it is difficult to understand the meaning of these images in terms of geological processes. In the case of southern Africa, seismic images calculated from two suites of garnet xenocrysts of differing age indicate there has been significant thermal and metasomatic activity in the lithosphere in the recent past, and the effects of this activity are still evident in modern seismic images. It therefore can be misleading to assume modern geophysical images of lithosphere necessarily represent a steady-state regime. It is also problematic to try to constrain modern seismic models with ancient xenoliths due to the likely change in the thermal and/or compositional state of the lithosphere since the removal of the xenoliths from the mantle.

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