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Tectospheric structure beneath southern Africa

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Abstract. P-wave and S-wave delay times from the broadband data of the southern Africa seismic experiment have been inverted to obtain three-dimensional images of velocity perturbations in the mantle beneath southern Africa. High velocity mantle roots appear to extend to depths of at least 250 km, and locally to depths of 300 km beneath the Kaapvaal and Zimbabwe cratons. Thick roots are confined to the Archean cratons, with no evidence for similar structures beneath the adjacent Proterozoic mobile belts. The Kaapvaal craton was modified ca. 2.05 Ga by the Bushveld magmatic event, which affected a broad swath of cratonic mantle beneath and to the west of the exposed Bushveld Complex. The mantle beneath the extended Bushveld province is characterized by seismic velocities lower than those observed in regions of undisturbed cratonic mantle. The mantle beneath the Limpopo Belt, an Archean collisional zone sandwiched between the Kaapvaal and Zimbabwe cratons, exhibits a cratonic signature.

1. Introduction

Archean cratons comprise the ancient cores of continents. Considerable evidence has accumulated that these oldest cratons formed by processes or under conditions different from those that dominated post-Archean continental formation [e.g., *Jordan*, 1988]. A unique characteristic of cratons is that they are underlain by a high-velocity "keel" that extends to depths of at least 200-300 km [e.g., *Jordan*, 1975; *Lerner-Lam and Jordan*, 1987; *Rudnick and Nyblade*, 1999]. Jordan proposed the term "tectosphere" both to describe the deep conductive (non-convecting) root beneath cratons and to distinguish it from other lithosphere [*Jordan*, 1975]. The unique chemical and physical properties of the Archean tectosphere make it a prime target for seismological investigation. A key objective of the Kaapvaal Project was the high-resolution seismic imaging of upper mantle structure beneath southern Africa. In this paper we present three- dimensional P-wave and S-wave tomographic images of upper mantle structure beneath the Kaapvaal and Zimbabwe cratons and their adjacent Proterozoic mobile belts. We interpret the seismic results in terms of the geology, geochemistry and petrology of the crust and mantle beneath southern Africa and consider their implications for craton formation and evolution.

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2. Seismic Deployment and Data

Fifty-five broadband seismic stations were deployed at 82 sites across southern Africa from April 1997 to July 1999. The array spans geological provinces that are Early Archean to Phanerozoic in age embracing regions of South Africa, Zimbabwe and Botswana (Figure 1). The region, both on and off craton, is characterized by an abundance of xenolith-bearing kimberlite pipes from which mantle nodules were erupted. The nature of these nodules provides a unique yardstick for interpreting the results of the seismic imaging [*Jordan*, 1979].

We analyzed broadband seismic waveform data to determine teleseismic P-wave and S-wave delay times across the array. We retrieved relative arrival times of phases P, PKPdf, S, and SKS via a multi-channel cross-correlation procedure using all possible pairs of waveforms [*VanDecar and Crosson*, 1990]. Typical delay time standard deviations for the southern Africa data are approximately 0.03 s for P-waves and 0.06 s for S-waves. The timing accuracy for most of the individual seismic traces is about 0.001 sec, and all traces with potential timing errors greater than 0.01s were eliminated from the analysis. The P-wave inversion results are based on 8693 rays from 234 events; the S-wave results are based on 4834 rays from 148 events. Event coverage is show in Figure 2.

The inversion method we use for obtaining velocity structure is described in *VanDecar* [1991]. P- and S-wave delay times are inverted independently for structure beneath the array. The model is parameterized identically for the P- and the S-wave inversion with splines under tension constrained by a series of regular knots. Within the interior portion of the model, the knots are spaced 50 km apart in depth and 1/2 degree in latitude and longitude. We applied both elevation corrections and crustal time delay corrections based on receiver function results from *Nguuri et al.* [2001]. We inverted the data simultaneously for the slowness perturbation field, earthquake relocations, and station corrections to assure that the resulting velocity model will be constrained to contain the least amount of structure required to satisfy the observations within their estimated standard errors.

The tomographic images presented in this paper were determined using linear inversion, appropriate for southern Africa where the velocity perturbations are comparatively small. We have designed simple resolution tests to assess the analytical results presented. The tests indicate that both the lateral and vertical extent of the cratonic roots is well recovered. Downward smearing of structure does occur, but the effect is small and does not preclude reasonably accurate estimates of keel thickness. Summary results from the tests and a discussion of their significance are contained in the

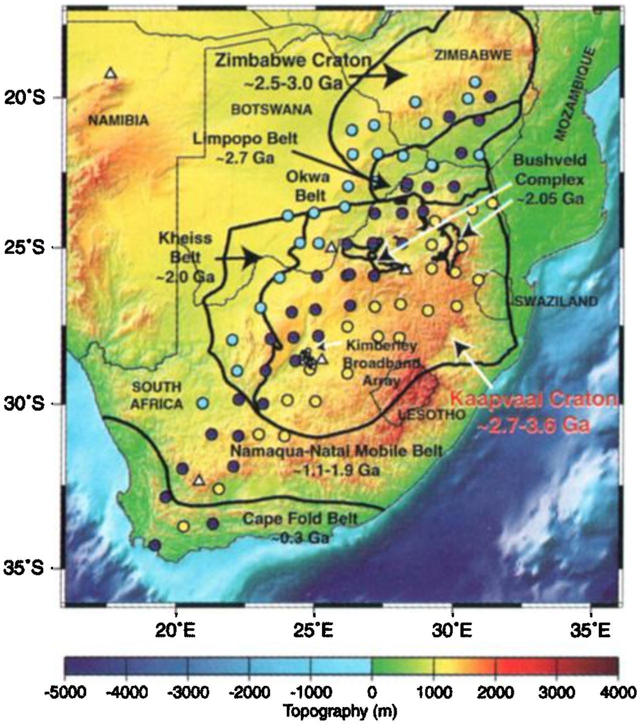

Figure 1. Map showing station locations, topography, and principal geologic provinces in the region of study within southern Africa. Fifty-five broadband (REFTEK/STS-2) stations were installed in April 1997 in South Africa, Botswana, and Zimbabwe. Stations in light blue were re-deployed in April 1998 to sites indicated in yellow. A total of 82 sites were occupied over the two-year deployment. GSN broadband stations used in the analysis are denoted by white triangles. The array extends from the Cape Fold Belt in the south, through the Proterozoic Namaqua-Natal mobile belt, across the Kaapvaal Craton and Bushveld Province, through the Archean Limpopo Mobile Belt and into the Zimbabwe Craton. The array covers part of the Kheis and Okwa Proterozoic Fold and Thrust Belts on the west and extends into the Early Archean Barberton terrane on the east, near the border with Swaziland.

electronic supplement to this paper.[1] Station spacing (~ 100 km) is such that shallow structures (above ~ 50 km) are sampled by few crossing paths from teleseismic events and are largely absorbed in the station terms.

3. Inversion Results

Results for the linear travel-time inversion for P- and S-waves are shown in Figure 3. With a few notable exceptions, high velocity mantle material coincides with the boundaries of the Kaapvaal and Zimbabwe cratons. The region of maximum positive velocity perturbations (blue regions, Figure 3) outlines the undisturbed part of the Kaapvaal craton, from the southernmost Bushveld province SSW to the inferred contact with the Namaqua-Natal mobile belt. Here, the cratonic root may attain depths of 300 km and perhaps more (Figure 3c). Except for regions of disrupted craton (as in the Bushveld), the tectospheric root appears to attain a minimum thickness of ~ 200 – 250 km beneath most cratonic regions, including the Archean Limpopo mobile belt.

The most remarkable "modification" of the Kaapvaal craton is associated with the Bushveld province. Low mantle velocities associated with the Bushveld appear to extend not only into the mantle beneath the intrusion itself, but also well to the west. Although these low velocities are well- resolved overall, the localized "patchiness" of the low velocity perturbations seen in Figure 3 is not. Moreover, while the Bushveld zone of lower mantle velocities is clearly real, the observed seismic velocity contrast between craton and Bushveld, ~ 0.5% in P and ~ 0.8% in S, is rather loosely constrained (see supplemental discussion on resolution). The tomographic results are consistent with geological evidence that Bushveld age events extend westward into Botswana (H. Kampunzo, pers. comm., 2000). The other major tectonic feature within the cratonic region is the Limpopo belt, which exhibits mantle structure largely indistinguishable from that of the cratons north and south. The similarity with cratonic mantle structure contrasts markedly with results from crustal structure measurements [*Nguuri et al.*, 2001], which show the Limpopo belt to be characterized by thick crust and poorly developed Moho relative to the adjacent cratons.

The Proterozoic Namaqua-Natal mobile belt, thought to be the remnants of a major N-S convergent margin that extended as far north as the Zimbabwe craton [*De Wit et al.*, 1992], is characterized by velocity perturbations slightly lower than those observed beneath the craton. Patches of higher velocity material are seen in the 200-400 km depth range beneath the belt, however, and these higher velocities typically exhibit continuity with the high velocity material beneath the adjacent Kaapvaal craton.

4. Discussion

The depth extent of cratonic roots has long been an issue of some controversy, dating back to Jordan's early work in the mid-1970s. The results presented in this paper indicate that cratonic root structures extend to at least 250 and perhaps as deep as 300 km beneath southern Africa. The notion of deep roots is buttressed by petrologic and geochemical studies of mantle nodules, where Re-Os age determinations show that nodules erupted from even the greatest depths beneath the craton (~ 200 km) are Archean in age [e.g., *Carlson et al.*, 2000; *Pearson et al.*, 1995]. More-

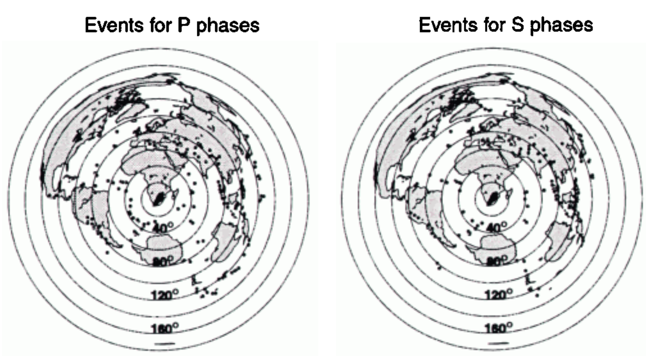

Figure 2. Location map of events used for P-wave and S-wave tomographic inversions, centered on the southern Africa array. Epicenters are from the NEIC bulletin.

[1]Electronic supplement is available via Web browser or anonymous FTP from ftp://agu.org/apend. Information on searching electronic supplements is found in http://www.agu.org/pubs/.

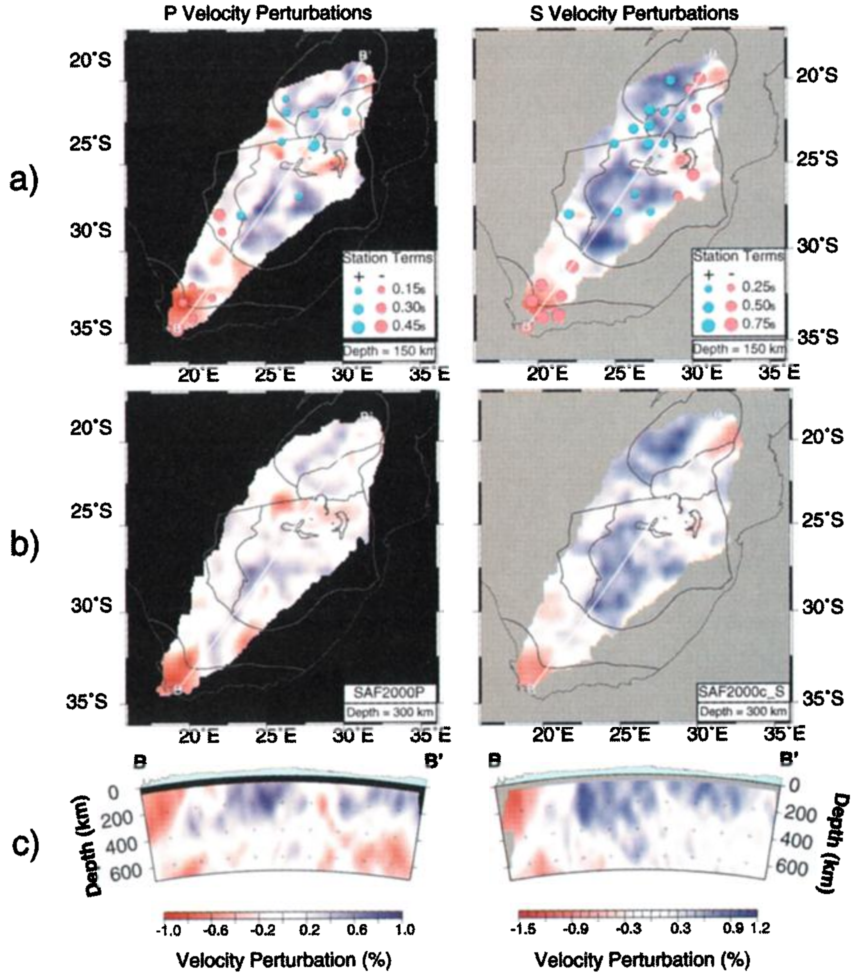

Figure 3. P-wave (left) and S-wave (right) velocity perturbations from inversion of delay times corrected for elevation and crustal thickness. (a) Map views of velocity perturbations at 150 km depth. Station terms (circles) are delay time residuals specific to each station. (b) Map views of velocity perturbations at 300 km depth. (c) Vertical cross-sections along profile B-B' shown in panel (a). Surface topography plotted at 40 times actual scale. Uppermost 50 km (solid gray or black) denotes regions where station delay time residuals are incorporated in model calculations. Topography is shown in light green. The agreement between P- and S-wave models is good, although the S-wave model has lower resolution by virtue of fewer observations and greater uncertainties in relative time delays.

over, recent estimates based on analyses of heat flow and xenolith P-T data suggest that the intersection between the craton geotherm occurs in the range 220-250 km beneath the cratons [*Jones*, 1988; *Rudnick et al.*, 1998; *Rudnick and Nyblade*, 1999]. Our results suggest that these xenolith and heat flow estimates of depth may be on the low side. We find no evidence for a low-velocity asthenospheric layer beneath the Archean keel, in agreement with other studies across southern Africa [*Zhao et al.*, 1999; *Ritsema and van Heijst*, 2000; *Freybourger et al.*, 2001] but notably contrary to results reported by Priestley and co-workers [*Qiu et al.*, 1996; *Priestley*, 1999].

The most prominent velocity anomaly within the Kaapvaal craton is associated with the Bushveld Complex and its western extension into Botswana. The Bushveld is the largest layered intrusion in the world. The low mantle velocities beneath it may indicate chemical modification of the mantle during magmatic emplacement, an hypothesis consistent with Re-Os results showing that mantle nodules from the Bushveld region have been reset to Proterozoic ages (~ 2.05 Ga) [*Carlson et al.*, 2000]. The isotopic resetting of an entire volume of Archean Kaapvaal mantle apparently required material addition to the mantle [*Carlson et al.*, 2000]. While a thermal anomaly of ~ 100°C could produce the 0.5% velocity perturbation observed [*Christensen*, 1982], there is little evidence for higher geotherms in the region of the Bushveld either from the observed heat flow measurements or from thermobarometric determinations on mantle nodules [*Danchin*, 1979; *Jones*, 1988]. On the other hand, "refertilization" (i.e. iron enrichment) of the mantle during the Bushveld event could significantly reduce seismic velocities in the underlying mantle. Jordan showed that refertilized cratonic samples with significant weight percentages of both clinopyroxene and garnet result in seismic velocities up to 1% lower and densities up to 2-3% higher than those of depleted nodular peridotites [*Jordan*, 1979]. Similarly, eclogitic materials, if present in significant volumes [*Shirey et al.*, 2001], would both reduce average velocity and increase average density of the depleted peridotitic mantle. The smaller positive velocity perturbations seen in the Proterozoic belts probably reflect a combination of more fertile compositions and higher geothermal gradients. The range in

S-wave velocity perturbations obtained in this study (about 2.5%) is slightly lower than that computed from surface wave studies [*Ritsema and van Heijst*, 2000], but given the differences in data and methodologies as well as the much poorer resolution of the surface wave studies, the results are not inconsistent.

5. Conclusions

Velocity images beneath southern Africa exhibit a clear correspondence with geologic terrane boundaries. Cratonic root structures are irregular, with evidence for keel depths of at least 250-300 km locally in the southern part of the Kaapvaal craton and in regions of the Zimbabwe craton. Variation in velocity perturbation within the craton is about 0.5%, consistent with compositional variations observed in mantle nodules. The mantle beneath the Bushveld province exhibits anomalously low velocities suggesting refertilization of the cratonic mantle during the Bushveld magmatic event. The Archean Limpopo mobile belt appears to be underlain by a mantle root of typical cratonic character. No low velocity asthenospheric zone has been detected in the upper mantle anywhere beneath the cratons.

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