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Crustal structure beneath southern Africa and its implications for the formation and evolution of the Kaapvaal and Zimbabwe cratons

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Abstract. The formation of Archean crust appears to involve processes unique to early earth history. Initial results from receiver function analysis of crustal structure beneath 81 broadband stations deployed across southern Africa reveal significant differences in the nature of the crust and the crust-mantle boundary between Archean and post-Archean geologic terranes. With the notable exception of the collisional Limpopo belt, where the crust is thick and the Moho complex, the crust beneath undisturbed Archean craton is typically thin (∼ 35–40 km), unlayered, and characterized by a strong velocity contrast across a relatively sharp Moho. This crustal structure contrasts markedly with that beneath post-Archean terranes and beneath Archean regions affected by large-scale Proterozoic events (the Bushveld complex and the Okwa/Magondi belts), where the crust tends to be relatively thick (∼ 45–50 km) and the Moho is complex.

1. Introduction

With few exceptions, the oldest crustal cores of the continents formed during Archean time [e.g. *de Wit et al.*, 1992; *Windley*, 1995]. Evidence presented below indicates that the process of crustal formation in the Archean differed from that of post-Archean time. In this paper we highlight characteristics which distinguish the Archean crust and the crust/mantle interface from that of disturbed Archean and post-Archean terranes. The evidence from this study suggests that the M-discontinuity (Moho) beneath undisturbed Archean terranes tends to be a relatively simple interface characterized by a significant velocity contrast of at least 1 km/s. In contrast, Archean terranes that have been modified by Proterozoic events typically exhibit complex Moho signatures and comparatively thick crustal sections, similar to what is observed in the Proterozoic mobile belts bordering the cratons.

Seismic station locations and a schematic outline of the principal geologic provinces of southern Africa are shown in Figure 1. The Archean Kaapvaal and Zimbabwe cratons form the continental nucleus of southern Africa. The intracratonic Bushveld Complex, the outcrop limbs of which are shown in Figure 1, is the largest known layered mafic intrusion in the world (0.5–1.0 × 10^6 km^3) [*Von Gruenewaldt et al.*, 1985]. It disrupted the northern Kaapvaal craton ca. 2.05 Ga and is seen as a major geologic domain, extending westward as far as Botswana [H. Kampunzu, pers. comm., 2000], far beyond the region of Bushveld outcrop and well into the mantle [*James et al.*, 2001]. Sandwiched between the cratons is the Limpopo mobile belt, a collisional terrane formed when the Kaapvaal and Zimbabwe cratons were consolidated in late Archean time [*Van Reenen et al.*, 1992]. The Limpopo belt is divided into a Northern Marginal Zone, a Central Zone, and a Southern Marginal Zone. Evidence presented below confirms that the two marginal zones are overthrust belts atop cratonic crust and that the Central Zone was a deep zone of tectonic deformation. The Kaapvaal

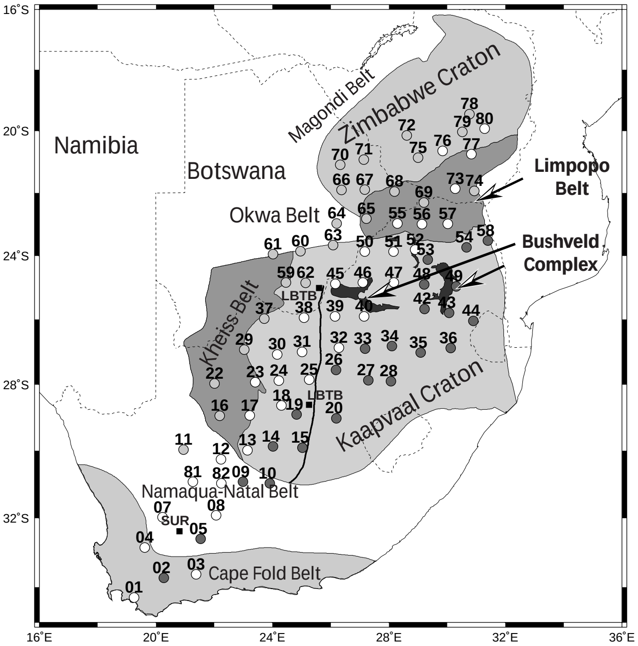

Figure 1. Location map for the southern Africa seismic array with a schematic overlay of southern African geological provinces. Station symbols in light gray denote stations deployed during the first year of the experiment, symbols in dark gray denote stations deployed during the second year of the experiment, and symbols in white denote stations deployed for the full two years of the experiment. Black squares denote global digital seismic stations.

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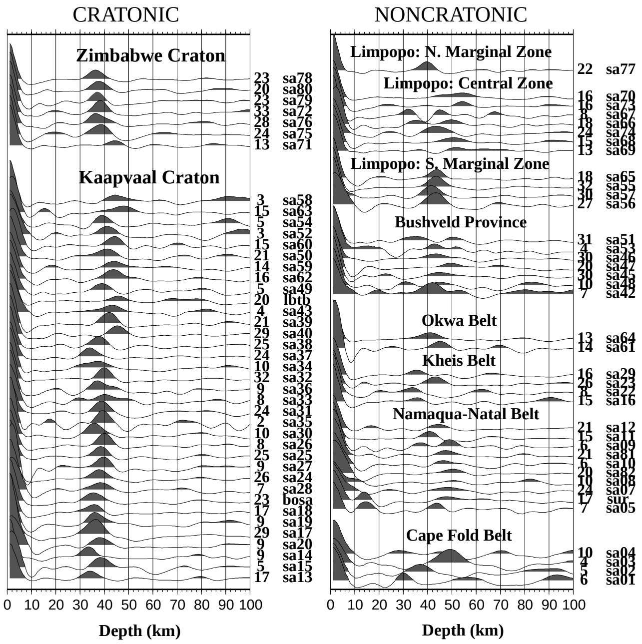

Figure 2. One-dimensional phasing depth images for southern Africa based on receiver function stacks as described in text. Images organized north to south by geologic province. The station name and number of events included in the stack are shown to the right of each trace. The dominant signal on the depth images is the *Ps* conversion from the Moho. Thin crust and strong amplitude *Ps* Moho conversions are associated with undisturbed craton; Moho images for disrupted craton and post-Archean terranes tend to be more diffuse and of smaller amplitude. Areas of disrupted craton, including the Bushveld Complex and the Magondi belt affecting the southwest corner of the Zimbabwe craton have been classified as "noncratonic," as is the Limpopo belt. Several stations in the vicinity of the Bushveld Complex and along a zone extending westward into the Okwa belt are grouped as part of the Kaapvaal craton, although their structure suggests they were affected by Proterozoic events (see text).

craton is bounded on the south and east by the subduction-related Namaqua-Natal Proterozoic orogenic belt (ca 1.1–1.9 Ga) and on the west by the Kheis overthrust belt (ca 2.0 Ga) [*de Wit et al.*, 1992]. The complex region north of the Kheis belt and west of the Limpopo belt and Zimbabwe craton is part of the $\sim$ 2 Ga Okwa and Magondi belts. The geology of the Okwa/Magondi region remains poorly understood owing to complex tectonic and magmatic overprinting of Proterozoic events on Archean basement, as well as to the fact that extensive Kalahari sand cover obscures much of the regional geology. The Cape Fold belt in the southernmost part of the region of study is Phanerozoic in age.

2. Data and Methodology

The southern Africa seismic experiment utilized 55 broadband REFTEK/STS2 instruments deployed at 81 stations between April 1997 and July 1999. The continuously recorded data of the portable experiment were supplemented by data from three global digital stations in the region of the array (Figure 1). We processed 35 teleseismic events to yield a comprehensive set of high-quality receiver functions (see [*Ammon*, 1991] for review and other references). Receiver functions were corrected for moveout, binned by station and stacked at depth intervals of 0.5 km between 1 km and 101 km. The resulting spatial (phasing depth) spike series image reflects primarily the S-velocity discontinuity structure beneath each station [*Dueker and Sheehan*, 1998; *Gurrola et al.*, 1994]. The crustal model for the moveout correction is based on a refraction seismic model for the Kaapvaal with an average P-wave velocity for the crust of 6.5 km/sec, Poisson's ratio of 0.25, and Moho depth of 38 km [*Durrheim and Green*, 1992]. The phasing depth images for the southern Africa array are plotted in Figure 2 and arranged by geological province. The first (zero-depth) peak, partially truncated, is simply the coherence peak of P-wave arrivals. Subsequent peaks on the records are related to velocity discontinuities at depth. As seen from Figure 2, only one consistent Ps signal occurs, and it is readily associated with the Moho. The results shown in Figure 2 are summarized in the form of a color-coded map of Moho depth in Figure 3. As the velocity-depth model was constructed by averaging seismic refraction results for the Kaapvaal craton, the model may be an underestimate of mean crustal velocity and crustal thickness for off-craton or modified cratonic regions. Crustal thickness data tabulated by station may be downloaded from www.ciw.edu/kaapvaal/pubs/crust/nguuri_table1.pdf.

3. Results

Phasing depth images based on receiver functions are shown in Figure 2, arranged by geologic province. The organization of stations by province is ambiguous in places, notably in the Okwa/Magondi belt of eastern Botswana, where cratonic structures are overprinted by late Archean and Proterozoic (2 Ga) events, and in the general vicinity of

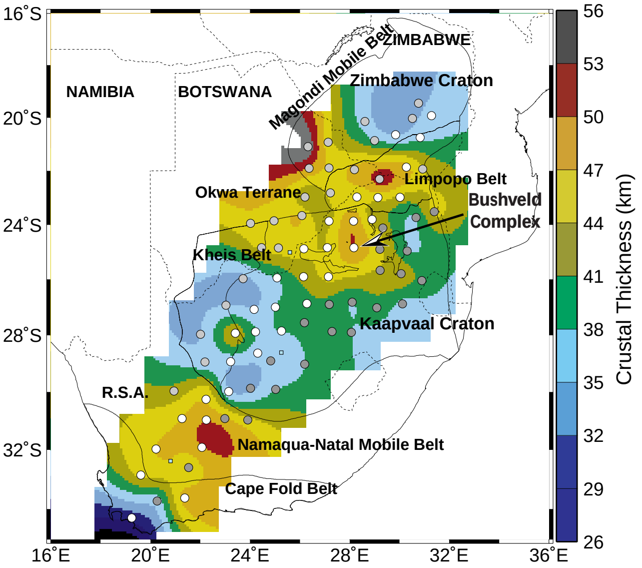

Figure 3. Color-coded contour map of depth to Moho beneath the southern Africa array based on phasing depth images of Figure 2 and as tabulated in the electronic supplement to this paper. Crustal thickness color scale is shown on right. Thin crust tends to be associated with undisturbed areas of craton, particularly in the southern and eastern parts of the Kaapvaal craton and in the Zimbabwe craton north of the Limpopo belt. Greater crustal thickness is associated with the Bushveld region and its westward extension into the Okwa and Magondi belts. Crustal thickness is also greater in the central zone of the Limpopo belt and in the Proterozoic Namaqua-Natal mobile belt.

the Bushveld, where the boundary between disturbed and undisturbed craton is poorly defined. The crust beneath Proterozoic belts and cratonic terranes modified in Proterozoic time is in almost all cases thicker than that beneath the cratons.

3.1. Kaapvaal and Zimbabwe cratons.

Stations located within undisturbed Kaapvaal or Zimbabwe craton typically have sharp, large amplitude Ps converted signals from the Moho. Distinctive among the cratonic results are those from stations located in the Zimbabwe craton, where Moho depths, with one exception, cluster between 34 and 37 km. Results for the Kaapvaal craton exhibit more variability, with crustal thickness varying between about 33 and 45 km, but averaging close to 38 km. Most of the Kaapvaal stations exhibiting greater crustal thickness are situated in regions immediately adjacent to the Bushveld and Okwa/Magondi terranes, suggesting that crustal modification in Proterozoic time may have been more widespread than is indicated by surface geology. Crustal reworking in the Proterozoic would be consistent with tomographic results [*James et al.*, 2001] which show that most of the northern stations of the Kaapvaal craton overlie modified mantle characterized by lower seismic velocities. Thus the stations in the extended region of the Bushveld and Okwa/Magondi Proterozoic terranes may represent disturbed rather than stable craton.

3.2. Bushveld and Okwa/Magondi terranes.

The crust thickens systematically across the boundary between undisturbed craton and stations near and in the Bushveld Complex and the Okwa/Magondi terranes. As seen in Figure 3, the lithosphere disturbance associated with the Bushveld event appears to be part of a broad zone of 2 Ga activity that may extend from the Bushveld into the Okwa/Magondi belt of similar age in eastern Bostwana. Relative to the undisturbed craton to the south, that entire region is characterized by thick crust and lower upper mantle velocities [*James et al.*, 2001]. The evidence reported here for a thick crust and a relatively diffuse Moho beneath the Bushveld is consistent with the notion of a broadly continuous mafic body at depth [*Cawthorn and Webb*, 2001; *Webb et al.*, 2000]. The substantial load of material added to the crust during the Bushveld event appears to have produced a downward crustal flexure of several km [*Webb et al.*, 2000]. The nature of the 2 Ga crustal overprint associated with the Okwa/Magondi belt is poorly understood, although it is evident from the wealth of diamond production that the Archean geotherms were not significantly elevated during the Proterozoic event.

3.3. Limpopo belt.

The intercratonic Limpopo belt remains the subject of geological debate over its presumed origin as an Archean collisional zone [*Van Reenen et al.*, 1987; *Van Reenen et al.*, 1992]. Depth images for the marginal zones are typical of cratonic structure, both in character of the Ps conversion and in crustal thickness. The northern marginal zone is underlain by crust about 37 km thick, typical of the adjacent Zimbabwe craton, and the southern marginal zone has a crust around 40-42 km thick, consistent with that of the adjacent Kaapvaal craton (see Figure 2). The central Limpopo belt, the site of pervasive deformation during the collision of the Kaapvaal and Zimbabwe cratons in the Archean, displays particularly complex structure. In some instances (e.g., stations sa66 and sa67) the identification of the Moho is ambiguous and could be resolved only with constraints from two-station surface wave phase velocity inversions, where thicker crust is required to satisfy the dispersion data. The broad and comparatively weak Ps images have maxima that indicate depths between 40 and 53 km and are indicative of a structurally complex Moho. While there is some evidence for a deep crustal discontinuity at about 30-35 km depth beneath some stations, interstation surface wave phase velocity inversion results show unambiguously that the crust must be in excess of 40–45 km thick beneath the Limpopo Central Zone (unpublished data). As with the Bushveld, the relatively thick crust beneath the Limpopo is not compensated by higher elevations, suggestive of a dense lower crust.

3.3.1. Kheis belt The clear cratonic signatures of the northern and southern marginal zones of the Limpopo belt are not evident in the Kheis Thrust belt of the western Kaapvaal (Figure 1). Although the Kheis belt is known from nodule studies to overlie the craton, the observed Ps Moho signals are weak. The lack of a purely "cratonic" signature is consistent with tomographic images of the upper mantle, where strong positive seismic velocity perturbations in the mantle beneath the central region of the craton diminish beneath the Kheis belt [*James et al.*, 2001]. The crust beneath the Kheis belt is generally thin (< 40 km), however, more characteristic of the undisturbed cratonic crust to the east than of the extended Bushveld and Okwa/Magondi terranes to the north.

3.4. Namaqua-Natal and Cape Fold belts.

While results are comparatively sparse for the Namaqua-Natal and Cape Fold belts, measurements of crustal thickness are typically 40–50 km throughout the Namaqua-Natal belt and northern Cape Fold belt. Within the Cape Fold belt, the crust thins to about 30 km near the African coast.

4. Discussion

Among the most significant findings of the present study is evidence for pervasive Proterozoic (ca 2 Ga) modification and thickening of Archean crust across a broad east-west zone bounded on the east by the Bushveld and on the west by the Okwa/Magondi terranes. The area of thickened crust corresponds closely to the zone of reduced upper mantle velocities found from body wave tomography [*James et al.*, 2001]. Moho Ps conversions for stations in this region of disturbed craton tend to be low in amplitude and in some cases ambiguous, suggesting that the Moho is a weak and/or transitional (e.g., > 5 km) boundary. One possible interpretation of the poor Ps signals is that they reflect Proterozoic age magmatic underplating or reworking of Archean crust (e.g., [*Griffin and O'Reilly*, 1987]). While magmatic addition to the crust is plausible beneath the Bushveld Complex, the cause of increased crustal thickness elsewhere in the region of Proterozoic overprinting is not so apparent. Both crustal thickness and the Moho signature observed in the region of modified Archean crust are similar to those observed at stations in the Proterozoic Namaqua-Natal belt.

Durrheim and Mooney found that Archean crust worldwide is typically 27–40 km thick, whereas Proterozoic crust is about 40–55 km thick, with higher velocity material (> 7 km/s) at its base [*Durrheim and Mooney*, 1994]. Our findings are in substantial agreement with that conclusion. The thinnest crust (35–40 km) is found beneath those regions of the Kaapvaal and Zimbabwe cratons that have been undisturbed since Archean time. The clear Ps Moho conversions for undisturbed craton indicate a strong velocity contrast (1 km/s or more) across a sharp Moho. Seismic refraction results and studies of crustal xenoliths suggest that the lower crust of cratonic southern Africa may be less mafic on average (and hence less dense and lower velocity) than that of post-Archean lower crust [*Durrheim and Mooney*, 1994; *Griffin and O'Reilly*, 1987; *Rudnick and Fountain*, 1995]. Results from this study, while not definitive, are consistent with an intermediate or intermediate-to-mafic lower crustal composition beneath undisturbed cratons.

The central zone of the Limpopo belt is characterized not only by thick crust (up to 50 km or more) and complex Moho structure, but geologic evidence indicates that 20-30 km of crustal uplift and exhumation have taken place since Archean time [*Treloar et al.*, 1992]. If correct, this implies that the crustal section beneath the Limpopo belt in the Archean was comparable to the thickest crust observed today anywhere in the world.

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