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Fine structure of the lowermost crust beneath the Kaapvaal craton and its implications for crustal formation and evolution

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Abstract

High quality data from a dense seismic array covering an area of approximately 60×40 km^2 are used to obtain tight quantitative estimates of the fine-scale velocity and density structure of the lowermost crust and the crust–mantle boundary (Moho) beneath the Kaapvaal craton in the vicinity of Kimberley, South Africa. Results based on a modified receiver function waveform analysis of Moho conversions and crustal reverberation phases show that the crust beneath the array is thin (35.4 km) with an average Poisson's ratio of 0.254. The minimum S-wave velocity contrast across the Moho is 17.3% while the contrast in density is 15.4%. The density contrast across the Moho is particularly diagnostic. For an assumed uppermost mantle density beneath Kimberley of 3.3 gm/cc as determined from mantle xenoliths, the density of the lowermost crust is 2.86 gm/cc, indicating rocks of felsic to intermediate composition. Analysis of waveform broadening of the crustal reverberation phases relative to that of the direct P-wave shows the thickness of the Moho transition zone to be less than 0.5 km and the maximum variation in crustal thickness over the region of the array to be less than 1 km. The flat and almost perfectly sharp Moho, together with the absence of a mafic lower crust, suggests large-scale crustal reworking in the period between crustal formation and the time of cratonic stabilization.

Keywords: composition; crust; continental crust; evolution; earth

1. Introduction

Understanding the formation and evolution of the Earth's continental crust requires knowledge of its composition, both on average and as it varies as a function of depth. For example, if the Archean crust formed by partial melting of mantle at high temperature [1] the felsic rocks that dominate the upper crust must be compensated by lower crust that is overwhelmingly mafic or even ultramafic in composition [2]. While the upper crust is accessible to geological sampling and measurements, the deeper parts of the crust are relatively inaccessible in most areas. Even in the Kimberley region, where kimberlite pipes have carried impressive volumes of mantle and crustal material to the surface, there is a paucity of lower crustal xenoliths [3]. In the absence of direct knowledge of lower crustal compositions, seismic data, mainly compressional velocities from refraction and reflection profiling, are often compared with laboratory determinations of seismic velocities in rocks to infer the composition of the lower

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crust [4]. The interpretation of seismic data is nearly always ambiguous, however, and there remains considerable controversy as to whether the Archean lower crust is comprised dominantly of rocks of felsic to intermediate [5] or mafic composition [6], or even whether it is feasible to ascribe a 'characteristic' composition to the Archean lower crust in a global sense.

The present study is part of the Southern Africa Seismic Experiment under the Kaapvaal Project (Fig. 1) [7]. The data used in our analysis are from the PASSCAL broadband telemetered array deployed near Kimberley, South Africa. The telemetered array was installed as a high-resolution augmentation to the regional southern Africa array shown in Fig. 1. The southern Kaapvaal craton in the vicinity of the Kimberley array is a prototypical example of Archean tectosphere [8], famous as a historic diamond-producing region and extensively studied as a result. Despite the region's economic significance, however, there were few seismic investigations of the crust prior to the Southern Africa Seismic Experiment. Previous refraction studies [9] found that the relatively well constrained P-wave velocity of the Kaapvaal lower crust is rather low (<7 km/s), which could be explained by either a less mafic composition or a lower metamorphic grade. Previous refraction [9] and receiver function [10] studies have shown that while the Kaapvaal crust is relatively thin, there is a relatively large range in thickness (34–40 km). As for the crust–mantle transition, Durrheim and Green [9] reported that it occurs over a depth range of 1–3 km, while Nguuri et al. [10] qualitatively described the Moho as 'sharp' but did not give an estimate of the thickness of the transition zone.

In this paper we present quantitative results suggesting that the lowermost crust beneath the region of study in the Kaapvaal craton must be intermediate rather than mafic in composition. We show moreover that the Moho itself is both remarkably flat beneath the area of the seismic array and extremely sharp. Our analysis employs a methodology that makes use of Moho converted phases and crustal reverberations to determine precisely the Poisson ratio of the crust, as well as the velocity and density jump across the Moho. Moho reverberation phases (Fig. 2) are the weak signals reflected by Earth's surface and the Moho that occur in the coda of the direct P-wave arrival. Although the P to S converted wave from the Moho, the dominant phase on typical receiver function records [11–13], is widely used to determine Moho depth, the later reverberation phases are seldom used, simply because of a poor signal to noise ratio and the difficulty of obtaining reliable waveforms or even of detecting them at all. Nevertheless, these reverberations can be extremely useful for estimating the velocity and density structure of the lowermost crust and the fine structure of the crust–mantle boundary. In particular the travel times of the reverberation phases place a tight bound on the V_p/V_s ratio and therefore the Poisson ratio of the crust, and their amplitude ratios provide constraints on the velocity and density jump across the Moho (see Section 2).

The exceptionally high quality array data coupled with the new methodology described below allow precise constraints to be placed on the density and on the minimum S-wave velocity jump across the Moho. Our ability to determine these parameters is a critical step toward obtaining direct understanding of the composition of the Kaapvaal crust. The density constraint is particularly critical in that density (unlike seismic velocity) is a comparatively unambiguous indicator of rock composition. It alone provides clear evidence for a lowermost crust of intermediate composition. Moreover, both the sharpness and the topographic relief on the Moho are quantitatively constrained to a hitherto unprecedented level of accuracy: the Moho is very sharp (<0.5 km across) and remarkably flat, with topographic relief of <1 km over the ~ 2400 km^2 footprint of the array. These findings provide critical constraints on the mechanisms of crustal formation and evolution in Archean time.

2. Methodology

We assume that the crust has an average P-wave velocity V_p, S-wave velocity V_s and density ρ (Fig. 2). The incident angles of the P- and S-wave are i and j, respectively.

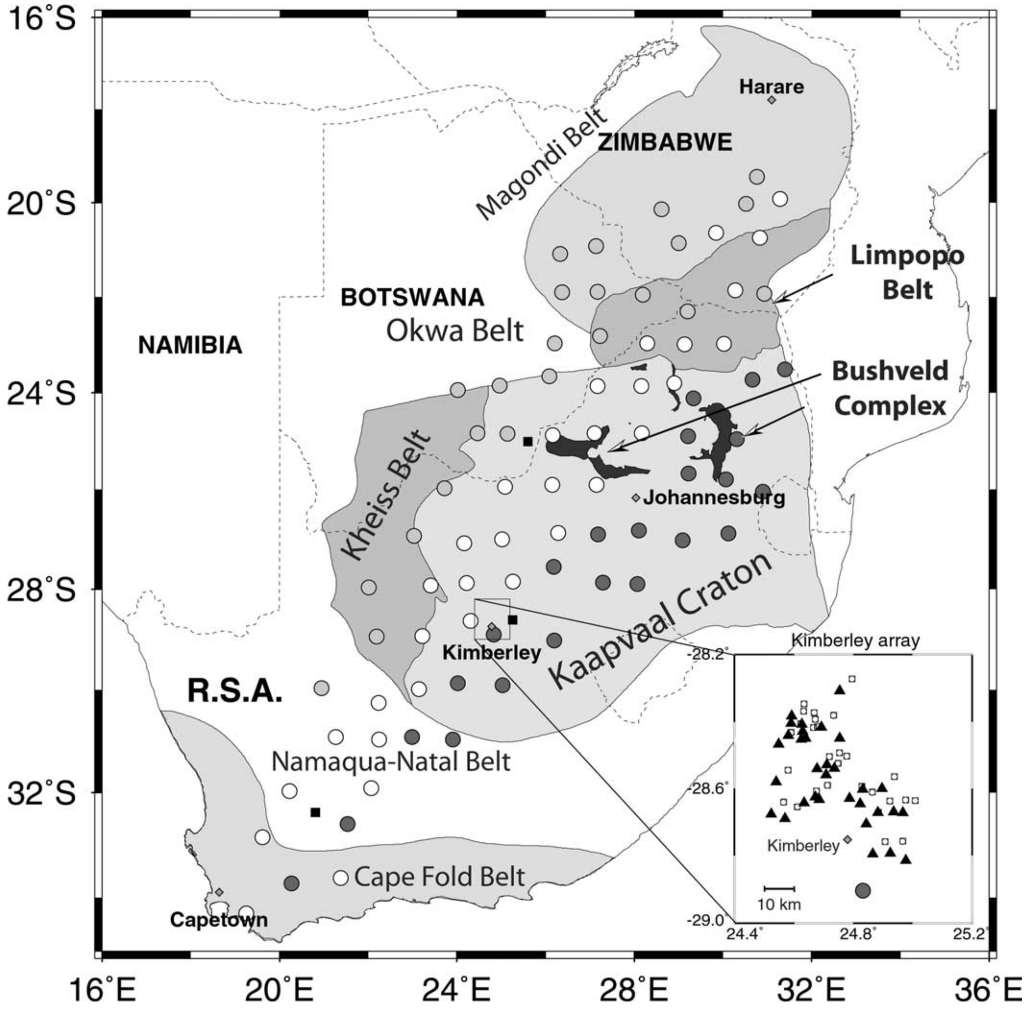

Fig. 1. Map showing the principal geologic provinces in southern Africa, and the 82 station locations (circles) of the Southern Africa Seismic Experiment. Black squares denote global digital seismic stations. The location of the Kimberley array is indicated by the box. Detailed distribution of the 31 broadband telemetered seismic stations of the Kimberley array, converted points of $0p1s$ (see caption of Fig. 2), and reflected points of $1p2s$ at the Moho are shown by triangles, circles and squares, respectively, in the inset.

2.1. Constraint on the Poisson's ratio

The travel time difference between phases $0p1s$, $2p1s$ and the direct P-wave can be written as:

$$T_{0p1s} = \left(\frac{\cos j}{V_s} - \frac{\cos i}{V_p}\right)h \tag{1}$$

$$T_{2p1s} = \left(\frac{\cos j}{V_s} + \frac{\cos i}{V_p}\right)h \tag{2}$$

From Eqs. 1 and 2, we can get:

$$\frac{V_p \cdot \cos j}{V_s \cdot \cos i} = \frac{T_{0p1s} + T_{2p1s}}{T_{2p1s} - T_{0p1s}} \tag{3}$$

If we write the right hand side of Eq. 3 as δT:

$$\delta T = \frac{T_{2p1s} + T_{0p1s}}{T_{2p1s} - T_{0p1s}}$$

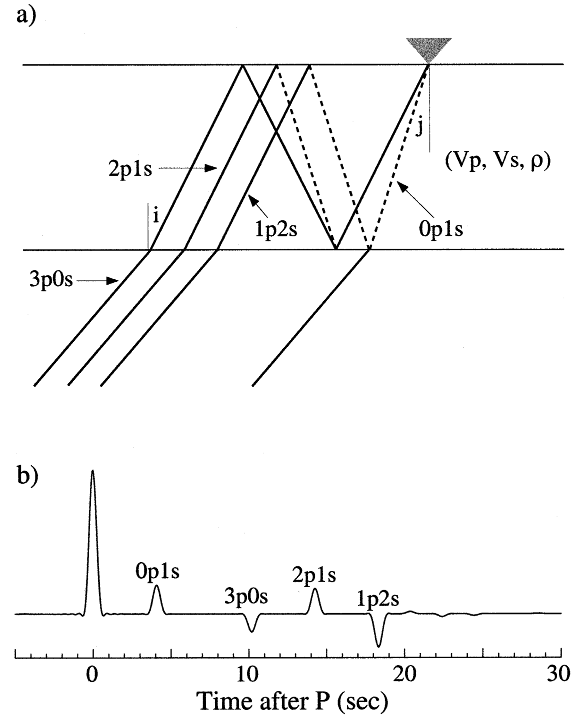

Fig. 2. (a) Ray paths of the direct P-wave, P to S converted wave, and the reverberation phases for a one-layer crustal model. The notation of *npms*, where *n* and *m* are the numbers of P- and S-wave legs within the crust, respectively, is used throughout this paper. For example, the P to S converted wave is defined as $0p1s$, which means that it has no P-wave path and one S-wave path inside the crust. (b) The radial component of a synthetic seismogram calculated by the Thomson–Haskell method [29] for a one-layer crustal model modified from iasp91 [30].

then we have:

$$\delta T \cdot \cos i \le \frac{V_p}{V_s} \le \delta T \tag{4}$$

Eq. 4 gives the range of the V_p/V_s ratio in terms of travel times of $0p1s$ and $2p1s$. When the incident angle of the P-wave in the crust, *i*, is given, the V_p/V_s and therefore the Poisson ratio (σ):

$$\sigma = \frac{\left(\frac{V_p}{V_s}\right)^2 - 2}{2\left(\left(\frac{V_p}{V_s}\right)^2 - 1\right)} \tag{5}$$

can be exactly determined.

2.2. Constraint on density

The P to S transmission coefficient for a near vertically incident P-wave can be written as a function of δV_s and $\delta\rho$ [14,15]:

$$A_{0p1s} \propto \left(a\frac{\delta V_s}{V_s} + b\frac{\delta\rho}{\rho}\right) \tag{6}$$

where:

$$|b/a| = 0.25\left|\left(\frac{V_p}{V_s} - 2\right)\right| \ll 1$$

Therefore, the P to S transmission coefficient is in fact a function of only δV_s:

$$A_{0p1s} \propto \frac{\delta V_s}{V_s} \tag{7}$$

On the other hand, the reflection coefficient of a near vertically incident S-wave at the Moho is:

$$A_{1p2s} \propto \left(\frac{\delta V_s}{V_s} + \frac{\delta\rho}{\rho}\right) \tag{8}$$

A combination of Eqs. 7 and 8 allows us to determine δV_s as well as $\delta\rho$ across the Moho.

3. Data and analysis

The Kimberley deployment consisted of 31 seismic stations of the PASSCAL broadband telemetered transportable array. The array covered a 60×40 km^2 area in the diamondiferous southern Kaapvaal craton near Kimberley, South Africa (Fig. 1). The stations recorded for a period of 6 months as an add-on to the Southern Africa Seismic Experiment of the Kaapvaal Project. The larger Southern Africa Seismic Experiment itself involved 55 broadband seismometers at 82 sites in South Africa, Zimbabwe and Botswana that operated between April 1997 and July 1999. The exceptionally high quality seismic data from the Kimberley array have presented a unique opportunity to image the fine structure of the crust and the Moho in a cratonic 'type locality' in unprecedented detail.

We analyzed the seismograms for a large shallow event ($M_b = 6.6$, depth = 15 km) that occurred in the Tibet–India border region on March 28 1999. The horizontal components are rotated and deconvolved to isolate seismic waves produced by receiver-side structures [16]. The resulting individual receiver functions (Fig. 3a) were further summed using an nth-root stacking method [17]. We chose $n = 4$ to reduce the uncorrelated noise relative to the usual linear stack ($n = 1$). The P to S converted phase ($0p1s$) and reverberation phases ($2p1s$, $1p2s$) are clearly shown in the 4th-root stacked receiver function in Fig. 3b.

4. Results

As shown above, the average V_p/V_s ratio could be derived from travel times of the $0p1s$ and $2p1s$. The resulting V_p/V_s ratio of the crust beneath the array is 1.742 ± 0.007, equivalent to a Poisson ratio of 0.254 ± 0.003. Here the 1σ error is estimated by a bootstrap method [18]. Waveform modeling of local mine events recorded by the same array [19] shows that the average P-wave velocity is 6.46 km/s in the studied region, which results in an average S-wave velocity of 3.71 km/s for the crust as a whole. The estimated thickness from the lapse time of $0p1s$ is 35.4 ± 0.2 km, in good agreement with previous results from receiver function and refraction studies of the same region [10,9].

The P to S transmission coefficient for a near vertically incident P-wave is most sensitive to the S-wave velocity contrast across the Moho, whereas the reflection coefficient of the near vertically incident S-wave at the Moho depends equally on the S-wave velocity and density variation. The S-wave velocity at the top of the mantle (Sn) determined from travel time data is about 4.7 km/s [19]. The S-wave velocity jump across the Moho estimated from the relative amplitude of $0p1s$ to the direct P is 17.3 ± 2.2% (Fig. 4a). We emphasize that this is a minimum estimate since any lateral heterogeneity of velocity within the crust or any lateral variation of Moho depth will produce phase shifts among $0p1s$ at different stations that degrade the amplitude of the stacked $0p1s$ waveform.

The estimated density contrast across the Moho is derived from the relative amplitude of $1p2s$ to

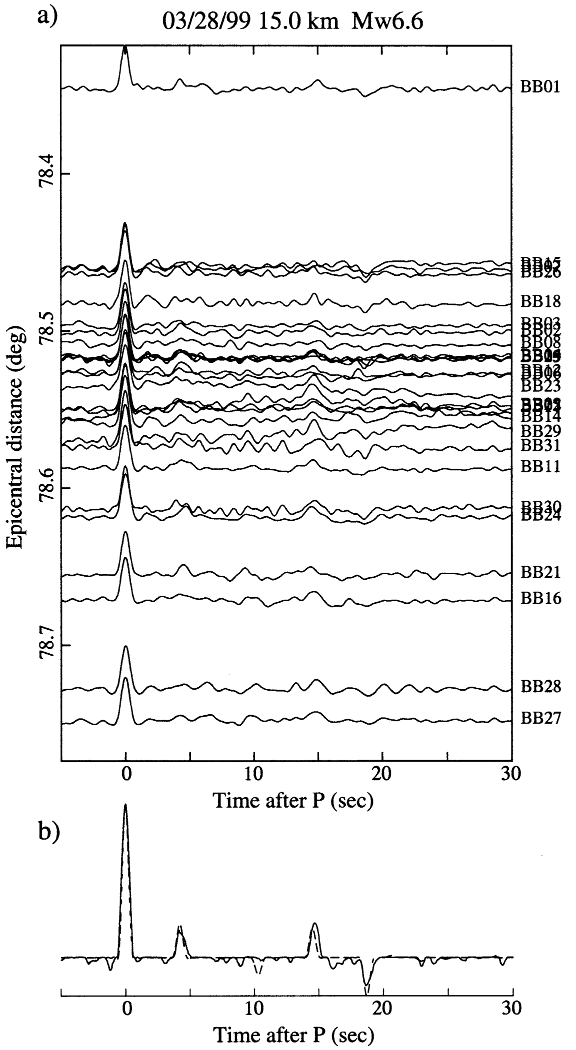

Fig. 3. (a) Deconvolved radial components of seismograms (receiver functions) recorded by the Kimberley array for the event 03/28/99 that occurred in the Tibet–India border region. (b) The 4th root stacked waveform (solid line) is shown with a synthetic seismogram calculated for a one-layer crustal model with a P- and S-wave velocity and density of 6.46 km/s, 3.71 km/s and 2.86 gm/cc, respectively. The jump of S-wave velocity and density across the Moho is 17.3% and 15.4%, respectively. The absence of $3p0s$ in the data is probably due to its small amplitude.

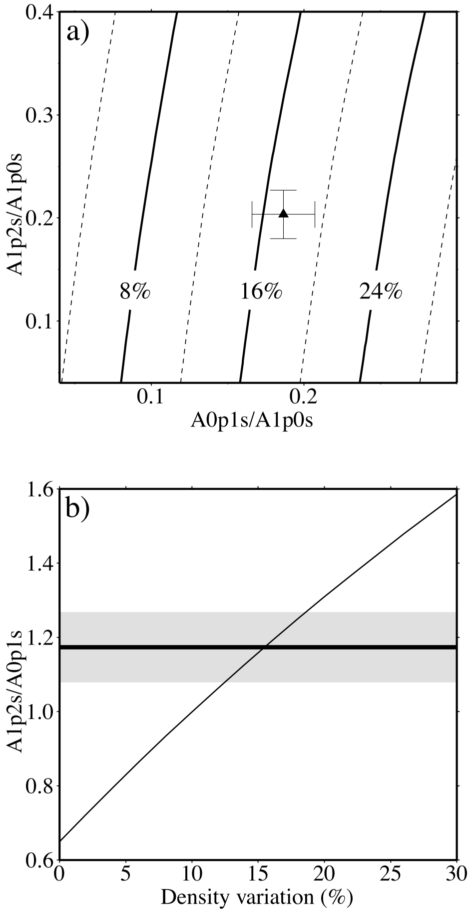

Fig. 4. (a) Contour of S-wave velocity jump across the Moho, shown as a function of amplitude ratios of $0p1s/1p0s$ and $1p2s/1p0s$. The triangle and bars represent the observed amplitude ratios and their 1σ errors. (b) Relative amplitude of $1p2s$ to $0p1s$ is shown as a function of density change at the Moho (thin solid line). The observed amplitude ratio of $1p2s/0p1s$ is shown (thick solid horizontal line) with its 1σ error (gray shadowed region).

$0p1s$ and is calculated to be 15.4 ± 2.3% (Fig. 4b). For an assumed density of 3.3 gm/cc for the uppermost mantle estimated from xenolith samples [20], the calculated density of the lowermost crustal layer is 2.86 ± 0.06 gm/cc. This density value is characteristic of intermediate composition rocks at lower crustal pressures under dry conditions, where gabbros and mafic granulites typically have densities in excess of 3.0 gm/cc [21].

The later arriving phases on the receiver function exhibit waveform broadening relative to the direct P-wave in the stacked receiver function (Fig. 3b). If the broadening is caused entirely by a velocity gradient across the Moho, then the width of the waveform of $1p2s$ constrains the allowable extent of the transition zone to be less than 0.5 km (Fig. 5a). If the broadening is produced entirely by lateral variation in depth of the Moho and/or by velocity heterogeneities within the crust, the maximum allowable depth variation must be less than 1.0 km (Fig. 5b). Both of these

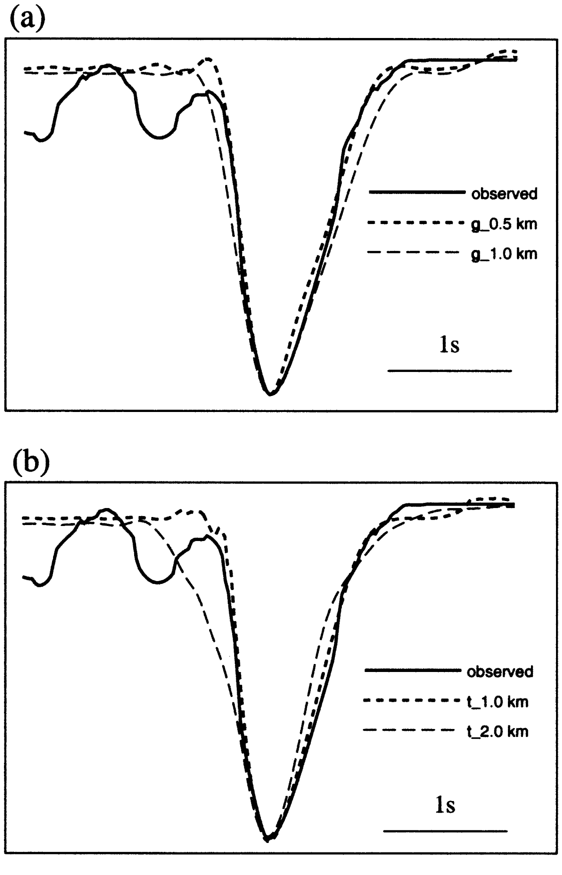

Fig. 5. Observed $1p2s$ waveform (solid) is shown with synthetics calculated for Moho models with a transition thickness of 0.5 km (dotted) and 1.0 km (dashed) in (a), and a lateral variation in depth of 1.0 km (dotted) and 2.0 km (dashed) in (b), respectively. Synthetic seismograms are calculated by the Thomson–Haskell method and stacked in the same way as for the observed data. Note that the synthetic waveforms for both models with a transition thickness of 1.0 km and a lateral variation in depth of 2.0 km are too broad to fit the data.

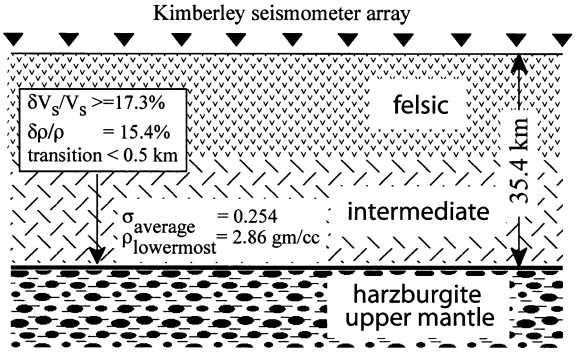

Fig. 6. Interpretive cross-section of crust and Moho structure of the Kaapvaal craton beneath the Kimberley array. σ is the Poisson ratio averaged for the entire crust. ρ is the crustal density at the crust–mantle boundary. Stations of the Kimberley array are shown schematically as solid inverted triangles.

constraints are extraordinarily tight in light of what is typically observed of Moho structure and topography.

5. Discussion

The results presented in this paper are perhaps the most precise quantitative seismic measurements of crustal and Moho properties ever obtained for southern Africa. While our results are strictly applicable only to the region of the Kimberley array, their qualitative similarity with results from regional single station receiver function studies for undisturbed cratonic crust of southern Africa [10] suggests that the structures observed beneath the Kimberley array may be characteristic of much of the Kaapvaal craton. Both the low Poisson ratio of 0.254 for the crust as a whole and the density of 2.86 gm/cc for lowermost crustal rocks provide compelling evidence that the lower crust beneath the Kaapvaal craton is dominated by rocks of intermediate to felsic rather than mafic composition [4]. The required S-wave velocity contrast across the Moho $>17.3\%$ is consistent with but not diagnostic of intermediate compositions. While suggestions that Archean lower crust is less mafic than that of post-Archean crust in southern Africa have been published previously [5,10,22], the issue remains controversial. Indeed, Zandt and Ammon [6] in a global study concluded that the lowermost crust of ancient platforms is characterized by a relatively high Poisson ratio (~ 0.28), indicative of mafic material. For the region of the Kaapvaal studied here, however, the properties measured for the lowermost crust indicate that it can accommodate only relatively small amounts of granulite-facies mafic components. The absence of a mafic signature in the seismic results is consistent with the fact that mafic granulite xenoliths from the lower Archean crust are rare [23,24].

Two additional and quite important constraints emerge from this study as to the structure and morphology of the Moho beneath the Kimberley array. First, we have shown that within the area of the array the cratonic Moho is an extremely sharp boundary, with a transition less than 0.5 km. Second, the Moho is extremely flat, with a maximum variation in crustal thickness of 1 km over the approximately 2400 km^2 area of the array. Both of these determinations are calculated under the assumption that other variables remain fixed. The Moho transition thickness and the variation in crustal thickness are therefore maximum estimates.

The observed sharpness and flatness of the Moho have fundamental implications for crustal formation and evolution in the Archean. While it may be possible to produce a crustal section such as that observed beneath the Kimberley array simply by direct emplacement of evolved melts to form crust by means of subduction or quasi-subduction melting processes, we still require some means of preserving original Moho structures during late Archean tectonomagmatic events. The assembly history of the Kaapvaal crust is complex, spanning nearly 1 billion years of geologic time [25]. Although details of crustal aggregation are still unclear, models typically involve extensive collisional accretion of island arcs and microcontinental blocks to form nuclear continental masses [25]. Such accretionary processes may be expected to produce a complicated mosaic of varying Moho structures and diverse crustal lithologies. Just such structures were observed in the Limpopo Belt, a late Archean collisional zone between the Zimbabwe and Kaapvaal cratons that exhibits many traits of tectonic deformation seen in modern continent–continent collision, including extensive crustal thickening and a highly complex Moho [10]. On the other hand, relatively flat Moho structures have been found to be preserved over areas of significant extent in some Phanerozoic accretionary terranes in western Canada [26], so it remains possible that the Moho structures observed today are simply those preserved from the time of crustal formation.

An alternative and more plausible explanation of our observations is that the Kaapvaal crust was indeed assembled by accretionary tectonics, but that the flat and sharp Moho was achieved in a later stage of crustal evolution. This explanation implicitly requires that a large volume of the Kaapvaal crust has been re-melted on a regional scale since its formation. Such large thermal events, mainly involving the lower crust, were suggested by a recent geochronological study [27] of crustal rocks exposed in the Vredefort dome located some 300 km northwest of Kimberley. Much of what we know about the deep crust beneath the Kaapvaal craton has come from the study of rocks exposed in the Vredefort complex in which an almost complete section of cratonic crust has been turned on-edge by isostatic rebound following a massive meteor impact around 2.0 billion years ago (Ga). Moser and co-workers [27] carried out a detailed study of mid and lower crustal rocks (which are dominantly felsic to intermediate in composition) exposed in the eroded remains of the crater. They presented evidence that the rocks exposed in the Vredefort dome record a complex history of crustal formation around 3.5 Ga followed by large-scale re-melting during a craton-wide thermal event at 3.11 Ga. Based on the distribution and ages of rocks in the Vredefort crustal section, they concluded that as much as 40% of the crust, chiefly the lower crust, was re-melted during that event. We further speculate that the very large degree of crustal melting proposed by Moser et al. [27] is sufficient to form something resembling an ‘ocean’ of melt in the cratonic lower crust near the crust–mantle boundary. The magmatic differentiation and layering accompanying the crystallization of that lower crustal melt ‘ocean’ is one possible means for producing both a flat and sharp Moho as well as the evolved rock compositions that we infer from the seismic data.

6. Summary of conclusions

We have introduced in this paper a refined technique for using reverberation phases in receiver function analysis of high quality broadband data. The method yields well determined average seismic velocities and Poisson ratios for the crust. The S-wave velocity jump and density jump across the Moho are also obtained from the analysis. When coupled with high quality array data, the technique also places quantitative constraints on both the sharpness of the crust–mantle boundary and the topographic relief on the Moho. We have applied the methodology to high quality teleseismic data recorded on the broadband Kimberley array to obtain quantitative constraints on the nature of the lower crust and Moho of the Kaapvaal craton of southern Africa. The primary results of the analysis reveal the following features of the crust and crust–mantle boundary beneath the array: (1) the crust is relatively thin (35.4 km) with a low average crustal Poisson ratio of ~0.254; (2) the density contrast across the Moho is ~15.4%, indicating a lowermost crustal density around 2.86 gm/cc; (3) the Moho is very sharp, with a crust–mantle transition zone less than 0.5 km; and (4) the Moho is surprisingly flat with topographic relief less than 1 km over a region of ~2400 km^2. An interpretive summary of these results is shown in Fig. 6. The evidence for a flat and almost perfectly sharp Moho, together with the absence of a mafic lower crust, suggests large-scale crustal reworking during a major thermomagmatic event in the period between initial crustal formation and the time of cratonic stabilization at the end of the Archean.

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