V_S structure of the crust containing the Bushveld Complex

E. M. Kgaswane[1,4], A.A. Nyblade[2], R.J. Durrheim[3,4], J. Julià[5],
P.H.G.M. Dirks[4,6] and S.J. Webb[4]

1. Council for Geoscience, South Africa, ekgaswane@geoscience.org.za
2. Pennsylvania State University, USA
3. Council for Scientific and Industrial Research, South Africa
4. University of the Witwatersrand, South Africa
5. Universidade Federal do Rio Grande do Norte, Brazil
6. James Cook University, Australia

ABSTRACT

The crustal structure of the Bushveld Complex is investigated by jointly inverting high-frequency teleseismic receiver functions and 2–60 sec Rayleigh wave group velocities for 16 broadband seismic stations spanning the Bushveld Complex. Rayleigh wave group velocities for 2–15 sec periods were obtained from a surface wave tomography using local and regional events, while group velocities for 20–60 sec periods were taken from a published model. The 1-D V_s models obtained for each station show the presence of a thickened crust in the centre of the Bushveld Complex, and that $V_s \geq 4.0$ km/s over a significant portion of the lower crust (≥30 km depth). The 1-D V_s models also reveal that the upper crustal structure (≤10 km depth) across the Bushveld Complex is characterized by V_s as high as ~3.7–3.8 km/s, consistent with the presence of mafic lithologies. These results support a "continuous-sheet" as opposed to a "dipping-sheet" model for the Bushveld Complex. However, detailed modelling of receiver functions at one station within the centre of the complex suggests that the mafic layering is inhomogeneous and could have been locally disrupted by diapirism and metamorphism.

Key words: Bushveld Complex; joint inversion; receiver functions; Rayleigh wave group velocities

INTRODUCTION

The Bushveld Complex (BC) (Fig. 1, end of paper) was emplaced at ca. 2.06 Ga in the northern part of the Kaapvaal Craton, South Africa and is one of the largest mafic layered igneous intrusions in the world. It covers an area of ~66,000 km^2 within the craton (e.g., Walraven, 1997; Eglington and Armstrong, 2004; Webb et al., 2004). It has an abundance of platiniferous group metals, as well as large reserves of chromium, titanium, vanadium, nickel and gold (e.g., Cawthorn et al., 2006). It intruded into the intracratonic sedimentary sequences of the Transvaal Supergroup and is stratigraphically divided into the Rooiberg Group (RG), the Rashoop Granophyre Suite (RGS), the Lebowa Granite Suite (LGS) and the Rustenburg Layered Suite (RLS; e.g., South African Committee for Stratigraphy, 1980; Hatton and Schweitzer, 1995; Cawthorn and Webb, 2001; Cawthorn et al., 2006).

The mafic components of the RLS crop out in five geographically distinct areas: the Eastern Limb, the Western Limb, the Far Western Limb and the two Northern limbs (Figure 1a; e.g., Webb et al., 2004). A sixth limb, the Southeastern or Bethal Limb (Cawthorn and Webb, 2001), is buried under Karoo sediments. The BC is disrupted in several places by alkaline intrusions (Fig. 1a). Much of the subsurface structure of the BC above 10 km depth is reasonably well understood, but the deep structure of the BC and how it was emplaced remains a subject of ongoing research. The BC was originally thought to be a laccolith (e.g., Mellor, 1906) or lopolith (e.g., Molengraaff, 1902). However, gravity modeling by Cousins (1959) showed that the Bouguer gravity low in the geographic centre of the BC is inconsistent with these models. The "dipping-sheet" model of Meyer and De Beer (1987) exhibited detached limbs that extended to 15 km depth, with no compensation at the Moho (Fig. 2a).

Later geological and geophysical studies (Cawthorn et al., 1998; Cawthorn and Webb, 2001; Webb et al., 2004) proposed the existence of continuous mafic layering at depth across the centre of the BC, connecting the various limbs (Fig. 2b). In this model, hereinafter called the "continuous-sheet" model, a downwarped Moho isostatically compensates for the continuous mafic layering in the upper crust, consistent with seismic constraints provided by receiver function studies (Nguuri et al., 2001; Nair et al., 2006; Kgaswane et al., 2009). The study by Nguuri et al. (2001) suggests Vs≈4.0 km/s within the upper 10 km of the crust for one location near the centre of the BC. The recent findings by Webb et al. (2010) of mafic xenoliths in the Palmietgat kimberlite pipe (Fig. 1a) further supports the hypothesis of continuous mafic layering in the centre of the BC. The purpose of this study is to use new seismic velocity models of the crust containing the BC to evaluate the geometric models.

METHODOLOGY

Rayleigh wave group velocity maps in the period of 2–15 sec (~2–15 km depth) were tomographically derived by measuring Rayleigh wave group velocities produced by 197 mining-related and regional seismic events (see Fig. 1b) recorded by 45 broadband seismic stations. Mining-related earthquakes account for 81% of the total number of earthquakes used for the measurements, the majority originating within the gold mining districts of the Witwatersrand Basin. The locations of the 45 broadband seismic stations with respect to the outcrop pattern of the BC are shown in Fig. 2c: 43 stations belong to the Southern African Seismic Experiment (SASE) network (Carlson et al., 1996), and the remaining stations to the Global Seismic Network (GSN) and South African National Seismograph Network (SANSN). The measurement of the Rayleigh wave group velocities was done using a multiple filter technique (e.g., Dziewonski et al., 1969; Keilis-Borok, 1989; Claerbout, 1992; Levshin et al., 1992) incorporated in a code written by Ammon (2001). Kgaswane et al. (2012) reviews these methods.

The receiver functions and surface wave dispersion measurements for each recording station were jointly inverted to yield 1-D Vs models of the structure beneath each station. Julià et al. (2000, 2003) reviews this method. Quality receiver functions were obtained for 16 stations that fall within the area of best resolution (Kgaswane et al., 2012). The receiver functions were processed using a frequency of 1.25 Hz (Gaussian bandwidth of 2.5 s) and were computed for each teleseismic event with a maximum number of 200 iterations using the iterative deconvolution code based on the method by Ligorría and Ammon (1999). These high-frequency receiver functions were finally stacked according to backazimuth and ray-parameter. Rayleigh wave group velocities obtained in the 2-15 sec period were combined with the group velocities for 20-60 sec from Pasyanos and Nyblade (2007) to create a composite dispersion curve for each station. The composite dispersion curves were smoothed with a 3-point running average prior to using them in the joint inversions with the receiver functions. Kgaswane et al. (2009, 2012) describe the processing of both datasets and the application of the joint inversion technique.

RESULTS

The quasi–3D V_s model (from depths of 2–15 km) computed from Rayleigh wave group velocity tomography is shown in Fig. 3 (end of paper). Apart from an occasional indication of high V_s bodies at 4–6 km depth associated with the northern limb of the BC, the model fails to image the mafic limbs (~Vs≥3.7 km/s) at shallow depths as the spatial resolution (125 x 125 km^2) is too large.

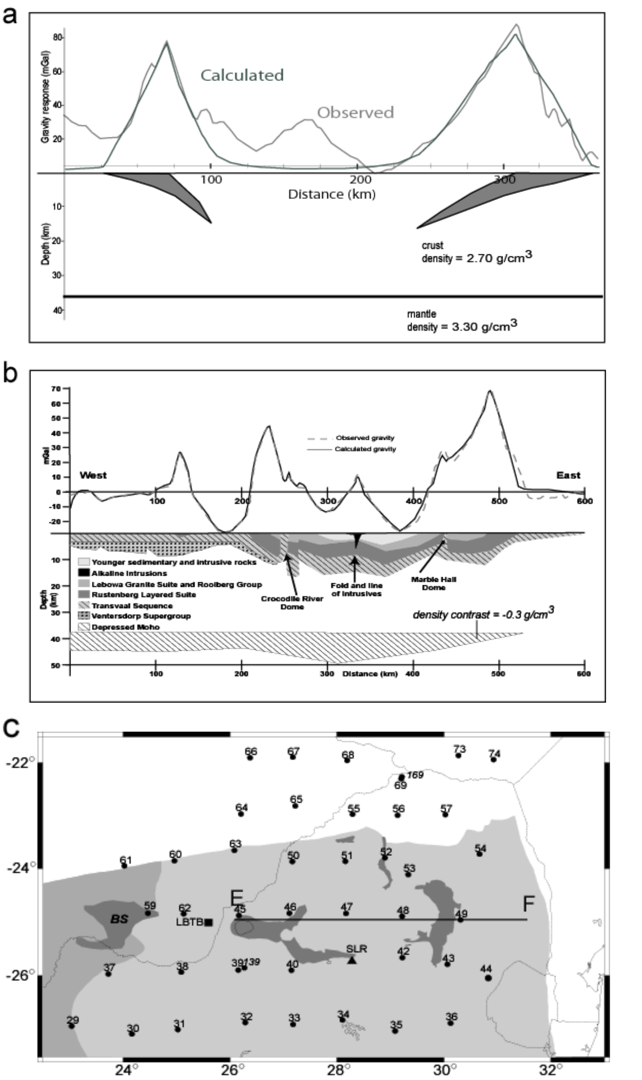

Figure 2. Gravity models of (**a**) Meyer and De Beer (1987), and **(b)** Webb et al. (2004), reproduced from Webb et al. (2004). (**c**) Locations of the broadband stations within and surrounding the BC: SASE (solid circles), GSN (solid square) and SANSN (solid triangle). The gravity model profile is shown by the solid line EF. The area marked BS is the Molopo Farms Complex and represents one of the Bushveld satellites. The gray-shaded regions show the Kaapvaal Craton. Terrain and political boundaries are shown by dashed black and gray lines, respectively.

However, the joint inversion results (see Fig. 4, end of paper) clearly show the presence of high Vs layers (≥3.7 km/s) at certain localities across the BC, as well as a 45 km deep Moho discontinuity in the centre of the BC (i.e., around station SA47) (see Fig. 1b). The joint inversion results were used to derive a density model using an empirical V_s–density relationship (Christensen and Stanley, 2003). Minor adjustments of the thicknesses of the upper crustal layers in the density model produce a model consistent with the gravity model by Webb et al. (2004) (see Kgaswane et al., 2012). Therefore, the seismic results obtained in this study are broadly consistent with the "continuous-sheet" model of Webb et al. (2004). However, a synthetic experiment on receiver functions for station SA47 indicated that the composition of the upper crustal layer in the centre of the BC is quite variable, in variance with both the Webb et al. (2004) density model and this study.

CONCLUSIONS

The V_s model derived from Rayleigh wave group velocity tomography has insufficient resolution to definitively image the BC. However, the 1-D V_s models obtained by jointly inverting high-frequency receiver functions ($f \leq 1.25$ Hz) and Rayleigh wave group velocities (2–60 sec period) for 16 broadband seismic stations spanning the BC indicate:

1. The crust beneath the centre of the BC is ~45 km thick, about 5–8 km thicker than the cratonic regions adjacent to the BC.
2. $V_s \geq 4.0$ km/s is found over a substantial portion of the lower crust (≥ 30 km depth) beneath the BC, indicative of a highly mafic lower crust.
3. There could be mafic lithologies in the upper crust with $V_s \geq 3.7$ km/s.

These results support a "continuous-sheet" model for the BC (e.g., Webb et al., 2004) as opposed to a "dipping-sheet" model (e.g., Meyer and de Beer, 1987). However, detailed modelling of receiver functions within the centre of the complex indicates that the mafic layering maybe locally disrupted by thermal diapirism triggered by the emplacement of the BC at ~2060 Ma (Uken and Watkeys, 1997) and/or metamorphism associated with a ~2040 Ma intraplate event (e.g., Alexandre et al., 2006, 2007)

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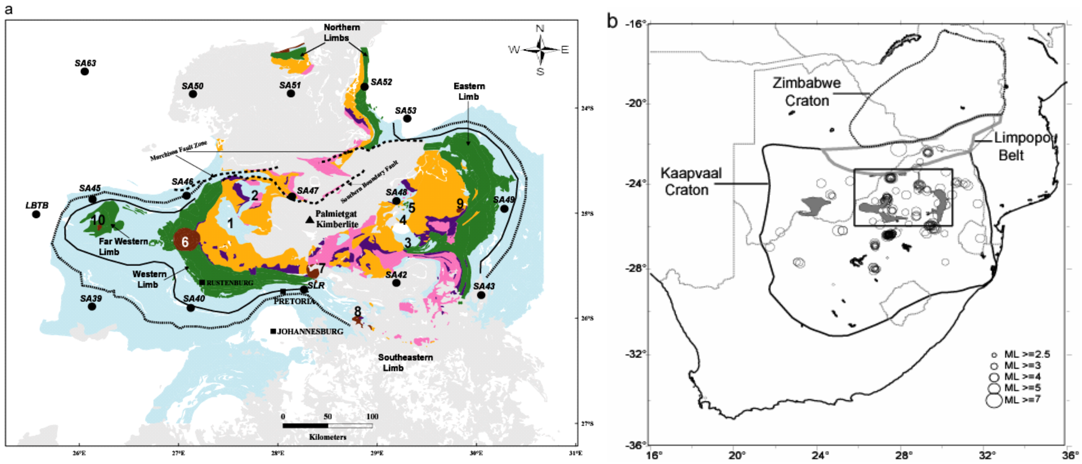


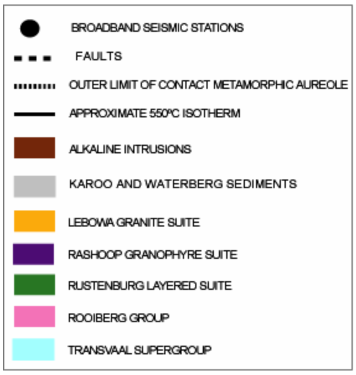
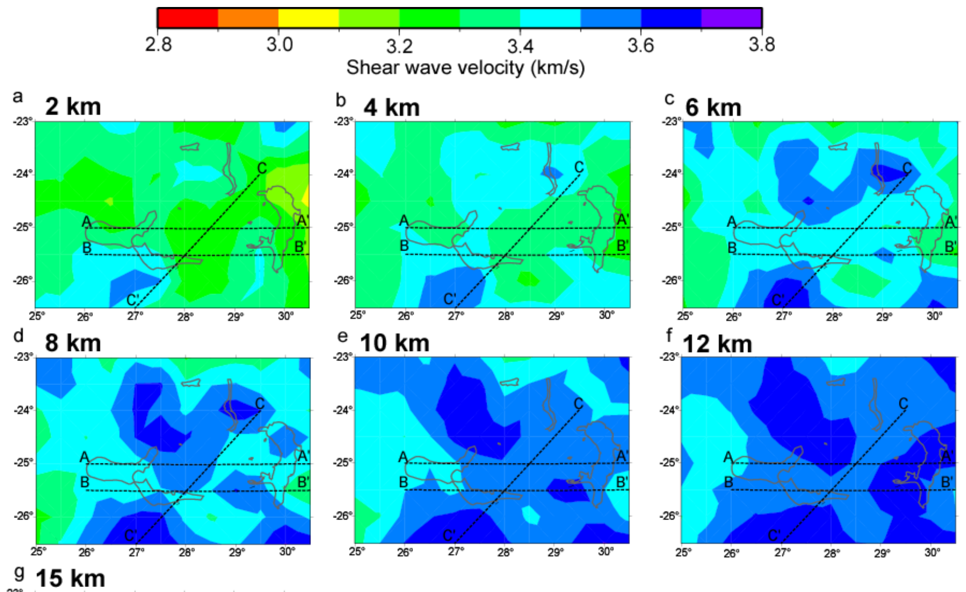


Figure 1 **(a).** Map of the Bushveld Complex showing simplified geology and its six limbs – the Eastern, Western, Far Western, Southeastern and the two Northern limbs (map modified from the 1:250,000 geology map of South Africa). The numbers 1, 2, 3, 4 and 5 show the position of some of the domes, and the numbers 6, 7, 8, 9 and 10 show the location of alkaline intrusions. The location of 16 broadband seismic stations for which Vs models are reported are shown. They are the permanent stations, LBTB and SLR and the temporary stations with prefix "SA". **(b).** Map of southern Africa showing the locations of earthquakes



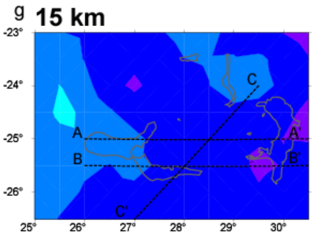


Figure 3 (a–g). Horizontal slices through the shear wave velocity model shown for depths of 2, 4, 6, 8, 10, 12 and 15 km. The dashed lines on the maps i.e., A–A', B–B', C–C' are the selected profiles for the vertical cross-sections. The vertical cross-sections also do not reflect a clear correlation of the layering with the surface mafic exposures.

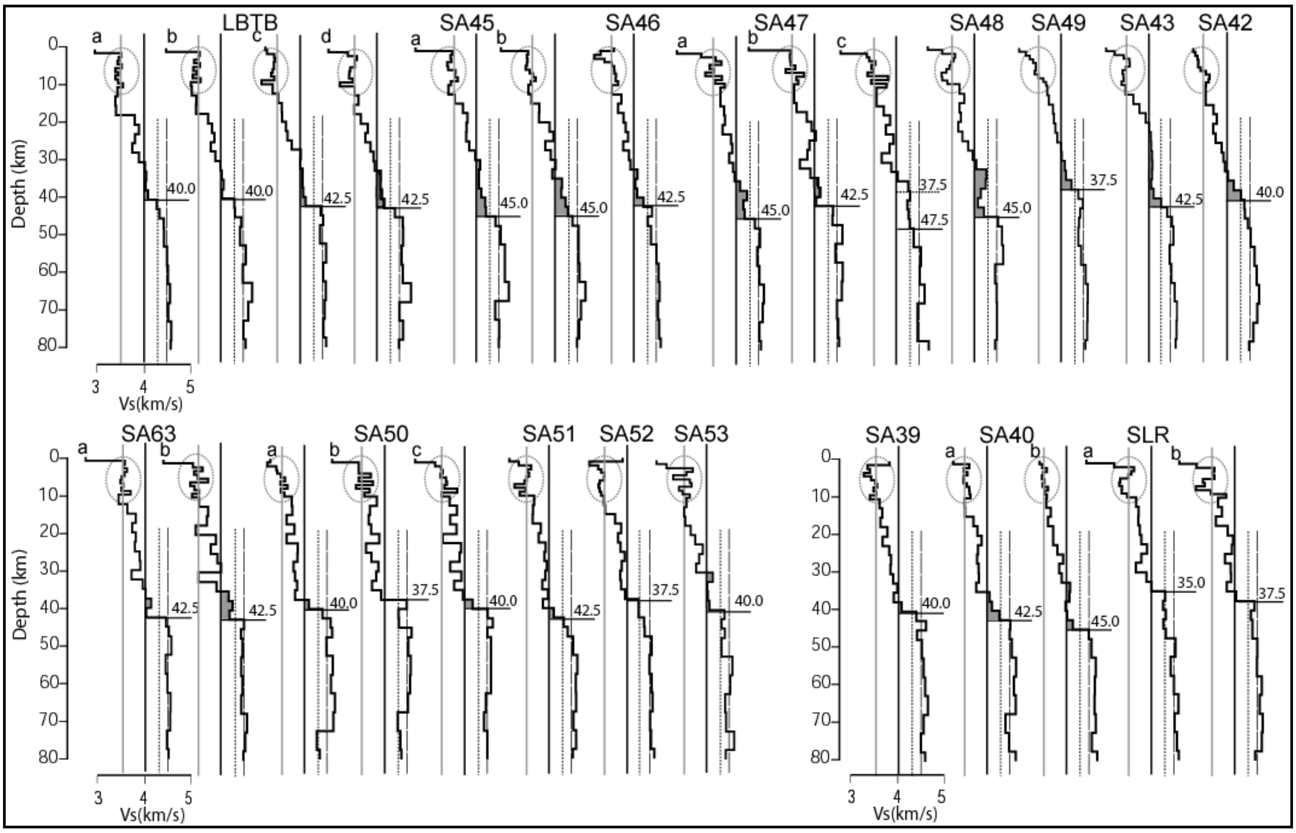


Figure 4. V_s profiles from joint inversion results showing Moho depths and details of the velocity structure in the upper and lower parts of the crust. The letters on top of each profile correspond to the backazimuths at which the receiver functions were stacked (see Kgaswane et al., 2012). The dashed ellipses enclose an area of the upper crust from 0 to 10 km depth. Crustal thicknesses are indicated with horizontal lines and numbers in km. Lower crustal layers with $V_s \geq 4.0$ km/s are shaded, and reference lines at 3.5 km/s (gray solid), 4.0 km/s (black solid), 4.3 km/s (dotted) and 4.5 km/s (dashed) are shown on each profile.