AfricaArray seismological studies of the structure and evolution of the African continent

R.J. Durrheim[1,2], A.A. Nyblade[3], M.C.B. Brandt[1,4], F. Tugume[3,5], G.D. Mulibo[3,6],
E.M. Kgaswane[1,4], A. Mangongolo[1,4], M.S.D. Manzi[1], N. El Tahir[1], and L. Loots[1,4]

1. The University of the Witwatersrand, South Africa, Raymond.Durrheim@wits.ac.za
2. CSIR Centre for Mining Innovation, South Africa
3. The University of Pennsylvania, U.S.A.
4. Council for Geoscience, South Africa
5. Department of Mines, Uganda
6. Nelson Mandela-African Institute of Science and Technology, Tanzania

ABSTRACT

The AfricaArray programme seeks to build geoscience capacity and conduct research that supports development in Africa. This paper reports on investigations of the structure and evolution of the African continent that have been concluded since the review presented at the 2009 SAGA Conference. The AfricaArray observatory network has been expanded from 33 to 49 stations, and 25 continuous GPS and 22 meteorological stations have been installed. A temporary seismic array has been deployed in Mozambique and Madagascar. Brandt and Mulibo elucidated the relationship between the African Superplume, Superswell and the East African Rift System by studying the seismic velocity structure of the mantle. Kgaswane jointly inverted P-wave receiver functions (PRFs) and surface waves, and found that the Kalahari Craton lower crust is largely mafic, except for a few terrains such as the Kimberley. Kgaswane also produced evidence that supports a link between the eastern and western lobes of the Bushveld Complex. Mangongolo used surface wave tomography to define the south-western boundary of the Congo Craton. El Tahir used PRFs to investigate the crustal structure of the Khartoum Basin. Tugume determined the Moho depths and Poisson's ratios of the Precambrian crust in East Africa. Manzi reprocessed 3D reflection seismic data covering part of the Witwatersrand goldfields using seismic attribute analysis methods, and has provided new constraints on the evolution of the Basin during the Neoarchean. Loots interpreted a 105 km 2D seismic reflection profile immediately to the north of the Cape Fold Belt, imaging the Karoo and Cape Supergroup rocks and the seismic fabric of the basement. A zone of strong reflectors was found beneath the Beattie Magnetic Anomaly.

Key words: AfricaArray, African Superplume, Congo Craton, Bushveld Complex, Khartoum Basin, Witwatersrand Basin, Beattie Magnetic Anomaly.

INTRODUCTION

AfricaArray is a pan-African initiative that promotes linked research and training programmes to build capacity in support of the mineral, energy, groundwater, environmental and natural hazard sectors in Africa. Established in 2004, AfricaArray is nearing the midpoint of its 20-year strategic plan. Here we report on investigations of the structure and evolution of the African continent that have been concluded since the last review that was presented at a SAGA Conference - in Swaziland in 2009 (Durrheim et al., 2009).

AFRICAARRAY SENSOR NETWORK

The observatory network started in 2005 with a handful of seismic stations in eastern and southern Africa. In 2009 the network consisted of 33 broadband stations. It now spans 19 countries and will soon include 49 observatories: 22 with co-located seismic, continuous GPS and meteorological sensors, 1 with a co-located seismic and GPS sensor, 24 with only seismometers, and 2 with only GPS receivers (Fig. 1). The GPS and meteorological sensors will support climate change, atmospheric, geodynamic and space weather research.

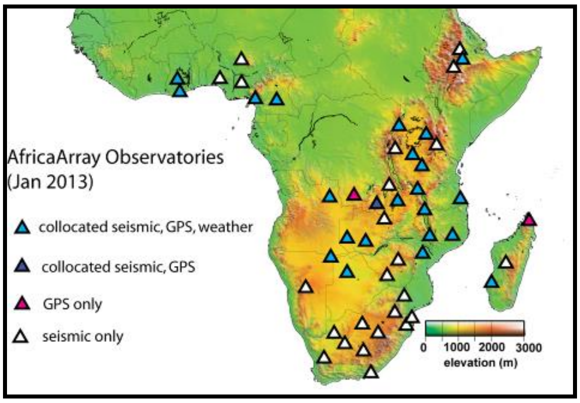

Figure 1. AfricaArray network of permanent observatories as at January 2013

AFRICAN SUPERPLUME

The African Superplume is a prominent and enigmatic feature in the Earth's lower mantle. The low V_s anomaly lies beneath much of the southern African subcontinent, an area with anomalously high topography. Many researchers have suggested a geodynamic relationship between the Superplume and the formation of plateaus and rift valleys in eastern and southern Africa. However, many questions remain unanswered. For example: Is there a transfer of material or heat between the Superplume and the magma chambers that feed the active volcanoes and dykes of the East African Rift System? The AfricaArray network provides seismic data that allows the Superplume and the roots of the East African Rift System to be imaged with greater resolution than ever before.

Brandt et al. (2012) derived a 1D SH-wave velocity model of the upper mantle beneath the Kalahari craton by inverting waveforms of regional seismograms from an M_w5.9 earthquake located near Lake Tanganyika (Fig. 2). It was found that the velocity in the lithosphere beneath the Kalahari craton is similar to that of other shields, with little evidence of a significant LVZ below the lithosphere. The lower part of the lithosphere (110-220 km) is slightly slower than other shields, due either to higher temperatures or a decrease in Mg number (Mg#). The buoyancy produced by a hotter lower lithosphere accounts for slightly less than half of the unusually high elevation of the Kalahari craton; while a decrease in the Mg# of the lower lithosphere would increase the density and counteract the buoyancy effect. The seismic model provides little support for an upper mantle source of buoyancy for Kalahari craton, and hence gives greater credence to models that attribute the Superswell to lower mantle processes.

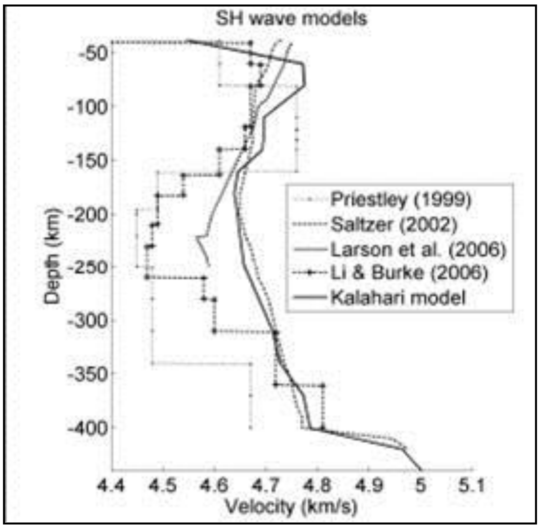

Figure 2. Comparison of the Kalahari model (Brandt et al., 2013) and other V_s-z models for the region

Mulibo and Nyblade (2013) inverted P- and S-wave relative arrival time residuals from teleseismic earthquakes recorded on over 60 temporary AfricaArray broadband seismic stations deployed in Uganda, Tanzania and Zambia between 2007 and 2011, together with relative arrival time residuals from earthquakes recorded by previous deployments, and derived a tomographic image of mantle wave speed variations extending to a depth of 1200 km beneath eastern Africa. The image (Fig. 3) shows a well-developed low wavespeed anomaly (LWA) at shallow depths (100-200 km) beneath the Eastern and Western branches of the Cenozoic East African rift system and north-western Zambia, and a fast wave speed anomaly at depths ≤350 km beneath the central and northern parts of the East African Plateau and the eastern and central parts of Zambia. At depths ≥350 km the LWA is most prominent under the central and southern parts of the East African Plateau and dips to the southwest beneath northern Zambia, extending to a depth of at least 900 km. The amplitude of the LWA is consistent with a ~150-300 K thermal perturbation, and its depth extent indicates that the African Superplume is likely a whole mantle structure. A Superplume extending from the core-mantle boundary to the surface suggests that the processes driving Cenozoic extension, volcanism and plateau uplift in eastern Africa are related to the dynamics of the lower mantle.

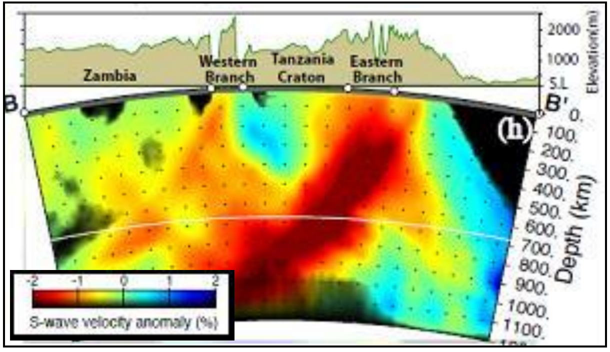

Figure 3. V_s depth-slice through the tomographic model of Mulibo and Nyblade (2013)

CRUST AND UPPER MANTLE

Mapping the extent of the Congo craton

Mangongolo (2010) inverted Rayleigh wave group velocity measurements to derive a 3D V_s model for the crust and upper mantle. V_s was found to be faster beneath the Congo and Kalahari cratons and slower beneath the intervening Damara mobile belt. The velocity differences are attributed to greater depletion of the mantle beneath the cratons.

Crustal structure of the Khartoum Basin

El Tahir et al. (2013) investigated the crustal structure of the northern part of the Mesozoic Khartoum Basin. H–k-stacking indicated that the crust is 33-37 km thick (av. 35 km) with V_p/V_s=1.74-1.81 (av. 1.78). Similar results were obtained from the joint inversion of receiver functions and Rayleigh wave group velocities. These results are the first seismic estimates of Moho depth for a basin in Sudan. When compared to average crustal thickness for unrifted Proterozoic crust in eastern Africa, the results indicated that at most only a few km of crustal thinning occurred beneath the Khartoum Basin. This finding is consistent with estimates of effective elastic plate thickness, which indicate little modification of the Proterozoic lithosphere beneath the Khartoum Basin, and suggests that there may be insufficient topography on the lithosphere–asthenosphere boundary beneath the Sudanese basins to channel plume material westward from Ethiopia.

Crustal structure in East Africa

The study by Tugume et al. (2013) of the Precambrian crust in Kenya and Tanzania using data from several campaigns (including one by AfricaArray) produced several surprising findings: (1) There is little variation in crustal thickness (37-42 km) and Poisson's ratio (ca. 0.25) for terrains spanning some 4 Ga of the Earth's history, in contrast to other Precambrian terrains. This suggests either that processes have not changed significantly in this time, or that the crust has been homogenized. (2) Crustal structure did not play a first-order effect on the location of rifting. (3) The poor correlation between elevation and Moho depth suggests that the source of buoyancy that supports the plateau lies within the mantle rather than the crust.

V_s in the lower crust of southern Africa

Kgaswane et al. (2009) investigated the nature of the lower crust across the southern African shield by jointly inverting receiver functions and Rayleigh wave group velocities for 89 broadband seismic stations located in Botswana, South Africa and Zimbabwe. For large parts of both Archaean and Proterozoic terrains, the velocity models obtained from the inversions show $V_s \geq 4.0$ km/s below ~20–30 km depth, indicating a predominantly mafic lower crust. However, for much of the Kimberley terrain and adjacent parts of the Kheis Province and Witwatersrand terrain in South Africa, as well as for the western part of the Tokwe terrain in Zimbabwe, $V_s \leq 3.9$ km/s is found below ~20–30 km depth, indicating a felsic-to-intermediate lower crust. In South Africa, these areas coincide with regions where Ventersdorp rocks have been preserved, suggesting that the more evolved composition of the lower crust may have resulted from crustal reworking and extension during the Ventersdorp tectonomagmatic event at ca. 2.7 Ga.

Continuity of the Bushveld Complex

Kgaswane et al. (2012) investigated the structure of the crust in the environs of the Bushveld by jointly inverting high-frequency teleseismic receiver functions and 2–60 s Rayleigh wave group velocities for 16 broadband seismic stations located across the Bushveld Complex. Group velocities for 2–15 s were obtained from surface wave tomography using local and regional events, while group velocities for 20–60 s were taken from a published model. 1D V_s models obtained for each station show the presence of thickened crust in the centre of the Bushveld Complex and a region at the base of the crust where $Vs \geq 4.0$ km/s. The V_s models also suggest that Vs in some upper crustal layers may be as high as 3.7–3.8 km/s, consistent with the presence of mafic lithologies. These results favour a model for the Bushveld Complex in which the outcropping mafic layers of the western and eastern limbs are continuous at depth beneath the centre of the complex.

Neoarchaean history Witwatersrand Basin

Manzi et al. (2013) mapped first-order scale structures in the West Wits Line and West Rand goldfields of the Witwatersrand Basin using the 3D reflection seismic method (Fig. 4). The structural models constrain the magnitude of displacement of thrusts and faults, the gross structural architecture and Neoarchaean tectonic evolution of the West Rand and Bank fault zones, which offset the gold-bearing reefs of the basin.

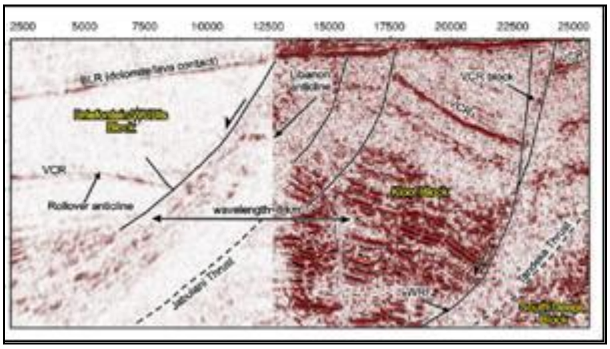

Figure 4. 8 km depth slice of 3D seismic cube showing the Libanon anticline (Manzi et al., 2013)

The 3D seismic interpretation confirms that the West Rand Group is unconformably overlain by the Central Rand Group, with tilting of the West Rand Group syn- to post-erosion at ca. 2.9 Ga; and that an unconformable relationship exists between the Central Rand Group and the auriferous Ventersdorp Contact Reef (VCR), with an easterly-verging fold-thrust belt being initiated concomitant to deposition of the VCR at ca. 2.7 Ga. Fold-thrust formation included the development of the (1) newly identified first-order scale Libanon Anticline, (2) the Tandeka and Jabulani thrusts, which displace the West Rand Group, and (3) parasite folds. The fold-thrust belt is crosscut by a macroscopic extensional fault array (or rift-like system of faults) which developed towards the end of extrusion of the Ventersdorp lavas, and certainly during deposition of the Platberg Group (2.7–2.6 Ga) when a mantle plume may have heated the lithosphere. The West Rand and Bank fault zones formed at this time.

Southern Karoo Reflection Seismic Profile

Several seismic reflection surveys were conducted in the late 1980s and early 1990s under the auspices of the SA National Geophysics Programme. Loots (2013) reprocessed and interpreted the ~105 km seismic reflection profile that crosses the Beattie Magnetic Anomaly (BMA), the Southern Cape Conductive Belt and the Karoo/Cape Fold Belt boundary. The profile was acquired in 1992, but the complete profile was not interpreted or published prior to this study (Fig. 5). Upper crust consists of the Karoo and Cape Supergroup rocks that dip slightly to the south. The middle crust is interpreted to consist of the granitic-gneisses belonging to the Bushmanland Terrane, part of the Namaqua-Natal Mobile Belt (NNMB). The seismic profile suggests that the NNMB gneisses continue beneath the Cape Fold Belt. The middle crust also hosts the source of the BMA, which is characterised by a bean-shaped cluster of strong reflections. It is ~10 km wide, with a thickness of ~8 km and its top at a depth of ~8 km. The lower crust is interpreted to consist of granites belonging to the Aracheap Terrane or rocks belonging to the Kheis Province. The seismic fabric of the lower crust dips steeply to the south. The Moho is encountered at ~37 km at one section of the profile, but no clear reflections are seen elsewhere.

CONCLUSION

Since 2009 the AfricaArray observatory network in sub-Saharan Africa has expanded from 33 to 49 stations; several landmark investigations of the crust and upper mantle have been conducted, including studies of the relationship between the Superplume and the East African Rift System; 11 MSc and 7 PhD students have graduated; and research findings have been published in more than 50 refereed papers. Details can be found at www.africaarray.org.

ACKNOWLEDGMENTS

Many persons have contributed to the work described in this review. In particular we would like to acknowledge the contributions of Steven Grand (University of Texas, USA), Jordi Julià (Federal University of Rio Grande do Norte, Brazil), Paul Dirks (James Cook University, Australia), Trond Ryberg (GFZ, Germany), Roger Gibson, Kim Hein and Zet Gumede (Wits University), Nick King (Gold Fields), and Damien Delvaux (Royal Museum for Africa, Belgium). We also acknowledge support from the National Science Foundation, IRIS and UNAVCO (USA); the National Research Foundation and the Council for Geoscience (South Africa).

REFERENCES

Brandt, M.C.B., Grand, S.P., Nyblade, A.A. and Dirks, P.H.G.M., 2012, Upper mantle seismic structure beneath southern Africa: constraints on the buoyancy supporting the African Superswell, Pure and Applied Geophysics, 169, 595–614.

Durrheim, R.J., Dirks, P.H.G.M., Nyblade, A.A., Graham, G., Webb, S.J. and Jones, M.Q.W., 2009, AfricaArray: aims, achievements and future activities, Proceedings of the 11th Biennial Conference of the South African Geophysical Association, 16-18 September 2009, Ezulwini, Swaziland.

El Tahir, N.A., Nyblade, A.A., Julià, J., and Durrheim, R.J., 2013, Crustal structure of the Khartoum Basin, Sudan. Tectonophysics, 593, 151–160.

Kgaswane, E.M., Nyblade, A.A., Julià, J., Dirks, P.H.G.M., Durrheim R.J. and Pasyanos, M.E., 2009, Shear velocity structure of the crust in southern Africa: evidence for compositional heterogeneity within Archaean and Proterozoic terrains, Journal of Geophysical Research, 114, B12304, doi:10.1029/2008JB006217.

Kgaswane, E.M., Nyblade, A.A., Durrheim, R.J., Julià, J., Dirks, P.H.G.M. and Webb, S.J., 2012, Shear wave velocity structure of the Bushveld Complex, South Africa, Tectonophysics, 554-557, 83-104.

Loots, L., 2013, Investigation of the crust in the southern Karoo using the seismic reflection technique, MSc dissertation, University of the Witwatersrand (unpublished).

Manzi, M.S.D., Hein, K.A.A., King, N. and Durrheim, R.J., 2013, Neoarchaean tectonic history of the Witwatersrand Basin and Ventersdorp Supergroup: new constraints from high-resolution 3D seismic reflection data, Tectonophysics, 590, 94-105.

Mangongolo, A., 2011, Surface wave tomography and shear wave velocity structure of the southwestern block of the Congo Craton, MSc dissertation, University of the Witwatersrand (unpublished).

Mulibo, G.D. and Nyblade, A.A., 2013, The P and S wave velocity structure of the mantle beneath eastern Africa and the African superplume anomaly, Geochemistry, Geophysics, Geosystems, in press.

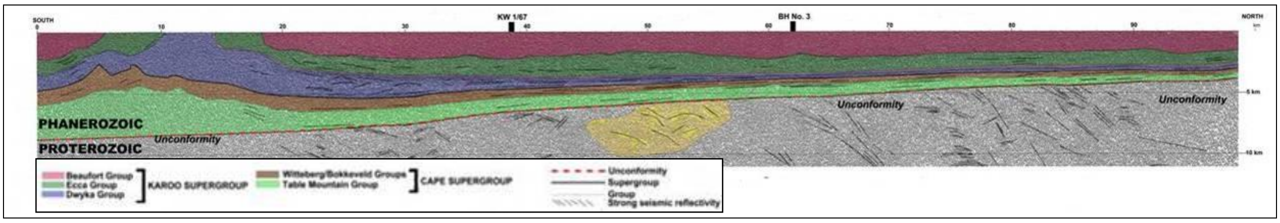

Figure 5. Interpreted image of the upper 10 km of the 105 km S Karoo reflection seismic profile (Loots, 2013)