Deep Electrical Resistivity Structure of the Kaapvaal and Rehoboth Terranes, Southern Africa, from Broadband Magnetotellurics, and Implications for Archaean and Proterozoic Lithospheric Evolution

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ABSTRACT

The configuration of the Rehoboth Terrane of southern Africa (also known as the Nama or Namibia Province), located beneath thick Kalahari sand cover, has been interpreted to date primarily on the basis of potential field data patterns. The thickness and stabilisation age of the Rehoboth lithosphere, and its tectonic relationship with the adjacent Archaean Kaapvaal Craton, are currently poorly constrained. Several magnetotelluric (MT) traverses acquired across the sub-continent, and forming part of the broader Southern African MT Experiment (SAMTEX), have provided deep 2-D electrical resistivity images that show significant differences between the lithosphere of the Rehoboth and Kaapvaal terranes. Electrical resistivities, lower by a factor of ~10 beneath the Rehoboth Terrane, are most readily explained by a hotter geotherm and thinner lithosphere beneath the Rehoboth in comparison with the Kaapvaal. However, systematic differences between the observed lithospheric resistivities and those predicted for dry olivine as a function of temperature complicate the reliable quantification of lithospheric thickness, and we assess the extent to which the resistivity anomaly amplitudes have been under-recovered in our 2-D inversions (e.g., through smoothing, crustal masking, choice of 2-D strike direction and MT station statics effects), and consider other processes potentially affecting our electrical resistivity observations (e.g., mineral hydration and the presence of graphite). Our MT models are consistent with peridotite xenolith geochemistry from the Gibeon kimberlites in Namibia, and point to a Proterozoic affinity and age of stabilization for the Rehoboth Terrane. (SAMTEX: http://www.dias.ie/~mh/samtex_html/participants.html).

Key words: Magnetotellurics, Lithosphere, Kaapvaal, Rehoboth, Proterozoic.

INTRODUCTION

The configuration of the Rehoboth Terrane (also known as the Nama or Namibia Province), located beneath thick Kalahari sand cover in southern Africa, is interpreted primarily on the basis of potential field data patterns (Figure 1). The thickness, internal structure and stabilisation age (Archaean or Proterozoic) of the Rehoboth lithosphere, as well as the tectonic style and timing of its accretion to the Kaapvaal Craton to the east, are poorly constrained by available information.

A 1,400 km-long magnetotelluric (MT) traverse was acquired across the Rehoboth Terrane and its margins to image the deep electrical structure of the lithosphere and provide constraints on the tectonic development of the terrane. This work forms part of the wider Southern African MT Experiment (SAMTEX) which has acquired over 500 MT stations across the sub-continent since mid-2003 (Figure 1).

Geological Setting

The Rehoboth Terrane is flanked to the east by the Kalahari Line, to the southwest by the ~1.1 Ga Namaqua-Natal Belt, and to the northwest by the late Proterozoic Ghanzi-Chobe Belt. The Kalahari Line is widely regarded as the western margin of the Archaean Kaapvaal Craton. The Kheis fold and thrust belt was emplaced from the west onto the western edge of the Kaapvaal Craton between 1.93-1.75 Ga (Tinker *et al*., 2004). A deep-crustal seismic reflection profile (see Figure 1 for profile location) indicates that the Kheis Belt is a "thin skinned" tectonic event and is underlain at depth by sequences correlated with ~2.7 Ga Ventersdorp Supergroup (Tinker *et al*., 2004), providing strong evidence that the terrane immediately east of the Kalahari Line had stabilised by the late Archaean.

The very long-wavelength signature of the magnetic anomalies located inside the Rehoboth Terrane (Figure 1) indicates a dramatic increase in the depth to magnetic basement, with estimates of the depth to magnetic basement from Euler deconvolution in excess of 10,000 m (Corner, 2006, pers. Comm.). The overlying sedimentary sequences are magnetically inert and have only been stratigraphically correlated unequivocally above the deepest borehole intersection, at 4,000 m, of the ~1 Ga Aubres "Red Bed" Formation. Although deep seismic reflection data have imaged the entire sedimentary succession within the eastern Rehoboth Terrane (Wright and Hall, 1990; see Figure 1 for profile localities), stratigraphic correlations are unconstrained, and the ages and lithologies of the succession below the Aubres Formation, and of the magnetic basement itself, are uncertain.

Constraints from Geochemistry

Two key observations from geochemistry suggest an early Proterozoic stabilisation age for the Rehoboth

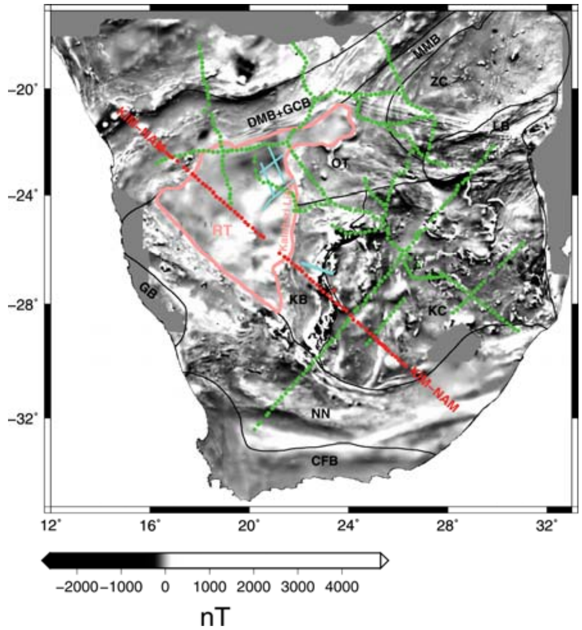

Figure 1. Magnetic image of southern Africa showing locality of MT stations along the KIM-NAM profile (red dots), and along all other SAMTEX profiles (green dots). The outline of the Rehoboth Terrane (thick pink line) and other major tectonic boundaries (thin black lines) are shown (boundaries courtesy S. Webb, University of the Witwatersrand). Also shown are deep seismic reflection profiles of Wright and Hall (1990) in the north and Tinker *et al*. (2004) in the south (blue lines). Tectonic domains abbreviated as follows: KC Kaapvaal Craton; ZC Zimbabwe Craton; LB Limpopo Belt; NN Namaqua-Natal Mobile Belt; KB Kheis Belt; MMB Magondi Mobile Belt; DMB+GCB Damara and Ghanzi-Chobe Belts; GB Gariep Belt; CFB Cape Fold Belt.

lithosphere. No Archaean dates have been reported for any rocks originating from within the Rehoboth Terrane.

(i) Crust: the Weener Intrusive Suite on the northern margin of the Rehoboth Terrane has been dated at 1723 Ma ($^{207}Pb/^{206}Pb$ zircon age) and between 1.7 and 2.3 Ga (Nd model ages) (Ziegler and Stoessel, 1991).

(ii) Mantle lithosphere: peridotite xenoliths from the Gibeon kimberlite field show maximum Re depletion ages of between 2.0 and 2.2 ± 0.2 Ga (Hoal *et al*., 1995). These depletion ages are ~1 Ga younger than those seen on the Kaapvaal Craton (Boyd *et al*., 2004).

Peridotite xenolith analyses indicate that the Rehoboth lithosphere is less depleted (average Mg# = 91.8, versus 92.6 for the Kaapvaal; Hoal *et al*., 1995), implying chemically more dense lithosphere, compensated isostatically in an isopycnic model of the lithosphere (Jordan, 1978) by hotter, and therefore thinner, lithosphere beneath the Rehoboth.

MT DATA ACQUISITION AND PROCESSING

Data Acquisition and Processing

MT data were acquired at 69 broadband stations, deployed at roughly 20 km intervals along the KIM-NAM profile, recording data for two- or three-night periods. Additionally, 10 coincident long-period stations were deployed at roughly 60 km intervals along the southern portion of the profile, recording data for approximately one-month periods. Data acquisition took place during the first and last quarters of 2004. The instrumentation consisted of Phoenix MTU5 broad-band and long-period LIMS units. The gap in station coverage, towards the midpoint of the line, is due to the lack of access inside the Kgalagadi Transfrontier National Park located in southern Botswana.

Three different robust processing codes (Jones, Egbert and Chave, see e.g., Jones *et al*., 1989) were tested and applied at different stations along the profile in an effort to derive optimal MT responses. While data quality across the Rehoboth Terrane is good, very poor data quality prevails within a radius of about 100 km around the town of Kimberley, due to the very high amplitude electrical-noise generated by the DC power-supply to both the mines and railway lines located in the area.

Data Decomposition

MT data at each site were decomposed using the method of Groom and Bailey (1989), as implemented in the STRIKE code of McNeice and Jones (2001), to remove local galvanic distortion of the data and isolate the 2-D regional geological response. No single electrical strike direction could be identified as appropriate for the entire profile. While a consistent strike direction of 5 – 25° E of N is observed within the crust and mantle lithosphere of the Rehoboth Terrane, the data suggest that a north-easterly strike direction would be more appropriate for both the Damara and Kaapvaal terranes. A strike direction of 25° was chosen as the best compromise and used in the decomposition of all the MT station responses along the profile.

2-D LITHOSPHERIC MODEL

Our most recent electrical resistivity model for profile KIM-NAM, derived by 2-D inversion of all decomposed MT station responses simultaneously, is shown in Figure 2 (see figure caption for details of the modelling methodology). Most of the station responses are matched to within a normalized RMS error < 2.

The primary observation in the model is that while the Kaapvaal Craton is characterised by thick, resistive lithosphere, both the Rehoboth Terrane and Ghanzi-Chobe/Damara Belts are characterized by significantly less resistive lithosphere. In the depth range 50-150 km, the range of resistivities observed beneath the Kaapvaal is 500-5000 Ωm, compared with 70-400 Ωm beneath the Rehoboth (Figure 3). A significant decrease in average lithospheric conductivity is also apparent beneath the western Kaapvaal, when compared to the eastern Kaapvaal Craton (Figure 3). In the vicinity of Kimberley the lithosphere structure is not fully recovered in the 2-D model due to poor data quality.

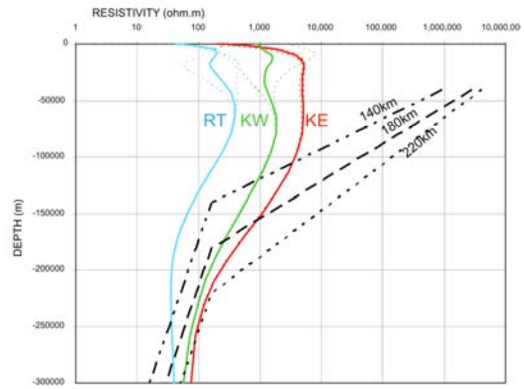

Figure 3. Average resistivity-depth profiles extracted from the 2-D section of Figure 2, for the Rehoboth (RT), and western (KW) and eastern (KE) Kaapvaal Craton, with variance indicated by dashed coloured lines (note the high crustal variance above 50 km depth). Black dashed lines indicate lithospheric resistivities predicted for dry olivine as a function of temperature (Xu *et al*., 2004) for several geotherms corresponding to different lithospheric thicknesses.

CONCLUSIONS

Given temperature as the primary control on dry mantle electrical resistivity (e.g., Xu *et al*., 2004), the observed resistivity structure beneath the Rehoboth Terrane is consistent with a significantly thinner lithosphere and an elevated geothermal gradient with respect to the Kaapvaal, and is typical of Proterozoic rather than Archaean lithosphere. However, systematic differences between the observed lithospheric resistivities and those predicted for dry olivine as a function of temperature (Figure 3) complicate the quantification of lithospheric thickness, and further work is required to assess the extent to which the resistivity anomaly amplitudes have been under-recovered in our 2-D inversions (e.g., through smoothing, crustal masking, choice of 2-D strike direction and MT station statics effects), and consider other processes potentially affecting our electrical resistivity observations (e.g., mineral hydration and the presence of graphite).

Our findings are consistent with xenolith geochemistry results from the Gibeon field that point to a Proterozoic affinity and stabilization age for the Rehoboth Terrane.

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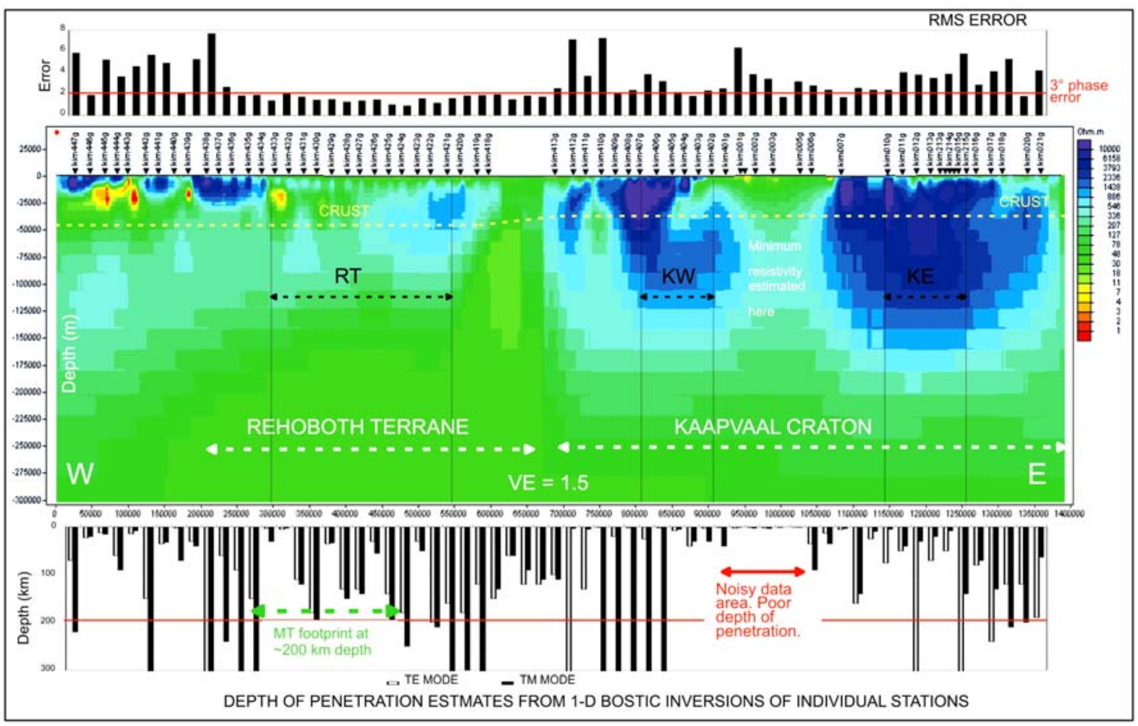

Figure 2. Electrical resistivity model for Profile KIM-NAM derived from 2-D smooth inversion of the decomposed and rotated MT data. The inversion method used is Rodi and Mackie (2001), implemented in WinGLink® software. Inversion parameters are: simultaneous inversion for TE and TM modes, smoothing factor τ = 3.0, phase and apparent resistivity error floors = 5% and 10% respectively, and inversion for static shifts allowed for selected stations and modes. Tipper (Hz) data, only available at some stations, were not used. Inset figures show: (i) RMS misfit error at each station, normalised by data error. An RMS error < 1.0 is equivalent to an error < 1.5° in fitting the MT phase observations. (ii) Estimates of depth of investigation at each station location for both TE and TM modes, calculated using 1-D Niblett-Bostick inversion (e.g., Jones, 1983).