Rapid Mesozoic thermal and chemical modification of the Rehoboth Terrane and Kaapvaal Craton from broadband magnetotellurics and xenolith geochemistry

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ABSTRACT

A 1400 km-long, 2-D magnetotelluric (MT) profile across the Archaean Kaapvaal Craton, the Proterozoic Rehoboth Terrane and the Late Proterozoic/Early Phanerozoic Ghanzi-Chobe/Damara Belt reveals significant lateral heterogeneity in the electrical resistivity structure of the southern African lithosphere. The profile indicates the following present-day average lithospheric thicknesses, to a precision of about ± 20 km, for each of the terranes traversed (inferred conductive geotherms in brackets): Eastern Kimberley Block of the Kaapvaal Craton 220 km (41 mWm^{-2}), Western Kimberley Block 190 km (44 mWm^{-2}), Rehoboth Terrane 180 km (45 mWm^{-2}) and Ghanzi-Chobe/Damara Belt 160 km (48 mWm^{-2}). Previously published mantle xenolith pressure-temperature (P-T) arrays from the Gibeon, Gordonia and Kimberley fields, however, suggest that the Rehoboth Terrane had equilibrated to a cooler conductive palaeo-geotherm (40 – 42 mWm^{-2}) very similar to that of Eastern Kimberley Block of the Kaapvaal Craton, at some (unconstrained) time prior to the Mesozoic eruption of the kimberlites. A model consisting of the penetration of heat transporting magmas into the lithosphere, with associated chemical refertilisation, at an early stage of Mesozoic thermalism appears to be the most plausible model at present to account for both the present-day lithospheric structure of the Rehoboth Terrane and an earlier, cooler palaeo-geotherm. Some problems, however, remain unresolved in terms of the isostatic response of the model. Based on a compilation of xenocryst Cr/Ca-in-pyrope barometry observations, the extent of depleted mantle in the Rehoboth Terrane is found to be significantly reduced with respect to the Eastern Kimberley Block: 117 km versus 138 – 167 km. It appears most likely that the chemical depletion depth in both terranes, at least in the vicinity of kimberlite eruption, is accounted for by refertilisation of the lower lithospheric mantle.

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

INTRODUCTION

A 2-D electrical resistivity model of the lithosphere beneath the Rehoboth Terrane of Namibia and western Botswana (Figure 1) was first presented at the 10th SAGA Biennial Meeting (Muller at al., 2007). At that time, differences were highlighted between the present-day lithospheric geotherm inferred from the resistivity model and the palaeo-geotherm for the terrane derived from Mesozoic kimberlitic xenolith pressure-temperature (P-T) arrays (Bell et al., 2003; Grütter and Moore, 2003; Boyd et al., 2004; Appleyard et al., 2007). Based on further consideration of both the P-T arrays and a compilation of xenocryst Cr/Ca-in-pyrope barometry observations, we now suggest a history for the Rehoboth Terrane in which an originally thicker lithosphere was rapidly heated, thinned and refertilised at an early stage of Mesozoic thermalism (Muller et al., 2009). A similar fate has also recently been inferred for the Kaapvaal Craton, in which a hotter geotherm was established and the lower lithospheric mantle refertilised, in the period between the eruption of Group 2 (143 – 117 Ma) and Group 1 kimberlites (108 – 74 Ma) (Kobussen et al., 2008), suggesting that thermal and chemical disruption of the lithosphere during the thermalism and magmatism associated with kimberlite genesis is possible over relatively short periods of time, perhaps of the order of ~50 Ma.

MT profile KIM-NAM (Figure 1) investigates a lithospheric accretionary history that was initiated during Palaeoarchaean times, with the first crustal formation and mantle melt depletion events recorded in the Kaapvaal Craton, and ended with the stabilisation of the Damara Mobile Belt following the Late Proterozoic/Early Palaeozoic Pan-African orogeny. The work presented here focuses on the evolution of the Early Proterozoic Rehoboth Terrane, in comparison with the Eastern Kimberley Block of the Kaapvaal Craton.

MAGNETOTELLURICS

2-D data modelling

MT data were acquired at 69 stations, deployed at 20 km intervals along profile KIM-NAM (Figure 1). Data acquisition took place during the first and last quarters of 2004 as part of the Southern African MT Experiment (SAMTEX). The data were processed variously using three different robust processing codes (Jones, Egbert and Chave, see Jones *et al.*, 1989) to derive optimal MT responses at each site. The MT responses were subsequently 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, isolate the 2-D regional geological response and identify the regional 2-D electrical strike direction. The final 2-D electrical resistivity model (Figure 2) was computed from the decomposed MT responses, for a 25° E of N strike azimuth for the Rehoboth Terrane, and a 45° E of N azimuth for all other terranes, using the smooth inversion method of Rodi and Mackie (2001).

Present-day lithospheric structure and geotherms

Electrical resistivity is significantly more sensitive to temperature variation in the lithospheric mantle than it is to compositional variation (Maumus et al., 2005; Jones et al., 2009). Given temperature as the primary control, the MT derived lithospheric thickness therefore provides a very reasonable proxy for the "thermal" thickness of the lithosphere (i.e., the thickness defined by the intersection of a conductive geotherm with the mantle adiabat) and allows approximate present-day geotherms to be calculated.

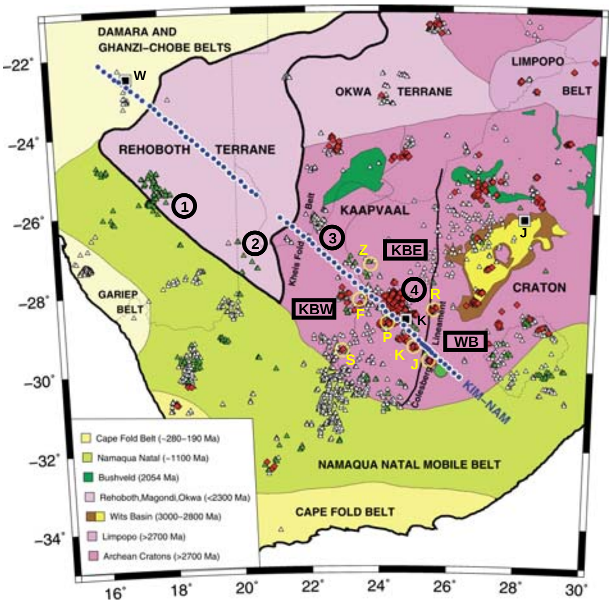

Figure 1. Locality of MT profile KIM-NAM on simplified tectonic map of southern Africa. Shown are MT sites (blue dots) and kimberlite occurrences (red diamonds = known diamondiferous, green triangles = known non-diamondiferous, white triangles = unknown or unspecified in databases). Annotated kimberlite fields are: (1) Gibeon, (2) Gordonia, (3) Tsabong and (4) Kimberley. Kimberlites providing Cr/Ca-in-pyrope barometry observations are shown by yellow circles: (J) Jagersfontein, (R) Roberts Victor, (K) Koffiefontein, (P) Paardeberg, (F) Finsch, (Z) Zero, (S) Sanddrift. Subdivision of Kaapvaal Craton into Western Kimberley Block (KBW), Eastern Kimberley Block (KBE) and Witwatersrand Block (WB) is shown. Major cities (black squares) shown are: Kimberley (K), Johannesburg (J) and Windhoek (W). Sources of kimberlite data: South African Council for Geoscience numerical database; Jelsma et al. (2004); Faure (2006). Terrane boundaries shown courtesy S.J. Webb, University of the Witwatersrand, and based on the magnetic field image of southern Africa.

Profile KIM-NAM reveals significant lateral heterogeneity in the electrical resistivity structure of the southern African lithosphere (Figure 2). The following present-day average lithospheric thicknesses, to a precision of about ± 20 km, are indicated for each of the terranes traversed, with inferred conductive geotherms in brackets (Figures 2 and 3): Eastern Kimberley Block of the Kaapvaal Craton 220 km (41 mWm^{-2}), Western Kimberley Block 190 km (44 mWm^{-2}), Rehoboth Terrane 180 km (45 mWm^{-2}) and Ghanzi-Chobe/Damara Belt 160 km (48 mWm^{-2}).

XENOLITH GEOCHEMISTRY

Thermobarometry

Mantle xenolith pressure-temperature (P-T) arrays from the Kimberley, Gibeon and Gordonia kimberlite fields (Figure 1) constrain lithospheric mantle geotherms and lithospheric thickness at time of kimberlite eruption between ~140 – 70 Ma. A number of xenolith studies (Bell et al., 2003; Grütter and Moore, 2003; Boyd et al., 2004; Appleyard et al., 2007) have found no significant difference between the Kaapvaal (Eastern Kimberley Block) and Rehoboth P-T arrays (see Figure 4) and the conclusion that has emerged from these studies is that, on balance, the Rehoboth Terrane and Eastern Kimberley Block had acquired similar thermal structures, defined by a conductive geotherm of about 40 – 42 mWm^{-2}, at some stage prior to kimberlite eruption. Geotherms of 40 – 42 mWm^{-2} correspond with a thermal thickness of the lithosphere of between about 225 – 205 km. However, the evidence of disruption of the Gibeon array data at high temperatures and pressures (Figure 4) suggests that the Rehoboth lithosphere subsequently experienced thermal perturbation either at, or sometime before, the time of kimberlite eruption (Bell et al., 2003).

Lithospheric mantle depletion

Available evidence from xenolith studies indicates that the lithospheric mantle of the Rehoboth Terrane is chemically less depleted on average, reflecting lower degrees of partial melting, and has a thinner highly-depleted upper lithospheric mantle layer, in comparison with the Eastern Kimberley Block of the Kaapvaal Craton. Low-temperature peridotites from the Gibeon field have an average Mg# for olivine equal to 91.6 in comparison with 92.6 for the Kaapvaal Craton (Boyd et al., 2004). Grütter et al. (1999, 2006) have used Cr saturation in garnet xenocrysts from kimberlites to define the maximum pressure (and therefore depth) of depleted peridotite in the mantle. Such maximum-pressure estimates from Cr-rich garnets from several southern African kimberlites (localities in Figure 1) indicate that the chemically depleted lithosphere extends significantly deeper beneath the Eastern Kimberley Block than beneath the Rehoboth Terrane: 138 – 167 km versus 117 km respectively (Figure 2), assuming a pressure-depth conversion factor of 3 km/kbar.

DISCUSSSION

We examine the notion that the Rehoboth Terrane might have, at some time in its past, been characterised by a cooler "Kaapvaal-like" palaeo-geotherm (40 – 42 mWm^{-2}) and a thicker lithospheric structure (~210 – 220 km) required to support the geotherm. The examination is made in the light of the Rehoboth's present-day thermal structure consisting of a ~45 mWm^{-2} geotherm, a ~180 km lithospheric thickness, a relatively fertile chemical signature and the absence of diamondiferous kimberlites. When the Rehoboth might have acquired its cooler palaeo-geotherm is not well constrained.

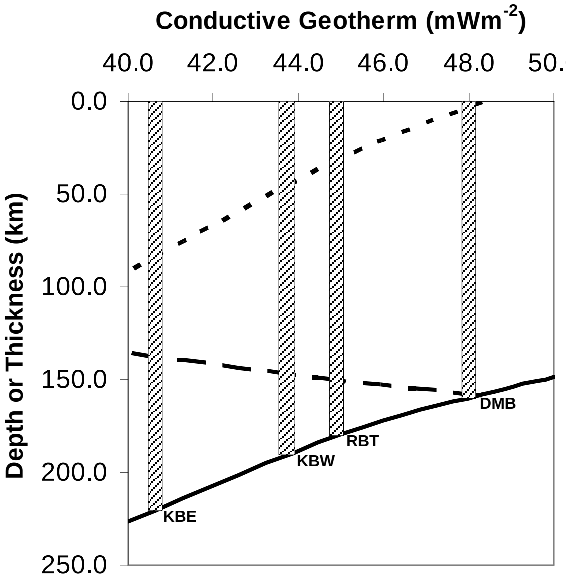

Figure 3. Depth to base of the "thermal" lithosphere (solid line) and top of the diamond stability field (long dashed line) as a function of lithospheric mantle geotherm, derived using Pollack and Chapman (1977) geotherms, the graphite/diamond equilibrium of Kennedy and Kennedy (1976) and a mantle adiabat with potential temperature T_P = 1300°C. Thickness of the "diamond window" (short dashed line) is the difference between the previous two curves. Overlaid are present-day lithospheric thickness results (shaded vertical bars) for each geological terrane derived from the MT electrical resistivity model for profile KIM-NAM (Figure 2). Terrane code names: Western Kimberley Block (KBW), Eastern Kimberley Block (KBE), Rehoboth Terrane (RBT) and Ghanzi-Chobe/Damara Belt (DMB).

In order to account for both the absence of diamonds and a hotter present-day thermal structure, any putative thicker, cooler lithospheric structure for the Rehoboth Terrane must have been thermally modified ***at some time prior*** to kimberlite eruption (75 – 65 Ma). How long before kimberlite eruption such a modification might have occurred is not constrained by this work. However, it should not have occurred too early, so as to disrupt the cool conductive geotherm in evidence in the upper lithospheric mantle. Bell et al. (2003) have inferred, from the disruption of the Gibeon xenolith P-T array at high temperatures (in evidence in Figure 4), that the Rehoboth lithosphere experienced significant thermal perturbation either at, or shortly before, the time of kimberlite eruption. They propose a model in which the geotherm of the Rehoboth Terrane was elevated by the penetration of heat transporting magmas into shallow levels of the lithosphere during the widespread thermalism that affected the subcontinent during the Mesozoic. They also argue that Proterozoic lithosphere was more susceptible to melt penetration than its Archaean counterparts through being not thinner, but more fertile and structurally weakened by old tectonism. Their model, essentially one of ***thermal advection*** of heat into the lithosphere, is attractive in that if the magmatism was also associated with extensive lithospheric refertilisation, of which there is evidence in the Rehoboth lithosphere (Griffin et al., 2003), it would help counter any isostatic uplift response to the decreasing thermal density of the lithosphere (by an increase in chemical density). Rather than significant uplift, the Rehoboth Terrane's recent history appears to be characterised by the accumulation of sediments in the form of Carboniferous to Cretaceous Karoo sediments preserved in the Aranos basin and Late Cretaceous to Recent Kalahari sediments preserved in the Kalahari Basin. There is also no clear evidence of differential uplift of the Rehoboth Terrane with respect to the terranes on its margins. To account fully for the present-day lithospheric structure, however, some lithospheric thinning during the thermal/magmatic event is required. Such thinning though remains problematic as it would contribute to an isostatic uplift response.

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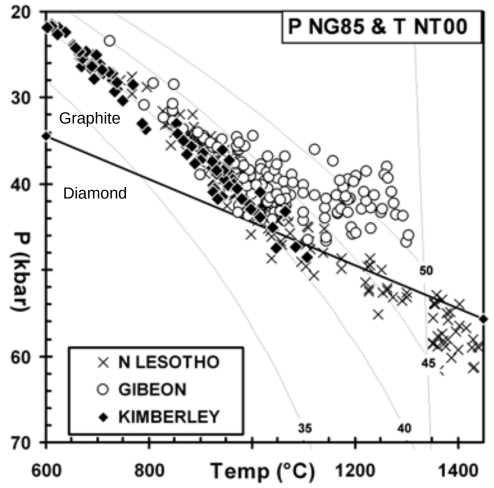

Figure 4. Peridotite xenolith P-T arrays for the Gibeon, Kimberley and Northern Lesotho kimberlite fields. Temperatures calculated using the thermometer of Nimis and Taylor (2000) and pressures using the barometer NG85 (Nickel and Green, 1985). Model conductive geotherms (thin black lines, 35 to 50 mWm-2) are after Pollack and Chapman (1977), terminating at a mantle adiabat with potential temperature T_P = 1300°C. The graphite/diamond equilibrium (thick black line) is that of Kennedy and Kennedy (1976). Gibeon localities dated 65 – 75 Ma, Kimberley localities 84 Ma and Northern Lesotho localities ~90 Ma. (References and localities for xenolith samples in Appendix 1, Muller et al., 2009).

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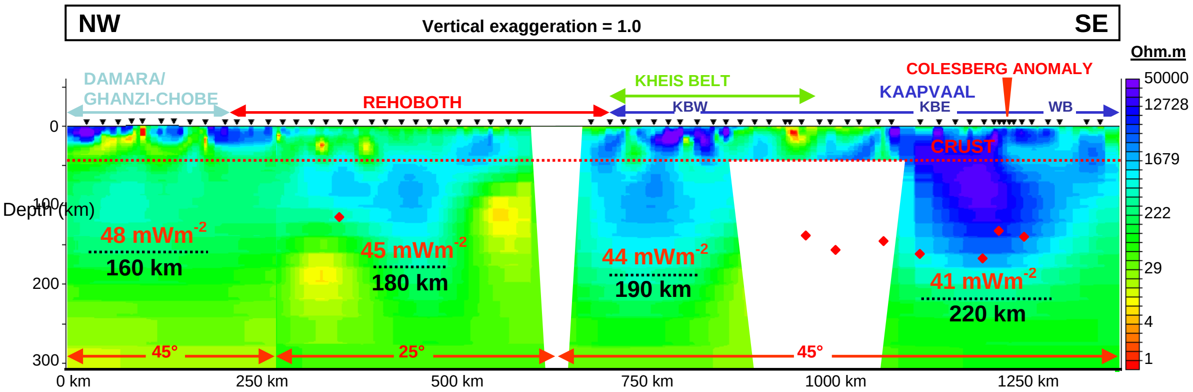

Figure 2. Composite electrical resistivity model for Profile KIM-NAM derived from 2-D smooth inversion of the decomposed, rotated MT data, using a 25° strike azimuth for the Rehoboth Terrane and a 45° azimuth for all other terranes. The model is blanked where unconstrained. Long-period data and depth of penetration in the vicinity of Kimberley were compromised by DC electrical noise from railway lines and operating mines. Interpreted depths to the base of the "thermal" lithosphere are shown (dashed black lines) where well constrained, with inferred conductive geotherms (red text). Red diamond symbols show the depth to the base of highly-depleted mantle, derived from xenocryst Cr/Ca-in-pyrope barometry observations at kimberlite localities shown in Figure 1. The 2-D smooth inversion method used is that of Rodi and Mackie (2001), implemented in WinGLink® software. Inversion parameters are: simultaneous inversion for TE and TM modes, smoothing factor $\tau = 3.0$, 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.