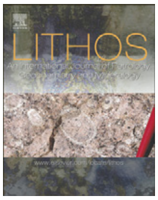
Lithos 112S (2009) 93–105

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos



Lithospheric structure, evolution and diamond prospectivity of the Rehoboth Terrane and western Kaapvaal Craton, southern Africa: Constraints from broadband magnetotellurics

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ARTICLE INFO

Article history:
Received 29 September 2008
Accepted 5 June 2009
Available online 1 July 2009

Keywords:
Magnetotellurics
Lithosphere
Xenolith
Geotherm
Southern Africa
Diamond

ABSTRACT

A 1400 km-long, 2-D magnetotelluric (MT) profile, consisting of 69 sites at 20 km intervals, across the western part of 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 lithospheric structures of the Rehoboth Terrane and Ghanzi-Chobe/Damara Belt have not been imaged previously by geophysical methods. Temperature is the primary control on the resistivity of mantle minerals, and the MT derived lithospheric thicknesses therefore provide 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), allowing approximate present-day geotherms to be calculated. The work indicates the following present-day average lithospheric thicknesses, to a precision of about ± 20 km, for each of the terranes traversed (inferred geotherms in brackets): Eastern Kimberley Block of the Kaapvaal Craton 220 km (41 mW m^{-2}), Western Kimberley Block 190 km (44 mW m^{-2}), Rehoboth Terrane 180 km (45 mW m^{-2}) and Ghanzi-Chobe/Damara Belt 160 km (48 mW m^{-2}). A clear relationship between the electrical resistivity structure of the lithosphere and the tectonic stabilisation-age of the terrane is evident. Good agreement between the inferred present-day lithospheric geotherms and surface heat flow measurements indicate the latter are strongly controlled by variations in lithospheric thickness. A significant difference in lithospheric thickness is observed between the Eastern and Western Kimberley blocks, and is consistent with previous seismic tomography images of the Kaapvaal Craton. The present-day lithospheric thickness, and reduced depth extent into the diamond stability field, accounts for the absence of diamondiferous kimberlites in the Gibeon and Gordonia kimberlite fields in the Rehoboth Terrane. Previously published mantle xenolith 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 mW m^{-2}), very similar to that of Eastern Kim-

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doi:10.1016/j.lithos.2009.06.023

berley Block of the Kaapvaal Craton, at some time prior to the Mesozoic eruption of the kimberlites. The timing and nature of both the thermal equilibration of the Rehoboth Terrane, and the subsequent lithospheric heating/thinning event required to account for its present-day lithospheric structure, are not well constrained. 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 palaeogeotherm. 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 depletion depth in both terranes, at least in the vicinity of kimberlite eruption, is explained by refertilisation of the lower lithospheric mantle.

1. Introduction

The Rehoboth Terrane (or Nama or Namibia Province) of southern Africa is accreted to the western margin of the Archaean Kaapvaal Craton (Fig. 1) and is largely hidden beneath thick Quaternary Kalahari sand-cover. Current understanding of the nature of the Rehoboth lithosphere is based entirely on the analysis of mantle xenoliths found in kimberlites from the Gibeon and Gordonia kimberlite fields, located on the western margin of the terrane (Fig. 1). The lithospheric root of the Rehoboth Terrane has not been imaged before using geophysical methods, nor are there any reported surface heat-flow measurements for the terrane. While available geochemical and isotopic data, discussed later in the paper, point towards an early Proterozoic, rather than Archaean, affinity and age of stabilisation for the Rehoboth lithosphere, the lithospheric thickness, mantle geotherm and diamond prospectivity of the terrane are all subjects of ongoing debate, principally due to the paucity of data.

A large number of kimberlite pipes have been discovered within the Rehoboth Terrane, in the Gibeon and Gordonia fields (Fig. 1), but none are reported to be diamondiferous[4]. Early reports of the extensively prospected Rietfontein pipe in the Gordonia field (Fig. 1) referred to it as being diamondiferous (e.g., Gurney et al., 1971), but more recent discussions suggest that the pipe is, in fact, non-diamondiferous (Gurney, 1984; Dawson, 1989; Appleyard et al., 2007). The absence of diamondiferous kimberlites in the Gibeon and Gordonia areas suggests a lithospheric thickness not significantly greater than the depth of the graphite-diamond stability field, at least at the time of kimberlite eruption (75–65 Ma; Spriggs, 1988; Allsopp et al., 1989; Davies et al., 2001). The Tsabong kimberlite field (Fig. 1), located in the western-most Kaapvaal Craton, in the area of the Kheis Fold Belt immediately east of the Rehoboth Terrane, is reported as being diamondiferous by an exploration company active in the area, based on macro and microdiamond recoveries (http://www.firestonediamonds.com/tsabong). No mines are yet operating in the area.

In this paper we present a new deep lithospheric electrical-resistivity model, provided by 2-D magnetotellurics (MT), along a profile that crosses the Kaapvaal Craton, the Rehoboth Terrane and the Damara and Ghanzi-Chobe Belts (Fig. 1). The geophysical model, which shows significant lateral heterogeneity in the present-day lithospheric structure, is compared with the mantle geotherms predicted by peridotite xenolith pressure–temperature (P–T) arrays from the 140–70 Ma Kimberley and Gibeon kimberlite fields (Bell et al., 2003; Grütter and Moore, 2003; Boyd et al., 2004). The comparison provides new constraints on the lithospheric evolution of the terranes traversed, and also helps explain the absence of diamondiferous kimberlites in the Rehoboth Terrane. Comparison between the MT and xenolith data is complicated by the time and spatial sampling-scale differences between the present-day MT observations and the xenolith results that reflect the characteristics of the lithosphere at the time of kimberlite eruption, or earlier. The latter data are also susceptible to thermal and/or chemical overprinting during the thermal event generating the eruption.

Magnetotellurics (MT) is a passive-source geophysical method used to derive electrical resistivity images of the subsurface. The method has been used widely in the investigation of lithospheric structure elsewhere in the world, for example in Canada (Jones et al., 2003), Europe (Korja, 2007) and Australia (Heinson and White, 2005). Magnetotellurics is an effective tool for investigating the thermal structure of the lithosphere, and hence lithospheric thickness, because the resistivity of the major mantle minerals (olivine, orthopyroxene and clinopyroxene) is highly sensitive to temperature variation (e.g., Constable et al., 1992; Xu and Shankland, 1999; Xu et al., 2000; Constable, 2006). For cratonic lithosphere, electrical resistivity is less sensitive to compositional variation in the mantle than is seismic velocity (Jones et al., 2009). Due to the close mapping between temperature and electrical resistivity in the mantle, lithospheric thickness is used throughout this paper, unless otherwise specified, in a "thermal" sense, i.e., the thickness defined by the intersection of a conductive mantle geotherm and the mantle adiabat.

2. Geological framework

MT profile KIM-NAM (Fig. 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 Kaapvaal Craton is subdivided into two tectonic blocks, the eastern Witwatersrand Block and the western Kimberley Block (de Wit et al., 1992), each with distinct geological fabrics and characteristics that attest to separate Palaeoarchaean to Mesoarchaean histories prior to their collision and accretion at about 2.9 Ga (Schmitz et al., 2004). The magnetic Colesberg Lineament (Fig. 1) defines the suture zone between the two blocks. Geological evidence, in the form of variations in magmatism and erosion levels on either side of the Colesberg Lineament, suggests that convergence between the two terranes was accommodated by subduction beneath the Kimberley Block (Schmitz et al., 2004).

A significant later tectonic event on the western margin of the Kaapvaal Craton resulted in the emplacement, from the west, of the thin-skinned Kheis Fold Belt (Fig. 1) onto the Kimberley Block sometime between 1.93 and 1.75 Ga (Tinker et al., 2004). Evidence presented later in the paper shows that the present-day lithospheric structure beneath the western part of the Kimberley Block, beneath the Kheis Fold Belt, is significantly different to that beneath the eastern part. The terms "Western Kimberley Block" and "Eastern Kimberley Block" are used throughout the text to refer to these two lithospheric blocks. Based on stratigraphic evidence in seismic reflection data, Tinker et al. (2004) and de Wit and Tinker (2004) interpret the presence of Ventersdorp Supergroup (2.70–2.65 Ga) stratigraphy across the entire Kimberley Block, including at depth below the Kheis Fold Belt. Whether the Western and Eastern Kimberley Blocks were ever separate entities is

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[4] The terms "diamondiferous" and "non-diamondiferous" are used loosely in the paper, and reports that refer to kimberlites as being diamondiferous or not have been taken at face value. None of the databases, papers or websites referred to in this work quantify diamond grade in any way.