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Density structure of the cratonic mantle in southern Africa: 1. Implications for dynamic topography

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ABSTRACT

The origin of high topography in southern Africa is enigmatic. By comparing topography in different cratons, we demonstrate that in southern Africa both the Archean and Proterozoic blocks have surface elevation 500–700 m higher than in any other craton worldwide, except for the Tanzanian Craton. An unusually high topography may be caused by a low density (high depletion) of the cratonic lithospheric mantle and/or by the dynamic support of the mantle with origin below the depth of isostatic compensation (assumed here to be at the lithosphere base). We use free-board constraints to examine the relative contributions of the both factors to surface topography in the cratons of southern Africa. Our analysis takes advantage of the SASE seismic experiment which provided high resolution regional models of the crustal thickness.

We calculate the model of density structure of the lithospheric mantle in southern Africa and show that it has an overall agreement with xenolith-based data for lithospheric terranes of different ages. Density of lithospheric mantle has significant short-wavelength variations in all tectonic blocks of southern Africa and has typical SPT values of ca. 3.37–3.41 g/cm^3 in the Cape Fold and Namaqua–Natal fold belts, ca. 3.34–3.35 g/cm^3 in the Proterozoic Okwa block and the Bushveld Intrusion Complex, ca. 3.34–3.37 g/cm^3 in the Limpopo Belt, and ca. 3.32–3.33 g/cm^3 in the Kaapvaal and southern Zimbabwe cratons.

The results indicate that 0.5–1.0 km of surface topography, with the most likely value of ca. 0.5 km, cannot be explained by the lithosphere structure within the petrologically permitted range of mantle densities and requires the dynamic (or static) contribution from the sublithospheric mantle. Given a low amplitude of regional free air gravity anomalies (ca. +20 mGal on average), we propose that mantle residual (dynamic) topography may be associated with the low-density region below the depth of isostatic compensation. A possible candidate is the low velocity layer between the lithospheric base and the mantle transition zone, where a temperature anomaly of 100–200 °C in a ca. 100–150 km thick layer may explain the observed reduction in Vs velocity and may produce ca. 0.5–1.0 km to the regional topographic uplift.

1. Introduction

The cratons of the southern Africa have an unusually high topography, 1.0–1.5 km on average, with an increase to 1.5–2.0 km in the eastern Kaapvaal and up to 2.5 km in Lesotho, and a depression down to 0.6–0.9 km in the Limpopo Belt (Fig. 1a). The topography of other cratons, including even the Archean parts of the Sino-Korean Craton which has been significantly affected by the India–Eurasia collision, is significantly lower, only 0.2–0.6 km (Fig. 2a, b). The only other high standing craton is the Tanzanian Craton, where the high topography may be caused by active mantle dynamics related to the Cenozoic rifting in East Africa. In southern Africa and the Tanzanian region, the high topography is a regional phenomenon that is observed both in the Archean and Proterozoic blocks, which have topography 500–700 m higher than any other craton worldwide (Table 1).

High surface elevation may result either from low density lithosphere or from the contribution (e.g. dynamic support) of the mantle below the LAB, or from the combination of both. The first factor is expected to play an important role in all Precambrian cratons, where the lithospheric mantle is depleted and has low-density (e.g. Gaul et al., 2000). In particular, petrological studies demonstrate that the lithospheric mantle beneath the Archean Kalahari Craton (which includes the Archean Kaapvaal and Zimbabwe cratons, melded along the Archean collisional Limpopo Belt) is depleted and has low-density (Boyd and Mertzman, 1987; O'Reilly and Griffin, 2006). Negative Bouguer anomalies (Fig. 3c) also indicate that low density material in the cratonic lithosphere contributes to high regional topography in southern Africa. Nonetheless, given a large number of craton-scale magmatic events in southern Africa (Fig. 1b), one may expect that the composition of the lithospheric mantle in the region could have been significantly modified through melt-metasomatism (Simon et al., 2007; Pearson and Wittig, 2008; Artemieva, 2009) with the

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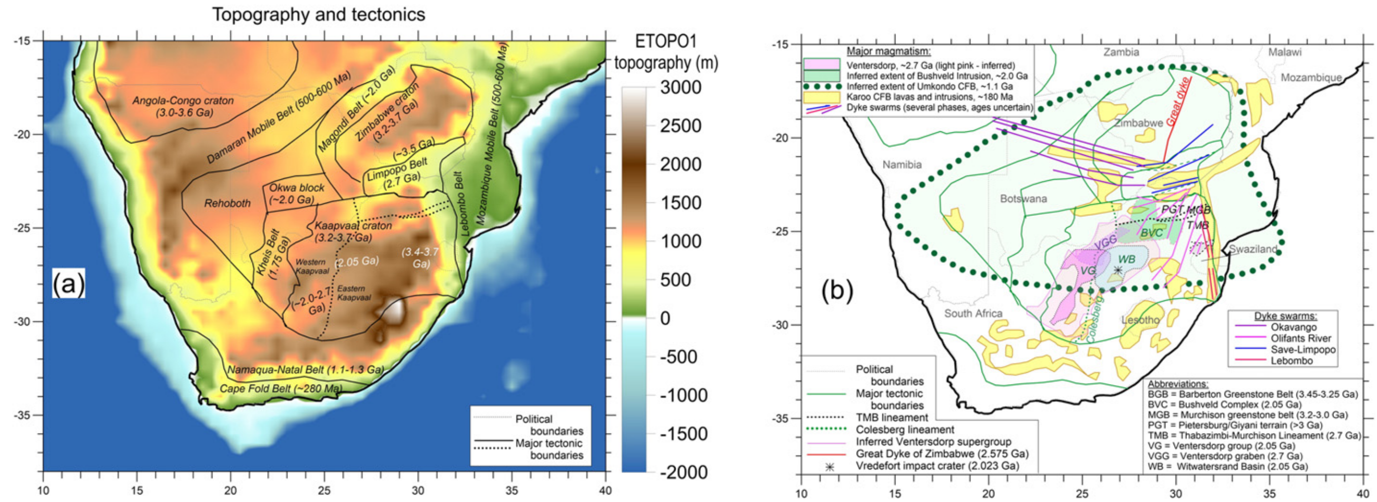

Fig. 1. Topography (a) (based on ETOPO1 global elevation model, Amante and Eakins, 2009) and major tectonic provinces (b) of the southern Africa. Tectonic boundaries — after de Wit et al. (1992) and Goodwin (1996); the Neoarchean Ventersdorp magmatic province — after Schmitz and Bowring (2003), the inferred extent of the Bushveld Igneous Complex — after Campbell et al. (1983) and of the Umkondo continental flood basalt province (CFB) — after Hanson et al. (2004); major Karoo lavas and outcrops — after Riley et al. (2006); locations and ages of kimberlites — based on database of Faure (2006).

corresponding increase in lithosphere mantle density, thus reducing the buoyancy contribution of the lithosphere to topography. Therefore, the dynamic support from the sublithospheric mantle (that is mantle residual topography caused by low density mantle anomalies of, primarily, thermal nature or dynamic topography caused by stresses associated with the mantle flow) should play an important role in providing high surface elevation in southern Africa. A simple comparison of topography in different cratons worldwide (Fig. 2a) suggests that the dynamic contribution of mantle convection to surface topography in the southern Africa is, at least, 500–700 m.

It has long been proposed that mantle plumes may have a strong effect on surface topography (Hager et al., 1985; Cox, 1989). Following this idea, the recent (Cenozoic) high topography of the southern Africa has been attributed to the dynamic effect of the proposed lower mantle plume (Lithgow-Bertelloni and Silver, 1998), which is seen as a ca. 1200 km wide, strong S-velocity anomaly (with a ca. 3% drop in Vs) in the lower mantle that extends upward from the core–mantle boundary to a depth of ca. 1500 km (Nyblade and Robinson, 1994; Ritsema et al., 1999; Ni and Helmberger, 2003). However, the wavelength of topographic uplift, if caused by the lower mantle plume, should be huge (comparable with large-scale geoid anomalies (Hager et al., 1985)) and significantly larger than the area with the high topography in southern Africa.

Despite an amazing number of publications on the African superplume and its effect on topography evolution (e.g. Hager et al., 1985; Gurnis et al., 2000; Simmons et al., 2007; Forte et al., 2010), there is still a lot of controversy in quantifying its dynamic effect because of a large uncertainty in mantle physical properties, particularly in mantle viscosity (Cadek and Fleitout, 2003). The values for dynamic topography in southern Africa range from near-zero (Forte et al., 2010) to more than 1.2 km (Flament et al., 2014); although many authors report the values around 600–700 m (Gurnis et al., 2000; Lithgow-Bertelloni and Silver, 1998; Conrad, 2013), which are consistent with our conclusion based on Fig. 2.

In a more general view, dynamic topography may be caused not only by temperature anomalies associated with mantle plumes, but by convective flow in the mantle which produces viscous stresses that may cause surface uplift above mantle upwellings (Hager et al., 1985) and basin subsidence above mantle downwellings (Heine et al., 2008; Downey and Gurnis, 2009). Numerical modeling of the dynamic effect

Table 1
Statistics for topography of Precambrian cratons worldwide.
Topography is derived from ETOPO1 global topographic model (Amante and Eakins, 2009) averaged on a 1° × 1° grid. Ages are based on the TC1 global lithosphere age model for the continents (Artemieva, 2006).

No. in Fig. 2	Region	All Precambrian		Archean only		Proterozoic only		[Archean topo] minus [Prot. topo], m
		Topo. average, m	St. dev., m	Topo. average, m	St. dev., m	Topo. average, m	St. dev., m	
1	Southern Africa cratons (south of 15S, excluding the Angola–Congo Craton)	1018	431	1053	369	983	472	70
2	Tanzanian craton (25–35N, 5N–10S)	952	390	948	389	958	398	−10
3	China cratons (east of 102E)	736	768	644	611	759	800	−115
4	West Africa, Congo, and Sahara (west of 25E, north of 15S)	531	345	623	371	471	280	152
5	Greenland	494	437	?		?		?
6	North America cratons	486	503	444	472	505	524	−61
7	Siberian Craton	474	416	635	405	323	247	312
8	South America cratons	338	408	413	302	325	418	88
9	India cratons	288	253	391	219	265	250	126
10	Australia cratons	278	177	302	164	268	184	34
11	East European Craton	178	150	160	86	185	165	−25
12	Arabia and Nubia shields (east of 30E, north of equator)	550	399	–		550	384	–