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Formation and temporal evolution of the Kalahari sub-cratonic lithospheric mantle: Constraints from Venetia xenoliths, South Africa

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ABSTRACT

The ~533 Ma Venetia Diamond Mine is located between the Kaapvaal and Zimbabwe Cratons and the study of selected xenoliths provides the opportunity to investigate the temporal evolution of the sub-continental lithospheric mantle (SCLM) underneath southern Africa, as well as the extent and potentially the timing and nature of the Si-enrichment that characterizes the Kaapvaal SCLM. Most peridotite xenoliths contain 15–25% orthopyroxene, confirming Si-enrichment of the Venetian SCLM. Mineral major element compositions for 36 peridotitic mantle xenoliths record less melt depletion than inclusions in Venetian diamonds (e.g., olivine Mg# 88.7–93.4; mode 92.5). Olivine Mg# suggest on average ~40% melt extraction and reconstructed whole rock HREE concentrations can be modelled by 20% fractional melting in the garnet stability field followed by ~10 to 13% in the spinel stability field. Calculated Nb/Sr and Ce/Yb ratios for melts in equilibrium with garnet and clinopyroxene suggest that the xenolith suite underwent metasomatism by both hydrous fluids and kimberlite/carbonatite-type melts. Garnet Nd (T_{CHUR}(Nd) = 2.1 Ga) and Hf (T_{CHUR}(Hf) = 1.8 Ga) model ages for one sample with an exclusively hydrous metasomatic character are indistinguishable from previously reported Re–Os ages of Venetian peridotitic and eclogitic diamond inclusions.

Based on a geochemical and isotopic approach, we propose that the Venetian SCLM formed by shallow melting in the Archaean followed by lateral accretion. Hydrous fluids, either associated with remobilisation due to regional heating or subduction, led to metasomatism and possibly to Si-enrichment at ~2.0 Ga before a final stage of metasomatism associated with kimberlite magmatism.

1. Introduction

Archaean cratonic lithosphere is known to extend to depths of ≥200 km. It is characterized by relatively fast seismic velocities implying that it is depleted in Fe and/or cold compared to asthenospheric mantle (James et al., 2001). Extensive studies on mantle xenoliths have revealed that the sub-continental lithospheric mantle (SCLM) underlying cratons is characterized by high degrees of major element depletion compared to fertile lherzolitic mantle (Boyd, 1989; Pearson et al., 2003). Many aspects of SCLM whole rock major element compositions (e.g., high MgO contents) can be modelled by ~40–50% melt depletion (Walter, 2003). The timing of melt depletion of the SCLM beneath the Kaapvaal Craton (a sub-area of the Proto-Kalahari Craton defined by Jacobs et al., 2008) is well constrained by Re-depletion ages (T_{RD}) >2.5 Ga (Carslon et al., 1999; Pearson, 1999), suggesting that the high degrees of partial melting took place in the Archaean. The melting and associated major element depletion resulted in a relatively buoyant SCLM, which is considered to be the major cause for the long-term stability of cratons (Jordan, 1988).

Initial melt depletion was followed by enrichment event(s) as evident from modal and cryptic metasomatism (Grégoire et al., 2003; Griffin et al., 2003). The Kaapvaal Craton is characterized by relatively high Si/Mg in peridotites, but data for the Zimbabwe Craton show low Si/Mg values (Smith et al., this issue). High Si contents in the Kaapvaal SCLM are reflected in high modal abundances of orthopyroxene of up to 40% (Boyd, 1989). Kelemen et al. (1998) proposed that the Si-enrichment resulted from metasomatism by Si-rich melts derived from subducting lithosphere. Among others, Walter (1999) and Simon et al. (2007) confirmed the metasomatic nature of the Si-enrichment, but its timing remains unclear.

The kimberlites from Venetia (Kalahari Craton, South Africa) were emplaced between ~533 Ma and ~519 Ma (Allsopp et al., 1995; Phillips et al., 1999). Venetian mantle xenoliths are thus unaffected by Phanerozoic magmatic events such as the eruption of the majority of Group I and Group II kimberlites and the Cretaceous Karoo flood basalts. Hence, in contrast to other South African kimberlites, mantle xenoliths from Venetia are ideal for unravelling the metasomatic evolution of the SCLM prior to 519 Ma and for determining the regional distribution, and potentially the timing and origin, of Si-enrichment. For this

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purpose, we sampled 550 Venetian mantle xenoliths and a selection of 36 samples was subjected to a combined major and trace element analysis as well as Sm–Nd and Lu–Hf isotope study. Inclusions in diamonds indicate extreme major element depletion of the Venetian SCLM (Viljoen et al., 1999), but diamond inclusion trace element data (Stachel et al., 2004) as well as major and trace element studies on other Venetian mantle xenoliths (Stiefenhofer et al., 1999; Barton and Gerya, 2003) suggest that cryptic metasomatism (silicate melt dominated) has occurred beneath this region of the craton.

2. Geologic setting

The Venetia cluster consists of 15 kimberlite pipes (Tait and Brown, 2008) situated in the Limpopo Mobile Belt, near the South Africa/Zimbabwe/Botswana triple junction (Fig. 1). The Limpopo Mobile Belt adjoins the Zimbabwe and Kaapvaal cratons. It mainly consists of high-grade metamorphic rocks (up to granulite facies) and is commonly subdivided into three zones, namely a Northern Margin, Central Zone and Southern Margin (Cox et al., 1965). Barton et al. (2006) proposed that the Central Zone consists of three amalgamated terrains. The Northern and Southern Margins represent the thrusted margins of the Zimbabwe and Kaapvaal Cratons, respectively. Stabilisation of the area began at 2.7 Ga (Kusky, 1998; Barton et al., 2006; Zeh et al., 2007).

Seismic tomography (James et al., 2001) records seismic velocities underneath the metamorphic crust of the Limpopo Mobile Belt that are comparable to the Kaapvaal and Zimbabwe Cratons. Furthermore, T_{RD} ages of mostly >2.5 Ga (Carslon et al., 1999) confirm an Archaean age for the Venetian SCLM.

3. Methods

Major elements in representative minerals were analysed with a Jeol JXA-8800M microprobe at VU University. An acceleration voltage of 15 kV and a beam current of 25 nA were used. Standards were natural and synthetic minerals and matrix corrections were performed with the ZAF method. Detection limits (99% confidence levels) are below 0.03 wt.% for all analysed oxides and relative uncertainties (1σ) are typically less than 2% for oxides with concentrations ≥1 wt.%. Cores and rims were analysed on five grains per sample where possible.

Trace elements were analysed by laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) using a Geolas 200Q Excimer 193 nm laser system coupled to a Micromass Platform quadrupole ICP-MS at Utrecht University (Mason and Kraan, 2002). The laser was operated at a frequency of 10 Hz with a spot size of 120 μm. Calcium was used for internal calibration and data were corrected for instrumental drift by analysing the external standard NIST SRM-612 after every four or five samples. Accuracy was checked against BCR2-G basaltic glass and data were typically within 10% of the recommended values (Rocholl, 1998). Two to three mineral grains were analysed per sample, but core and rim analyses could rarely be performed due to alteration of the grains.

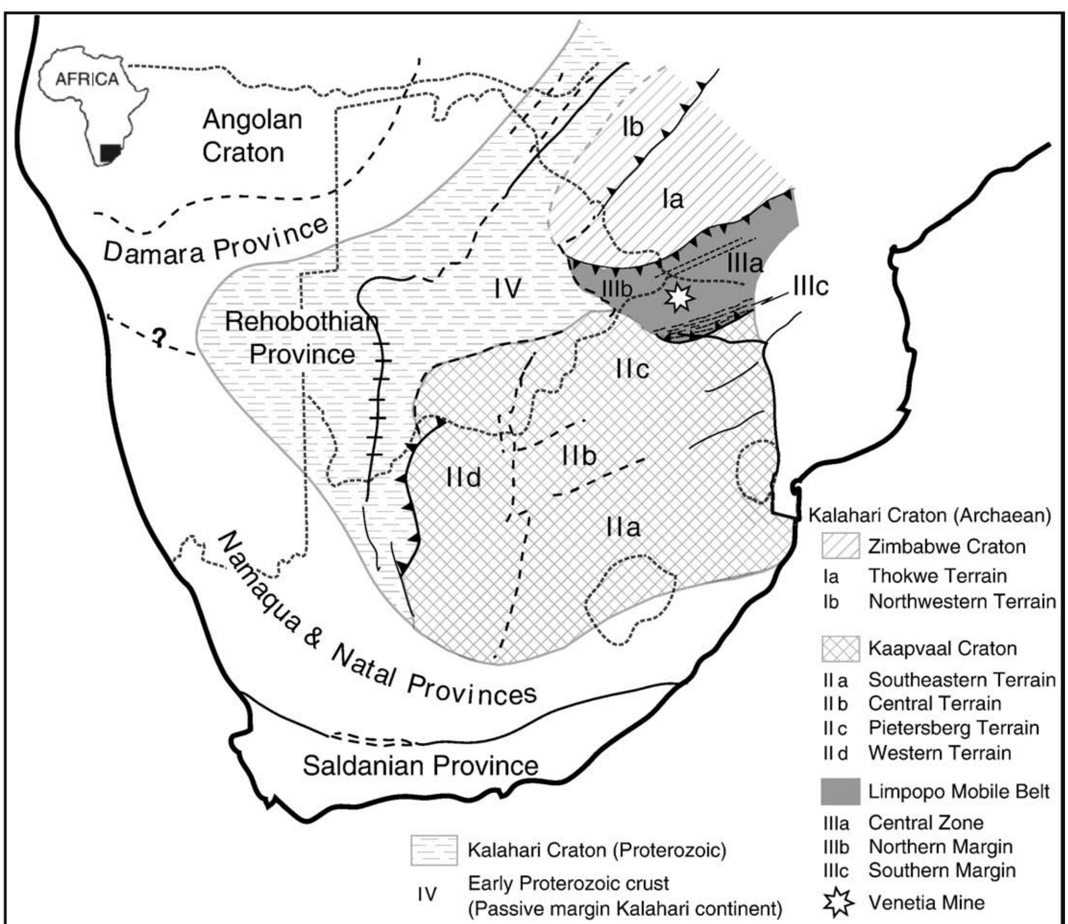

Fig. 1. Simplified geological map of the Kalahari Craton modified after de Wit et al. (1992) and Griffin et al. (2003). Limpopo Mobile Belt (grey) lies between the Kaapvaal (cross hatched) and Zimbabwe (diagonal lines) cratons, all three of which were part of the Proto-Kalahari Craton (Jacobs et al., 2008). The Venetia Diamond Mine (star) is situated in the Central Zone (IIIa) of the Limpopo Mobile Belt, which comprises three micro-continents of Early–Middle Archaean age (Barton et al., 2006).