

Probing the northern Kaapvaal craton root with mantle-derived xenocrysts from the Marsfontein orangeite diatreme, South Africa

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1. Introduction

Kimberlites, orangeites and lamproites define rare potentially diamondiferous igneous rocks of potassic affinity and volatile-rich character. Their parental magmas derive from mantle sources at >150 km depths, implying that they sample a portion of the lithospheric mantle inaccessible to most other magma types. These deep-sourced magmas are known to entrain lithospheric mantle material typically in the form of peridotite and eclogite xenoliths, but more commonly xenocrystic garnet, clinopyroxene and olivine, as well as rare diamond. These mantle-derived xenoliths and xenocrysts provide unique insights into the composition of the Earth's deep interior and invaluable information on the thermal conditions as well as the structure of the lithosphere (Pearson and Wittig, 2014). These mantle xenoliths also provide means of constraining the melt depletion and enrichment processes that shaped the subcontinental lithospheric mantle (SCLM) since Archaean times, allowing us to better understand the architecture of thick and diamond-bearing continental roots.

Kimberlites are widely distributed across different cratons worldwide, and despite their widespread occurrence through time they have relatively homogenous mineralogical and geochemical compositions (Kjarsgaard et al., 2009; Tappe et al., 2018). On the other hand, orangeites have been found to occur only on the Kaapvaal craton as a distinctive variety of lamproite magmatism (Mitchell, 1995). The Kaapvaal craton is also coincident with one of the world's geological marvels, the Bushveld Complex, which has long been believed to have overprinted the lithospheric mantle of the north-central region of the craton. However, the northern segment of the Kaapvaal craton is not as well studied as the mantle sections in the central, southern, and western craton domains, where the majority of historical and active diamond mining is located. As a result, very little is known about the diamondiferous potassic magmas of this region and the lithospheric mantle through which they passed (Smart et al., 2021).

We present the first comprehensive mantle xenocryst study for the diamondiferous Marsfontein orangeite. From a sample set of clinopyroxene and garnet xenocrysts, we analysed trace element compositions by LA-ICP-MS and major element compositions by electron microprobe analysis. These data were used as inputs to the thermobarometer of Nimis & Taylor (2000) and the thermometer of Canil (1999) to estimate the P-T conditions at which clinopyroxene and garnet crystals formed, respectively.

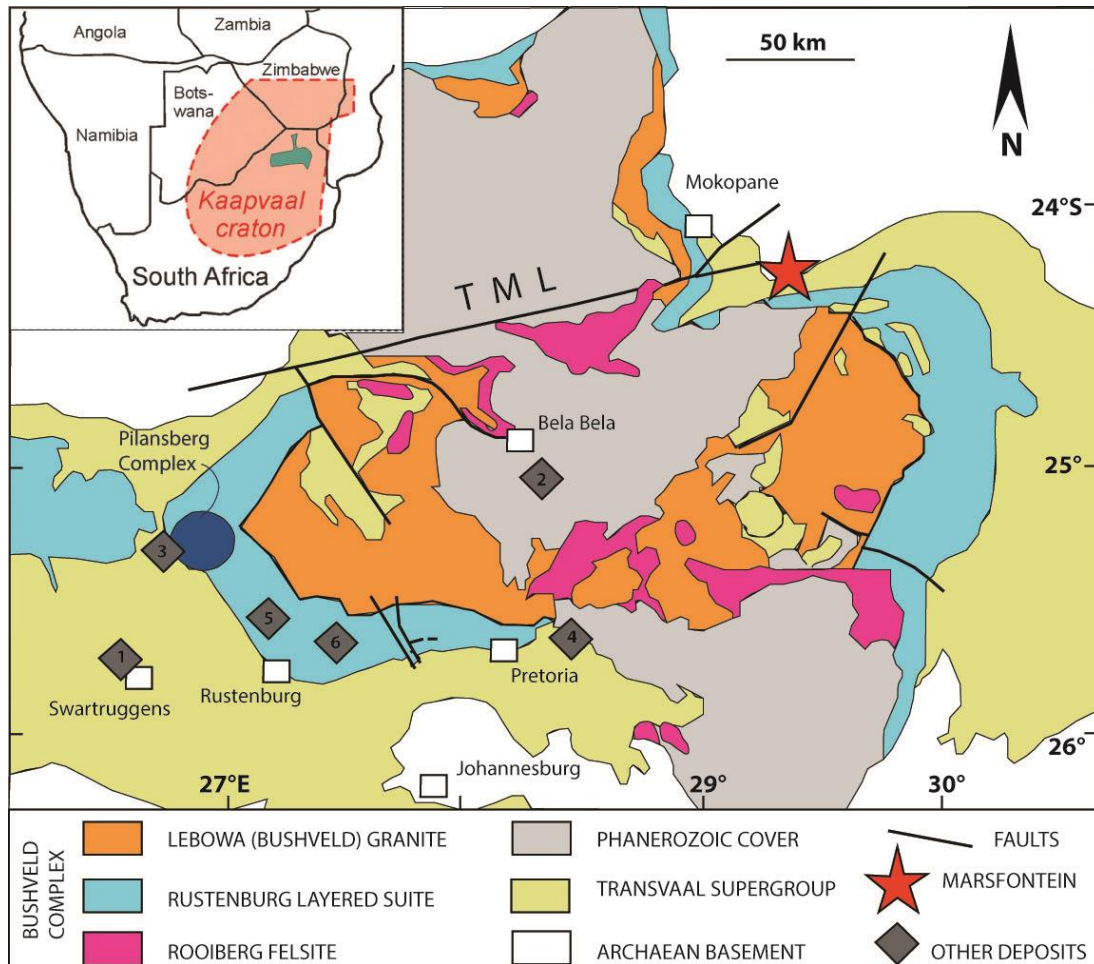


Fig. 1: Geological map of the Bushveld Complex and surrounding areas on the central Kaapvaal craton in South Africa (modified from Tappe et al., 2022). The red star indicates the position of the Marsfontein orangeite occurrence, and the grey diamond symbols indicate loctions of other kimberlites and orangeites in the vicinity of the Bushveld Complex.

2. Background

The Marsfontein orangeite diatreme is located at the northwestern edge of the Kaapvaal craton, approximately 180 km northeast of Cullinan Diamond Mine (craton center) and 200 km southwest of Venetia mine (off-craton in the Limpopo belt) (Fig. 1). The small Marsfontein deposit consists of a 0.5 ha pipe (M1) and a 0.5 m wide dyke (M8). The orangeite has $^{40}\text{Ar}/^{39}\text{Ar}$ phlogopite age of ca. 155 Ma (Tappe et al., 2018), and intruded the Archaean Meinhardskraal granite and a dolerite dyke. The M1 pipe comprises both coherent magmatic and volcanoclastic orangeite varieties. The diamond reserves exploited until 2000 were sourced from the high-grade M1 pipe (1.9 carats per tonne; Tappe et al., 2018), which was overlain by a high-grade surface enrichment zone (Field et al., 2008). For this study, we sampled mineral concentrate from operations that reprocessed the historical M1 and M8 orangeite tailings in 2019.

3. Results

Xenocrystic clinopyroxene classifies as Cr-diopside ($\text{Wo}_{(26-42)}\text{En}_{(35-55)}\text{Fs}_{(1-7)}$), showing Al/Ti trends of >3 . These grains are broadly comparable to clinopyroxene from metasomatized peridotite xenoliths, with Cr_2O_3 ranging between 0.5–2.5 wt.%, while Al_2O_3 and Na_2O range between 1–3 wt.%. Mg# values show a wide range (83–95), with the lower Mg# varieties classifying as low-Cr diopside megacrysts. Normalized REE

patterns evolve along ‘normal’ enrichment trends, with segregation into Group-I and Group-III clinopyroxenes on the basis of Group-III clinopyroxenes evolving along high LREE-enrichment trends. These Group-III clinopyroxenes also show enrichment in LILE (Rb, Ba, Pb) and HFSE (Th, U, Nb, Ta), while negative anomalies are observed for P and Ti for all clinopyroxene grains studied. Xenocrystic garnets have high Mg# values (72–89) and low Ca# values (9–15), and are classified on the basis of their Cr₂O₃ (<1–5 wt.%) and CaO (3–6 wt.%) contents, with G1 grains (low-Cr megacrysts) dominating over G9 grains (Iherzolites), followed by G3 and G4 grains (eclogites and pyroxenites), and a minor population of G10 grains (harzburgites). REE patterns dominantly evolve along ‘normal’ enrichment trends, with subordinate ‘sinusoidal’ trends, which may show LREE depletions. The garnet incompatible trace element systematics suggest multiple episodes of metasomatic overprinting, with evolution of Zr/Hf and Ti/Eu ratios that are consistent with both carbonatite- and silicate-dominated melt enrichment. Elevated Y and Zr contents between 10–30 ppm and 10–80 ppm, respectively, provide evidence for high-temperature melt-induced mantle metasomatism beneath the northern Kaapvaal craton.

Single-grain P-T estimations for clinopyroxene xenocrysts define a 40 mW/m² geotherm for the northern Kaapvaal craton at ca. 155 Ma, with the craton base located at ~215 to 230 km depth (lithosphere–asthenosphere boundary). Ni-in-garnet temperatures were calculated for the peridotite-derived xenocrysts, and these temperatures are projected onto the clinopyroxene-derived regional geotherm. Whereas the garnet xenocrysts are distributed regularly between 40 and 60 kbar, the clinopyroxene xenocrysts appear to cluster in low-PT and high-PT groups, corresponding to the geochemical Group-I and Group-III subdivision, respectively. An apparent lack of clinopyroxene samples occurs between 50 and 55 kbar. We interpret these data to reveal a layered cratonic mantle lithosphere structure, with evidence for enrichment by both carbonated silicate and pure silicate melts.

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