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A sheared ilmenite-dunite xenolith from Lesotho: witness of deformation, metasomatism and perturbation of the lithosphere

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Introduction

Sheared xenoliths from kimberlites record short-lived processes within the lower cratonic, lithospheric mantle shortly before kimberlite eruption. Their bimodal grain size (coarse porphyroclasts vs. fine neoblasts), are testimony to multiple magmatic/metasomatic events within a single sample (Heckel et al. 2022, 2023). Here, we present new major and trace element contents of olivine, orthopyroxene and ilmenite from a highly-deformed, unique ilmenite-dunite from Thaba Putsoa (northern Lesotho). Its connection to sheared peridotite and megacrysts gives insights into the highly dynamic environment in the lower lithospheric mantle beneath the southeast Kaapvaal craton 90 Ma ago.

Petrographic description and chemical composition

The sheared xenolith mainly contains porphyroclasts and neoblasts of olivine with minor amounts of orthopyroxene (opx) and ilmenite neoblasts (Fig. 1). Two different types of olivine porphyroclasts are observed: (i) large 2.5 cm in diameter porphyroclast comparable in size to olivine megacrysts found in kimberlites (Howarth 2018), and (ii) elongated relict clasts (up to 2 mm; Fig. 1b, c) within a fine-grained olivine matrix (grain size ~ 10 – 100 µm).

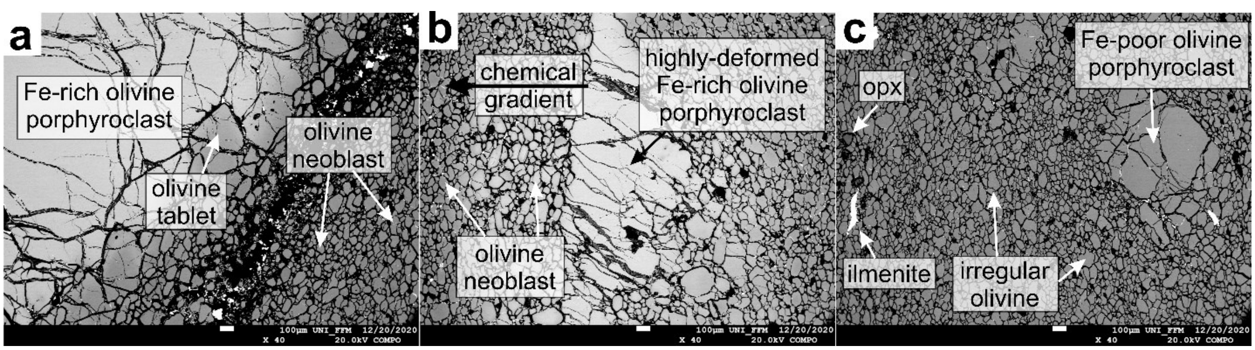

Figure 1: Backscatter-electron images of the sheared ilmenite-dunite BD2104.

The two different types of olivine porphyroclasts vary in their major, minor and trace element compositions and are split into: (i) Fe-poor olivines with Mg# ranging from 85 to 86 and (ii) Fe-rich olivines with Mg# of ~78 (Fig. 2a). The minor and trace element concentrations of Fe-poor olivines are comparable to those from other sheared peridotites, as well as the Cr-, Fe-poor olivine megacrysts found at Monastery (Howarth, 2018). In contrast, the Fe-rich olivine porphyroclasts are enriched in Mn (≤ 1600 µg/g), Zn (≤ 270 µg/g), Ge (≤ 2.6 µg/g) and depleted in Ni (≥ 500 µg/g), Ca (≥ 200 µg/g), Cr (≥ 10 µg/g), Al (≥ 10 µg/g), V (≥ 3 µg/g) and Cu (≥1 µg/g). This composition overlaps with the Cr-poor, Fe-rich olivine suite of megacrysts from Monastery (Howarth, 2018). V/Sc ratios differ between 2.7 to 3.5 (Fe-poor) and 1.1 to 1.6 (Fe-rich). Olivine neoblasts are intermediate in composition between the Fe-poor and -rich olivine porphyroclasts. Ilmenite neoblasts have a variable composition of 40 – 50 wt% TiO_2, 9 – 12 wt% MgO, and a calculated Fe_2O_3 content of 2 – 12 wt%. Orthopyroxene neoblasts have Mg# = 86.5, ~1 wt% CaO and variable Ti, Al and Cr contents.

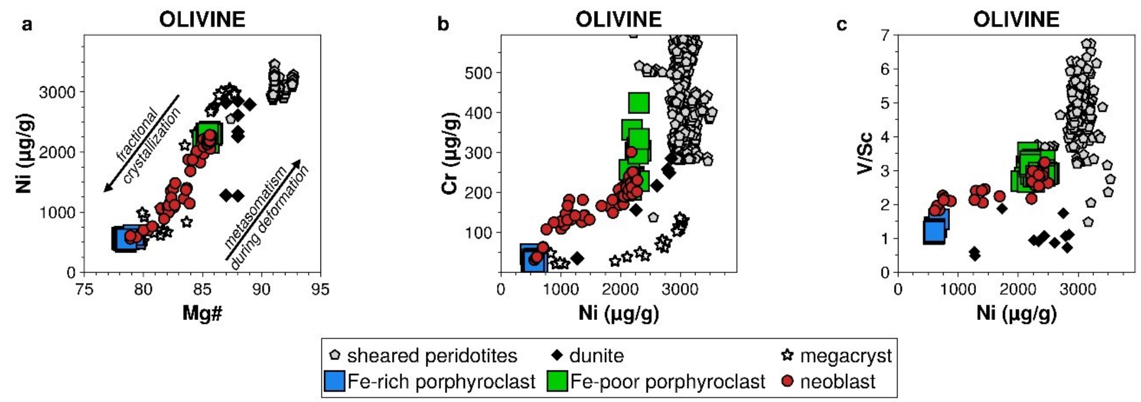

Figure 2: Chemical composition of olivine porphyroclasts and neoblasts. Literature data: Dunite xenoliths (Rehfeldt et al. 2007); sheared peridotites (Smith et al. 1993; Heckel et al. 2023); megacrysts (Bell et al. 2004; Howarth 2018).

Discussion

The olivine porphyroclasts record their original formation process. Similarities in olivine megacrysts (Howarth 2018) and the sheared ilmenite-dunite indicate a related origin (Dawson et al. 1981; Toth and Schulze 2017): Volatile-rich (Bell et al. 2004) proto-kimberlitic melts intruded into the lower lithosphere (shortly) before kimberlite eruption and crystallized megacrysts including olivine (Howarth 2018) (aka porphyroclasts). The different chemical compositions can be explained by fractional crystallization (Howarth 2018), starting with an Fe-poor composition, enriched in Ni, Ca, Al, Cr, Na, Ti, V and Cu. Late-stage crystallization products were enriched in Fe, Mn, Zn (Howarth 2018) and Ge. Decreasing V/Sc from Fe-poor to -rich olivine imply increasing fO_2 and oxidation during crystallization (Mallmann and O'Neill 2013), which is also observed in Fe^{3+} rich ilmenite megacrysts (Gurney and Zweistra 1995).

Olivine neoblasts have higher Mg, Ni, Al and Cr contents (Figs. 1 & 2) compared to the Fe-rich porphyroclast, indicating metasomatism during deformation by a less-fractionated melt. The heterogeneous Fe_2O_3 contents of ilmenite and heterogeneous V/Sc ratios indicate oxidation during deformation. We suggest that a new proto-kimberlitic pulse caused metasomatism and triggered deformation (Heckel et al. 2022, 2023), leading to mechanical mixing of different megacrysts. The chemical trends apparent in Fig. 2 also suggest mechanical mixing between peridotites and megacrysts.

Implications

Megacrysts and sheared peridotites record multiple metasomatic and deformation events (LeCheminant et al. 1998; Heckel et al. 2022, 2023), implying a dynamic mantle environment (Moore and Helmstaedt 2023). Similar to sheared peridotites, the ilmenite-dunite indicates: (i) Proto-kimberlitic melts intruded into the lower lithospheric mantle following weakened (metasomatized) "pathways" and shear zones (Heckel et al. 2023), resulting in an extended melt network where megacrysts crystallize (Nkere et al. 2021). The volatile-rich nature of these events prepares the lithosphere for enabling subsequent kimberlite pulses to reach the surface (Heckel et al. 2022). (ii) Strong metasomatism produced mechanical weakening and destabilization of the lower lithosphere (Heckel et al. 2023). (iii) Interaction with volatile-, Fe-, Ti-rich and oxidative melts will lead to resorption of pre-existing diamonds (Yaxley et al. 2017; Giuliani et al. 2023; Howarth et al. 2023). A (short-lived) metasomatism-deformation cycle (Heckel et al. 2022) has a positive feedback mechanism that progressively effects the lithospheric mantle at times of high magmatic activity. This cycle explains the observation that increasing and long-lived kimberlite magmatism leads to lower diamond grades of kimberlites (Gurney et al. 2010; Giuliani et al. 2023).

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