12TH INTERNATIONAL KIMBERLITE CONFERENCE
30 YEARS OF DIAMONDS IN CANADA
8-12 July 2024 • Yellowknife

12th International Kimberlite Conference Extended Abstract No. 12IKC-039, 2024

# Sheared peridotites: linking deformation and $H_2O$ metasomatism to the onset of craton destabilization

**Catharina Heckel[1,2], Alan B. Woodland[1,2], Sally A. Gibson[3], Jolien Linckens[1,4], Anthony (Tony) C. Withers[5], Hans-Michael Seitz[1,2], Thomas Ludwig[6]**

*1 – Goethe-University Frankfurt, Frankfurt Germany, c.heckel@em.uni-frankfurt.de, woodland@em.uni-frankfurt.de, linckens@em.uni-frankfurt.de, h.m.seitz@em.uni-frankfurt.de*
*2 – Frankfurt Isotope and Element Research Center (FIERCE), Frankfurt, Germany*
*3 – University of Cambridge, Cambridge, United Kingdom, sally@esc.cam.ac.uk*
*4 – Tata Steel R&D, Ijmuiden, The Netherlands*
*5 – Bayerisches Geoinstitut, Bayreuth, Germany, tony.withers@uni-bayreuth.de*
*6 – Ruprechts-Karls-University Heidelberg, Heidelberg, Germany, thomas.ludwig@geow.uni-heidelberg.de*

## Introduction

Kimberlite-hosted sheared peridotite xenoliths have a bimodal grain size consisting of relatively large (mm-sized) porphyroclasts surrounded by fine-grained (< 10 µm to 100s µm) neoblasts (Heckel et al. 2022). These highly-deformed mantle samples provide unique snapshots of the short-lived processes that occur in the cratonic mantle immediately prior to their entrainment and kimberlite emplacement.

We have investigated the olivine fabrics and $H_2O$ contents of porphyroclasts (olivines and pyroxenes) in 22 well-characterized sheared peridotites from Cretaceous kimberlite clusters at Kimberley and northern Lesotho on the Kaapvaal craton. Heckel et al. (2022, 2023) showed that these highly-deformed peridotites consist mainly of olivine, orthopyroxene (opx) ± clinopyroxene (cpx), garnet and spinel and may be classified into three distinct groups: (i) low-*T* formed at 850 – 1000°C and 3 – 4.5 GPa; (ii) moderate-*T* formed at 1200 – 1300°C and 5 – 5.5 GPa; and (iii) high-*T* sheared peridotites that equilibrated at 1350 – 1450°C and 5.5 – 6.5 GPa.

All of the sheared peridotites are geochemically depleted, with Mg# in olivine ranging from 91 to 94 (Fig. 1). An old metasomatic event is preserved in the porphyroclastic cores (olivine, opx, cpx garnet) and trace element signatures indicate a range from fluid (low-, moderate-*T*) to melt metasomatism (low-, moderate-, high-*T*; Figs. 1 & 2). According to the trace element composition of cpx, the low-*T* sheared peridotites were affected by PIC- or MARID-like metasomatic agents. The moderate- and high-*T* sheared peridotites were metasomatized by Cr-rich and Cr-poor megacryst-like melts, respectively (Heckel et al., 2022 & 2023).

The opx and garnet porphyroclasts in the low- and moderate-*T* sheared peridotites have complex zonation with increasing Fe, Ti and HREE contents towards their rims (Fig. 2), indicating multiple metasomatic enrichments before (and during?) deformation. The olivine, opx and cpx neoblasts have complex chemical variations compared to their corresponding porphyroclasts (Fig. 1), which are unique for each sample. The olivine neoblasts in the low-*T* samples have increasing Fe, Mn, Ti, Ca, Al, Cr, Na and decreasing Ni contents. Olivines in the moderate-*T* samples exhibit either increasing or decreasing contents in Ca, Al, Cr, Na and Ti, and high-*T* samples show increases in Ca and decreases or scattering Al, Cr and Na contents.

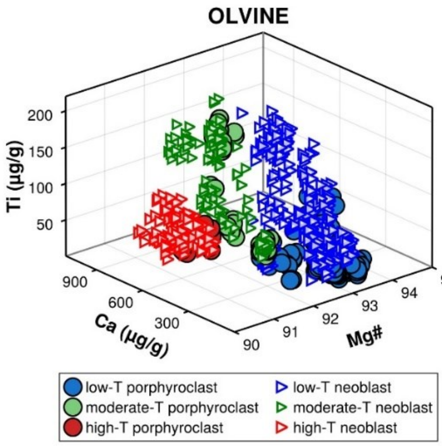


**Figure 1:** Mg#-Ca-Ti plot of olivine porphyroclasts (circle) and neoblasts (triangles) of low-, moderate- and high-*T* sheared peridotites.

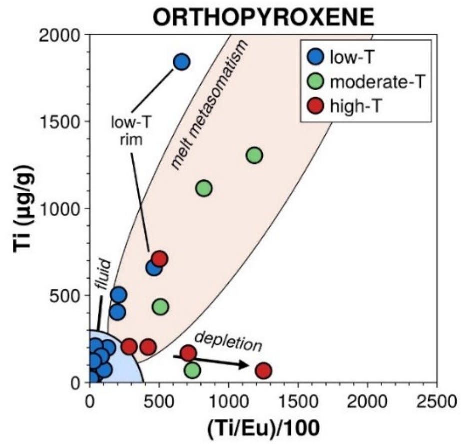


**Figure 2:** Ti-Ti/Eu plot of opx of low-, moderate- and high-*T* sheared peridotites with fields of fluid and melt metasomatism.

## Results and Discussion

Olivine crystal preferred orientations (CPOs) in the low-*T* sheared peridotites are A-, B-, AG- and E-Type, indicating the presence of low to medium $H_2O$ contents during deformation (Jung 2017). In the moderate-*T* sheared peridotites, the olivine fabrics are generally of B-, C- and E-Types, implying medium to high $H_2O$ contents during deformation (Jung 2017). Bimodal fabrics are found in all high-*T* sheared peridotites, which indicates high $H_2O$ concentrations during deformation (C-E-Transition, Wallis et al. 2019). To form bimodal fabrics, $H_2O$ concentrations similar to those in the olivine megacrysts (Bell et al. 2004) are necessary.

Measured $H_2O$ concentrations in olivine porphyroclasts (Fig. 3a) vary from 10 – 80 µg/g (low-*T*), 15 – 45 (moderate-*T*) and <1 – 70 µg/g (high-*T*). Interestingly, these concentrations are either higher (low-*T*) or lower (low-, moderate-, high-*T*) than predicted from the olivine fabrics. $H_2O$ concentrations in opx porphyroclasts (Fig. 3b) range from 100 – 520 µg/g (low-*T*), 140 – 190 µg/g (moderate-*T*) and 100 – 170 µg/g (high-*T*). $H_2O$ concentrations in cpx (Fig. 3c) range from 170 – 320 µg/g (low-*T*), ~140 µg/g (moderate-*T*) and 120 – 200 µg/g (high-*T*). For the Kaapvaal high-*T* sheared peridotites, partition coefficients indicate that the pyroxenes and olivine are not equilibrated (olivine $H_2O$ contents are too low).

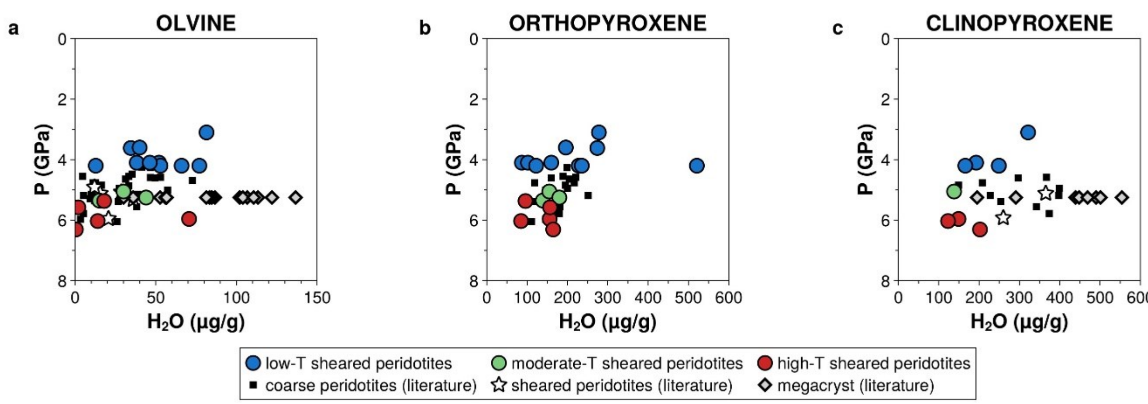


**Figure 3:** $H_2O$-P plot of (a) olivine, (b) opx and (c) cpx of sheared and coarse peridotites from the Kaapvaal craton (this study, Peslier et al. 2017). Megacryst data from Bell et al. (2004).

Once formed, olivine fabrics require high strain to be overprinted, and only slowly reach a steady-state (Boneh and Skemer 2014), and so are able to preserve older deformation conditions (Katayama et al. 2011). The contradicting results between fabric and measured $H_2O$ concentration may therefore indicate different events (pulses of proto-kimberlites) or changing deformation conditions. This means that during deformation, the $H_2O$ concentrations increased (Fig. 4; low-*T*) or decreased (Fig. 4; due to high $CO_2$ activity? – Baptiste et al. 2015; low-, moderate-, high-*T*).

## Implications

We suggest that the infiltration of Cretaceous volatile-rich fluids and melts into the roots of the Kaapvaal craton resulted in multiple metasomatic events coupled with focused deformation, i.e. a short-lived metasomatism-deformation cycle (Heckel et al. 2022). We propose that megacryst-forming magmas triggered the deformation of the moderate- and high-*T* sheared peridotites, resulting in $H_2O$-dependent olivine fabrics and $H_2O$ enrichment in both opx and cpx. Subsequent proto-kimberlite pulses led to the dehydration of olivine and the ascending kimberlites caused shearing of peridotites at lower temperatures and pressures. The resulting rheological weakening may have made this mantle more susceptible to metasomatism and deformation (Heckel et al. 2022) and the deep lithosphere prone to thermal erosion (Heckel et al. 2023). This is consistent with the lithospheric thinning at the southern margin of the Kaapvaal craton observed by seismic tomography (Celli et al. 2020).

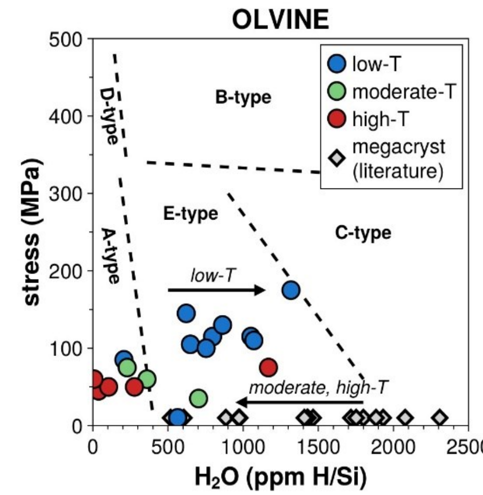


**Figure 4:** Fabric diagram of olivine modified after Jung (2017) and adjusted for Withers et al. (2012) calibration.

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