

Insights in Na-contents of kimberlite melts from experimentally determined partition coefficients between olivine and silicate-carbonate melt

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Introduction

Kimberlite magmas, with their roots deep within the Earth's mantle, offer unique insights into the geodynamic processes that occur in the Earth's interior. An intriguing aspect of kimberlites is their low bulk-rock Na concentrations, markedly lower than other mantle-derived alkaline rocks (e.g., lamproites or lamprophyres). In contrast, other mantle-derived melts, such as primitive mid-ocean ridge basalts, ocean island tholeiites, alkali basalts (all typically 2-3 wt%) to undersaturated alkaline basanites (3-5 wt%) display considerably higher sodium contents (de Paepe et al., 1974; Schilling et al., 1983; Winter, 2001). The enigma of the low sodium content in kimberlites is fundamental to understanding their genesis. An almost Na-free melt implies a Na-free source rock, which seems incongruous with the highly calcic composition of kimberlites requiring a clinopyroxene-bearing source (Stamm & Schmidt, 2017; Giuliani et al., 2023). This study aims to reconcile this contradiction and shed new light on the sodium puzzle in kimberlite petrogenesis by constraining Na-partitioning between olivine and silicate-carbonate (kimberlite) melts.

Experimental approach

Experiments were conducted in a ¾" piston-cylinder apparatus using kimberlite melt compositions as starting materials at 1-3 GPa, 1100-1350°C, and f_{O_2} close to the CCO buffer, representing likely conditions of initial kimberlite crystallization during ascent. Experimental phases and quenched melt were measured by EPMA and LA-ICP-MS to determine mineral-melt partition coefficients. The experimentally determined minor and trace-element partition coefficients between olivine and silico-carbonatitic equilibrium melt were then applied to several natural kimberlite samples for which olivine data have been previously determined (Howarth et al., 2022) as well as additional seven localities (Diavik, Gahcho Kué, Majuagaa, Karowe, Wesselton and Letšeng-la-Terae) examined in this study.

Experimental results

In the experiments at 3 GPa, olivine and spinel crystallize at 1300°C, clinopyroxene at 1250°C, while apatite + perovskite + phlogopite are stable at 1150°C. In the experiments at 1 GPa, clinopyroxene is not a stable phase. Olivine is the most abundant phase across all experiments. The silicate-carbonate melt consists of quench phases smaller than 5 µm, and its composition shows a decrease in SiO₂, FeO_T, and MgO with decreasing temperature, while CaO, total volatiles, and alkalis (Na₂O and K₂O) increase. The melt composition of our experiments does not correspond to the primary melt composition of kimberlites due to the lower pressure (1-3 GPa), literature data from carbonated peridotite melting indicates pressures of 5 – 10 GPa for kimberlitic melts.

As a moderately incompatible element, the partition coefficients of Na between olivine and melt vary little during olivine crystallization at the examined temperature conditions but show a marked pressure. Our determined Na partition coefficients ($D_{Na}^{ol-melt}$) range from 0.008 to 0.017, with a median value of 0.012 at 3 GPa, and range between 0.002 and 0.003, with a median 0.0025 at 1 GPa (Figure 1).

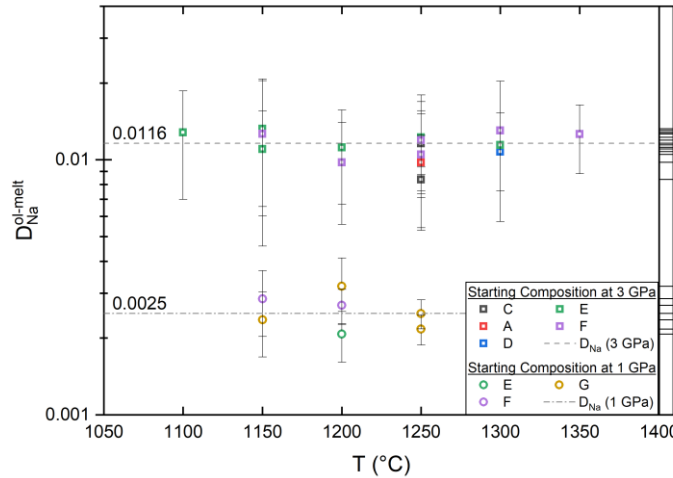


Figure 1: Olivine-melt partition coefficient of Na as a function of temperature. Error bars represent one standard deviation.

Implications for Na contents in kimberlite melts

The pressure at which olivine crystallizes in natural kimberlites is unknown, however, Fedortchouk & Canil (2004) propose a pressure <2 GPa, and Brett et al. (2015) constrain olivine saturation at pressures <1 GPa. Therefore, we here employ the median value of the olivine-melt partition coefficient for Na calculated at 1 GPa. The application of this $D_{Na}^{ol-melt}$ to magmatic olivine in natural kimberlite samples provides Na₂O contents of 1.9 to 8.0 wt.% in primary kimberlite melts with a median value of 4.2 ± 1.7 wt.% (n = 22 localities, Figure 2). A decrease in Na₂O can be observed in rinds of olivines with a median value of 3.41 wt.% Na₂O (n=3); however, the data is limited and exhibits a wide scatter, indicating a decrease in Na₂O concentration in the melt during kimberlite ascent.

A broad inverse correlation between Mg# in olivine and calculated Na contents in the melt suggests that Na₂O contents in the melt increase with increasing FeO, the latter previously attributed to increasing contribution by assimilation of metasomatized lithospheric mantle rocks (Giuliani et al., 2020; Howarth et al., 2022). This work indicates that kimberlite melts contain substantially more Na than observed in kimberlite rocks (<0.4 wt.%; Figure 2), which is broadly consistent with (i) previous studies of melt inclusions in kimberlites (e.g., Kamenetsky et al., 2009) and (ii) equilibration with typical mantle clinopyroxene in the source (Giuliani et al., 2023).

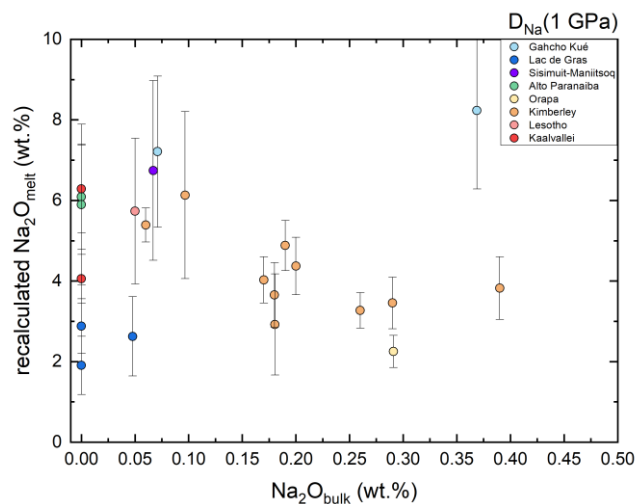


Figure 2: Recalculated bulk Na₂O of the melt as a function of Na₂O in bulk rock composition. Error bars reflect one standard deviation.

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