Quantifying the melting conditions of Archean cratonic peridotites

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Introduction

The sub-cratonic lithospheric mantle (SCLM) constitutes the deep ultramafic cores of continents that are produced by high degrees of melting. However, the depth and setting at which the SCLM experienced melt separation is argued to have occurred at both low or high pressure. In depleted cratonic peridotites, aluminous orthopyroxene is a typical residual phase after melting at any pressure. At the present-day most primary indicators of the original melting regime within mantle xenoliths are generally obscured by secondary processes e.g., silica enrichment and/or metasomatism. At depths within the present-day spinel field, secular cooling of the lithosphere since its formation caused these components to unmix, forming spinel ± clinopyroxene exsolution lamellae within an orthopyroxene host. This study focuses on a selection of spinel-harzburgite xenoliths from the 84 Ma Kimberly kimberlite, Kaapvaal craton, and will use thermodynamic modelling to constrain (a) equilibration conditions of the exsolved phase assemblage; and (b) the formation conditions of reconstructed precursor orthopyroxene.

Sample description

The spinel harzburgites are orthopyroxene rich and have coarse-grained textures. Based on orthopyroxene appearance, they broadly classify into bronzite-type ($n= 6$) or normal-type peridotite ($n= 7$). Bronzite orthopyroxenes appear blocky to irregular-elongate with phlogopite-amphibole rims, and with spinel ± clinopyroxene exsolution lamellae. Conversely, exsolutions in blocky, euhedral-anhedral orthopyroxene from normal-type peridotites are mostly absent. Olivine from both sample types are serpentinized along fractures and have tiny spinel exsolutions. Symplectites (up to 3% mode) comprising spinel/pyroxene were observed, nearly always in a 1:4 abundance ratio. Here, we pay a special focus on bronzite-type sample 13CLA066.
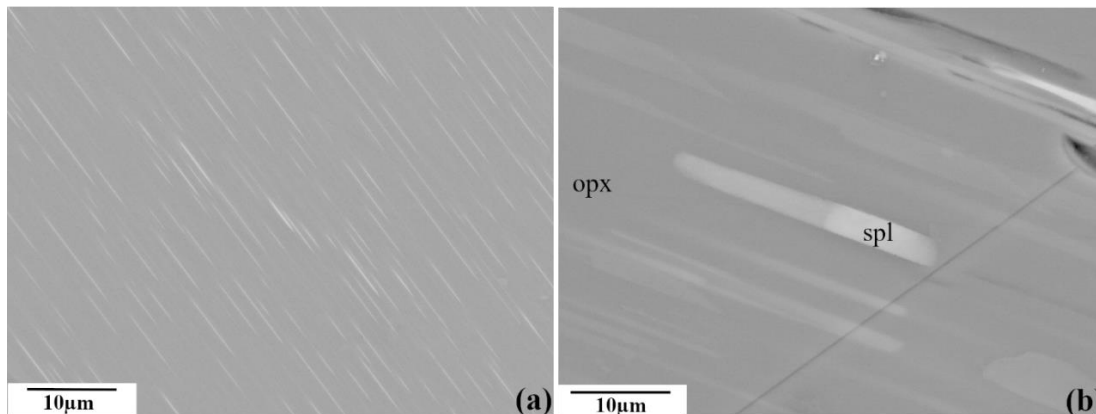

Fig. 1. BSE images of exsolved orthopyroxene. (a) Thin and parallel lamellae in orthopyroxene host. (b) Spinel is intergrown with non-stoichiometric garnet.

Orthopyroxene exsolution textures in 13CLA066

Bronzite-type orthopyroxenes contain variable sized (<0.5 to 4µm) spinel/clinopyroxene lamellae (Fig. 1). Exsolutions typically become larger and cluster along grain defects. Spinel is commonly intergrown (side-by-side or end-to-end) with clinopyroxene that sometimes resembles non-stoichiometric garnet (Fig. 1b).

Analytical results

Olivine compositions for all bronzite ($X_{Mg} = 0.921$-0.930) and normal-type peridotites ($X_{Mg} = 0.928$-0.936) are refractory. Bronzite post-exsolution orthopyroxenes i.e., $Wo_{0.3-1.2}En_{91.7-92.9}Fe_{6.7-7.1}$ and normal-type orthopyroxenes i.e., $Wo_{1.2-.17}En_{91.7-92.5}Fe_{6.2-6.6}$, have uniform enstatite compositions within a given sample. Exsolutions of clinopyroxene are Cr-diopsides. Spinel exsolutions display a large compositional range across all samples ($X_{Cr} = 0.31$-0.82, $X_{Mg} = 0.44$-0.72). Relative to the exsolved orthopyroxene e.g., sample 13CLA066 with 2.35 wt. % Al_2O_3, 0.59 wt. % Cr_2O_3 and 0.61 wt. % CaO, reconstructed precursor orthopyroxene compositions yield higher Al_2O_3 (2.90 wt. %), Cr_2O_3 (0.87 wt. %), and CaO (0.94 wt. %). Symplectite spinels are predominantly magnesiochromites ($X_{Cr} = 0.50$-0.86, $X_{Mg} = 0.46$-0.64), whilst clinopyroxene domains are Cr-diopsides that vary within error with the co-existing exsolved clinopyroxene. Rare orthopyroxene in symplectites is sub-calcic and Al-depleted relative to granular co-existing orthopyroxene. The high X_{Mg} in symplectite clinopyroxenes indicates equilibrium with other primary silicates and that they crystallized around the time of melting, which is why they were considered as part of the model bulk rock composition for phase equilibria modelling (below). However, given an alternate scenario where symplectites are considerably late secondary features i.e., added at sub-solidus conditions, we tested an appropriate model bulk rock composition of only precursor orthopyroxene and olivine which is comparatively Al-, Ca- and Cr-poor.

Phase equilibria modelling

P-T pseudosections were calculated in the system NCFMASTOCr (Tomlinson and Holland, 2021), and a representative sample 13CLA066 is described here (Fig. 2). Sub-solidus phase relations are characterized by a garnet-in boundary that extends to relatively low-P at low-T, and below this is a notable olivine-orthopyroxene field. Along a cooling trajectory within the olivine-orthopyroxene field, spinel and clinopyroxene are predicted to form at 900-1200 ºC. The pseudosection broadly illustrates that spinel stabilizes before clinopyroxene during cooling at relatively higher pressure, whilst the opposite order of exsolution may occur at pressures <20 kbar. The stability field corresponding to the phase assemblage (ol-opx-cpx-spl) of 13CLA066 is located at low P-T conditions. The exsolved orthopyroxene composition isopleths (Al = 0.0947, Cr = 0.0161, Ca = 0.0223 and Fe = 0.0649) suggest an estimated equilibration condition around 21 kbar and 750-800°C. The reconstructed precursor orthopyroxene yielded the following measured compositional variables: Al = 0.117, Cr = 0.0236, Ca = 0.0346 and Fe = 0.0512. Between 10-40 kbar along the solidus, Al, Cr and Ca variables have constant values nearly equal to the samples measured variables i.e., 0.118, 0.0286, 0.0342-0.0357, respectively. Only the Fe variable shows greater sensitivity as it ranges from 0.0642-0.0542. Despite this, all measured precursor variables intersect the solidus between 48-52 kbar and 1720-1750 °C.

Discussion

Current uncertainties with the THERMOCALC model withstanding, sub-solidus re-equilibration to low P-T conditions (as supported by exsolution phenomena) in sample 13CLA066 is constrained by the intersection of exsolved orthopyroxene composition isopleths at 750-800 °C and ~21 kbar (Fig. 2, open star). However, the Ca isopleth is displaced a bit to higher temperature/Ca-contents than predicted at the equilibration crossover, which indicates incomplete exsolution of Ca in orthopyroxene towards
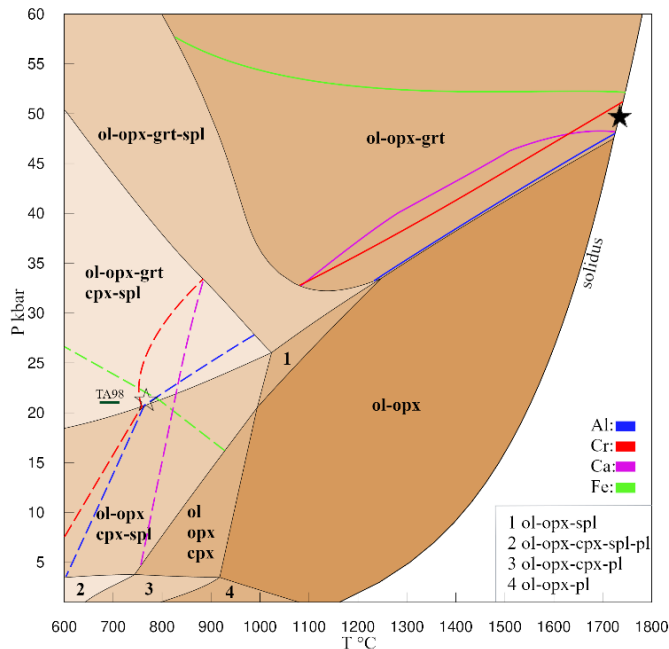
Fig. 2. 13CLA066 P-T pseudosection contoured with orthopyroxene reconstructed (solid) and exsolved (dashed) composition isopleths.

equilibration. This is consistent with clinopyroxene exsolving late while spinel exsolved earlier. Therefore, this precludes entering the spinel stability field from <20 kbar during cooling from the formation condition (Fig. 2). Constraining P-T conditions with this approach requires only whole rock and orthopyroxene composition. This is advantageous for low-T spinel peridotites that have attained equilibrium outside the high temperature calibration ranges of the limited spinel-peridotite thermometers. In this case, the resolved pressure was used as a preset parameter to get an equilibration condition using two-pyroxene solvus thermometry (Taylor, 1998). Exsolved orthopyroxene paired with adjacent clinopyroxene from exsolutions or symplectite result in temperatures that are slightly lower (670-710 °C).

In contrast, the focal point of the precursor orthopyroxene composition isopleths indicates that the SCLM experienced its final melt separation at ~50 kbar, 1720-1750 °C, a condition we infer as the orthopyroxene formation depth (Fig. 2, filled star). The high temperature is corroborated texturally by the presence of spinel exsolutions in olivine. Although the findings of this study are derived from spinel harzburgites, they agree well with a similar work applied to exsolved garnet peridotites from the same location e.g., Tomlinson & Holland (2021). However, we apply caution to our interpretation of the model since orthopyroxene composition variables along the low-pressure part of the solidus are nearly equal to the measured orthopyroxene variables. The Cr and Fe isopleths were the most effective to discriminate formation depth in this case. From the positions of the formation and equilibration points in the P-T space, we envision that orthopyroxene formed at relatively high pressure and underwent ascent to shallower depths sometime between formation and equilibration. This P-T change is analogous with an evolution by lithospheric thinning and uplift.

Another possibility is that after final melting the residue experienced buoyancy and an incoming plume-push from below, initiating a simultaneous sub-solidus decompression and slow cooling on approach to accrete beneath a nascent continental crust. After solidification, rapid cooling in the spinel stability field resulted in a chemical freeze corresponding to the then prevailing Archean geotherm, thus the cool, shallow spinel peridotites did not equilibrate to the 35-40 mW/m^2 geotherm operating when the Cretaceous Kimberly cluster erupted. This study demonstrates the value of samples containing unequivocal textural evidence of exsolution for unravelling the cooling path and formation conditions of cratonic peridotites.

References

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