

Revisiting the origin of Cr in cratonic peridotite

Emma L. Tomlinson

Geology, School of Natural Sciences, Trinity College Dublin, Ireland, tomlinse@tcd.ie

Introduction

The Archaean sub-cratonic lithosphere has uniformly high bulk Mg# (>92) and is widely considered to have formed during extensive and protracted mantle melting, which left a residue of olivine + orthopyroxene ± garnet. The Archaean lithosphere subsequently cooled from its solidus to the modern geotherm, a drop of 300-600°C. Additionally, parts of the lithospheric mantle may also have undergone a change in pressure e.g., during compressional thickening. At high temperature (e.g. at the peridotite solidus), orthopyroxene can accommodate higher concentrations of Al, Cr and Ca than it can at lower temperatures, therefore cooling and subsolidus re-equilibration cause Al-rich orthopyroxene to unmix to form relatively Al-poor orthopyroxene and garnet at pressures greater than 2 GPa. The extent to which subsolidus re-equilibration contributed to the overall abundance of garnet observed in Archaean peridotites is poorly constrained. If a depleted peridotite formed by melting in the spinel facies, or in the deeper mantle after garnet exhaustion, all garnet now present may have formed by unmixing of Al-rich orthopyroxene ± spinel breakdown. However, if a depleted peridotite formed by melting in the garnet facies, then the observed garnet represents the sum of residual garnet and garnet formed during subsolidus re-equilibration.

Pyroxene typically has higher Cr-numbers ($Cr\# = 100Cr/[Cr+Al]$ mol.) than garnet, therefore the presence and abundance of garnet in the melting residue has implications for the Cr-Al composition of peridotitic xenoliths. Cratonic peridotites are characterised by Cr-rich, Al-poor bulk compositions, and pyrope found in peridotite xenoliths and as inclusions in diamond typically have Cr# values of 10-40, occasionally reaching 60 in diamond inclusions. High Cr# is commonly attributed to melting in the absence of garnet and hence suggestive of a shallow origin. However, low Al₂O₃ may also reflect high pressure melting after garnet exhaustion. Here, we revisit the Cr-Al systematics of peridotite during progressive melting and investigate the constraints that Cr# places on the depth of melting of cratonic peridotites.

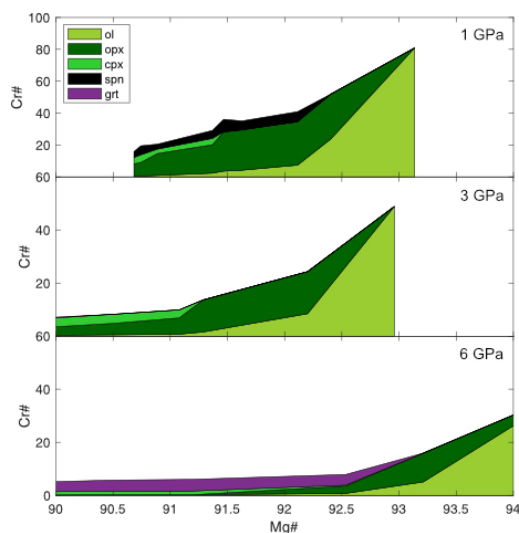


Figure 1: Evolution of bulk residue Cr# during experimental batch melting of peridotite. Data from Baker and Stolper (1994), Walter (1998) and Falloon et al. (1999), note that the MM3 starting composition used at 1 GPa is more Cr-rich ($Cr\# = 10$), than the KR4003 composition used at 3 and 6 GPa ($Cr\# = 6$). The higher Cr-content of the MM3 system stabilises spinel to higher melt fraction and increases the Cr# of mineral phases, as reflected in the y-axis scale. Phase contributions are calculated from molar composition as $Proportion_{phase} \times (Cr_{phase} + Al_{phase})$ normalised to Cr# of whole rock.

Results

The behaviour of Cr and Al during partial melting of peridotite can be demonstrated from experiments (Fig. 1). At low pressure, pyroxene is the main host of Cr and Al at the solidus; spinel is only a subordinate host that, despite its low abundances, does further increases the bulk Cr# until its exhaustion at ~20% melting. At higher pressure, garnet is the principal host of Al and Cr at the solidus and bulk Cr# is initially low, but Cr# increases markedly once garnet is exhausted and pyroxene becomes the main host of Al and Cr. As melting continues Cr# increases further as orthopyroxene is consumed and olivine becomes the principal host of Al and Cr. The degree of melting at which garnet and orthopyroxene are exhausted increases with pressure, therefore the Mg# at which a given Cr# is achieved increases with pressure. This relationship provides a framework for interpreting the pressure of peridotite melting (Fig. 2a).

Garnet harzburgites from Kimberley (Kaapvaal craton) have high Mg# plotting between the experimental trends for melting at 5 to 7 GPa (Fig. 2a). The samples span a range of Cr#, most sit in the orthopyroxene + olivine field, however, samples with the lowest Cr# plot within the garnet-bearing field in Cr# - Mg# space, suggesting that these peridotites had garnet in their melting residues. Heavy Rare Earth Elements (HREE) provide an independent tool to assess the presence or absence of garnet in the melting residue. Both garnet and orthopyroxene show a strong preference for HREE over the medium and light REE, however HREE partition coefficients are approximately two orders of magnitude higher in garnet than in orthopyroxene. Whole rock compositions of garnet harzburgites from Kimberley were calculated from the compositions and abundances of the constituent phases, they have uniformly low HREE concentrations at Cr# >12, but HREE contents increase sharply at lower Cr# consistent with the presence of garnet in the residue (Fig. 2b). It is notable that the HREE-rich samples are the same samples that are predicted to have had garnet in the melting residue on the basis of their Cr# - Mg# systematics.

For the studied Kimberley garnet harzburgites, only samples with observed garnet contents of >5 vol.% are predicted to have had garnet in their melting residues on the basis of their Cr# - Mg# and HREE systematics. This result is supported by thermodynamic modelling in the system NCFMASTOCr (Fig. 3). Pressure-temperature pseudosections for samples with Cr# > 12 do not have garnet at their solidi, meaning that all garnet present in these compositions must have formed during sub-solidus re-equilibration. By contrast, samples with low Cr#, a result of higher Al₂O₃, do have garnet at their solidi and their garnet contents were increased during sub-solidus re-equilibration.

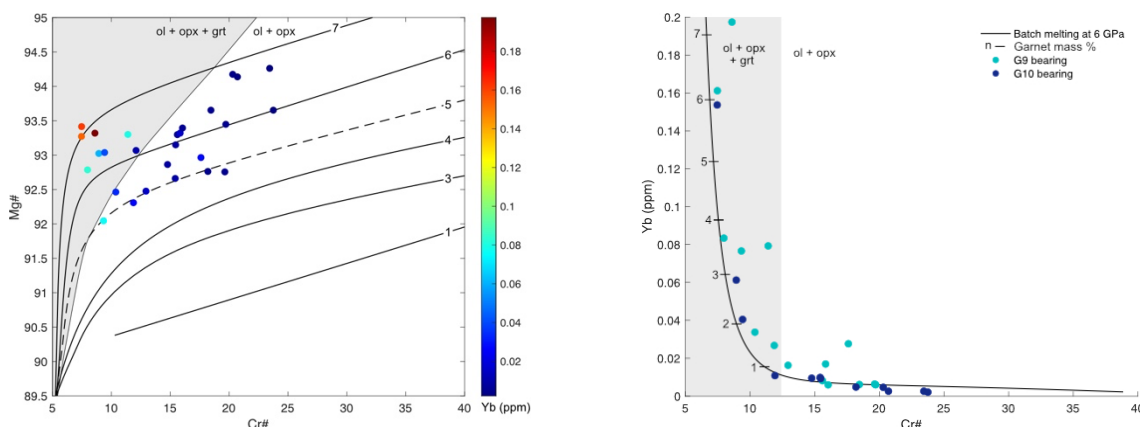


Figure 2: Whole rock Cr#, Mg# and Yb compositions of garnet harzburgites from Kimberley compared to: (a) Evolution of Cr# and Mg# during experimental batch melting of fertile peridotite, curves fit experimental data at 1 GPa (Baker and Stolper 1994; Falloon et al. 1999) and 3-7 GPa (Walter 1998, Melai unpublished); the 5 GPa curve is derived by interpolation. (b) Yb content of the residue after batch melting of primitive mantle was calculated using phase abundances in the 6 GPa experiments of Walter (1998) and partition coefficients from Sun and Liang (2013). Both plots are annotated to indicate the garnet-bearing field in experimental batch melting residues.

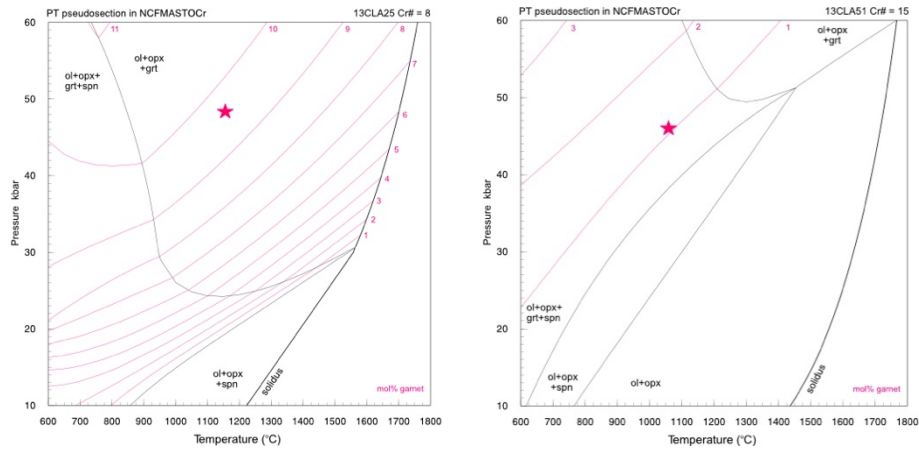


Figure 3: Pseudosections calculated for whole rock compositions of: (a) low Cr#, HREE-rich; and (b) high Cr#, HREE-poor garnet harzburgites from Kimberley in the system NCFMASTOCr using the model of Tomlinson and Holland (2021). Contours show the mass percent of garnet. Stars mark the conditions of equilibration.

Discussion

Bulk major (pseudosections) and trace (HREE) element compositions of low Cr# garnet harzburgites from Kimberley are consistent with their formation by garnet facies melting. For garnet to have persisted to such high Mg# requires that melting occurred at high pressures of 5-7 GPa. The abundance of garnet in these samples is unlikely to be due to later garnet addition as garnets from similar Cr-poor, HREE rich harzburgites from the same location have highly depleted Hf isotope compositions and Archaean depletion Hf T_{DM} ages (Branchetti et al. 2021). High Cr# (12-25) garnet harzburgites have low HREE contents consistent with the absence of garnet, however these are also considered to have formed at high pressures because their Mg-numbers are too high for their Cr# values to have been generated by low pressure melting.

The relationship between Mg#, a proxy for the degree of melting, and Cr#, a proxy for the presence of residual garnet, provides a tool for investigating melting depth. Applying this relationship to harzburgites from global locations suggest that melting took place over 1 to 6 GPa, with inferred melting depths for some locations being relatively shallow (e.g. Greenland 1-3 GPa) and others deeper (Tanzania, 3-6 GPa). Very few samples fall in the garnet field in figure 2a, suggesting that most garnet in peridotite xenoliths formed by solid state re-equilibration during cooling. For these samples, the bulk Cr# and trace element compositions (prior to secondary processes such as metasomatism) are controlled by the solidus phases orthopyroxene and olivine, this signature is then passed onto garnet upon its formation by exsolution from orthopyroxene. A key takeaway is that high Cr# is due to melting in the absence of garnet but does not necessarily indicate shallow melting, a Cr-rich xenolith or diamond inclusion may have formed at high pressure if high Cr# is accompanied by high Mg#.

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