Phosphorus and other trace elements from secondary olivine in composite mantle xenoliths (CMX) from Cima Volcanic Field (CVF; California, USA): implications for crystal growth kinetics

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Phosphorus(P)-rich zones in olivine may reflect excess incorporation of P during rapid growth; zoning patterns may then record growth rate variations (Milman-Barris *et al.*, 2008; Stolper *et al.*, 2009). We report data on interior cuts of two CMX from alkali basalt flows (Mukasa & Wilshire, 1997) in the CVF with second-generation P-rich olivines.

In *Ci-1-196*, a dark layer ($\sim$200 μm wide) between lherzolite and websterite is interpreted as a rapidly crystallized melt layer (ML), consisting of Ol+Gl+Pl+Spl+Cpx+Ap+Ilm. *Glass* ($\sim$15 vol%) is variable in composition ($P_2O_5 \leq$1.2 wt%, Li 8.22-20.0 ppm). *Olivines* in the layer have 0.03-0.62 wt% P_2O_5; P-rich Ol ($P_2O_5 >$0.1 wt%) are $Fo_{85-89.3}$. The lowest P concentrations are consistent with equilibrium with liquid parental to Gl, but the higher concentrations are not. Li concentrations, zoned from 3.84 to 4.90 ppm (core-rim), indicate equilibrium incorporation during crystal growth from a small, evolving melt pool and preservation of this rapidly relaxing gradient. REEs are mostly consistent with equilibrium growth from liquids evolving towards the observed LREE-enriched glass. Most of the *clinopyroxenes* are diopsides with some augites. *Apatite* inclusions occur in the rim of P-rich Fo_{85} and in An_{54}.

In *Ki-5-301*, a dark-coloured area of irregular shape ($\sim$200 μm wide) is present along the contact between lherzolite and orthopyroxenite, consisting of Ol+Pl+Gl+Cpx+Spl+Ilm+Ap. It resembles a tabular dyke but is connected to melt-patches infiltrating the host rock. Widespread Glass in the layer has variable composition with two populations not related by fractional crystallization: 1) P_2O_5 1.02-1.09 wt% and 2) P_2O_5 1.62-2.35 wt% (a Gl inclusion in Ol has P_2O_5 3.57 wt% may have captured melt from the P-rich boundary layer at the interface with the rapidly growing olivine). REEs cluster in the same two groups. Li is as low as 3.66 ppm group 1 and 3-4$\times$ higher (9.64-13.3 ppm) in group 2. *Olivine* occurs as small idiomorphic crystals embedded in Gl and as large ($\sim$100 μm) idiomorphic to hypidiomorphic crystals with Gl and Spl inclusions; Mg# ranges from $Fo_{74.5}$ (rim in contact with Gl) to $Fo_{90.3}$; P_2O_5 reaches 3.5 wt% (in a $\sim Fo_{84}$ rim); Li varies from 2.80 (core) to 6.35 ppm (rim). *Clinopyroxene* ($Wo_{41-43}En_{50-54}Fs_{5-8}$; P_2O_5 0.04-0.08 wt%; Li 3.33 ppm) is found both within the ML and as a reaction product between melt and matrix Opx. Trace element geochemistry shows possible equilibrium with ML glass for some elements, but clear disequilibrium for others. *Apatite* occurs as large ($\sim$100 μm) crystals in contact with Ol or Gl, as near-rim inclusions in P-rich Fo_{84} and as tiny prismatic crystals in Gl; REEs show slight negative Eu anomalies (Eu/Eu*=0.79-0.86) due to prior crystallization of plagioclase.

High-resolution X-ray mapping of P in Ol from Ci-1-196 reveals 3-7 μm wide P-rich bands parallel to facets. P_2O_5 correlates negatively with Si and Mg+Fe+Ca, suggesting a substitution $Mg_2SiO_4 + \frac{1}{2} P_2O_5 \rightarrow Mg_{1.5}[]_{0.5}PO_4 + \frac{1}{2}MgO+SiO_2$. P-Al-rich areas may grow in minutes, whereas P-Al-poor over few weeks (Jambon *et al.*, 1992). At such rates, dendritic growth (Welsch *et al.*, 2014) implies that core to rim zoning may not be simple growth stratigraphy. A slight correlation between P and Al in our data implies either diffusive relaxation of Al gradients or, judging by dynamic experiments (Grant & Kohn, 2013), cooling rates >10°C/h that generate disequilibrium solute trapping of P but near-equilibrium incorporation of Al.

The petrogenetic history following melt intrusion requires rapid cooling and reaction with matrix minerals and crystallization sequence Ol→Cpx→Pl→Ap→Fe-Ox→quench of Gl. P and Li concentrations set upper and lower limits on growth rates after intrusion of melt into CVF xenoliths. Early-crystallized olivine grew rapidly enough that sluggish P became over-enriched but not so fast as to over-enrich other elements. Cpx formed later either as neoblasts or reaction rims in which P was homogeneous (Baziotis *et al.* 2014) and growth was slower compared to Ol but fast enough to preserve the Li zoning. Li diffuses in Ol a factor of 3 faster than Mg-Fe (Qian *et al.*, 2010) and hence sets a lower limit on time from Ol growth to eruption.