# MAGMATIC COOLING HISTORY OF TROCTOLITE 76535 CONSTRAINED BY DIFFUSION MODELING OF OLIVINE AND PLAGIOCLASE COMPOSITIONAL ZONATION.

J.E. Hammer[1], T. Shea[1], G.J. Taylor[1,2], E. Hellebrand[1], and B. Welsch[1], [1]Dept. Geology and Geophysics, Univ. Hawaii; Honolulu, HI, USA (jhammer@hawaii.edu), [2]Hawaii Institute of Geophysics and Planetology, Univ. Hawaii, Honolulu, HI USA.

**Introduction:** Reconciling the paradoxical combination of primitive and highly evolved chemical attributes of the lunar Mg-suite has sustained decades of debate about mantle processes [1–4] during and after formation of the moon's major silicate reservoirs. Models must explain the unique chemical characteristics of the Mg-suite, satisfy phase equilibrium constraints imposed by the major element compositions of these rocks, and accommodate the heat budget associated with melting cumulate source materials. Most of the petrographic analysis on Mg-suite rocks in general, and troctolite 76535 (a cumulate of igneous origin with the texture of a high-grade metamorphic rock) in particular, have focused on low-temperature processes preserved in recrystallized or late-forming phases. In this study, we are extracting temporal constraints on the primary igneous history of 76535 using subtle compositional zonation inherited during initial growth of early-formed igneous mineral grains.

**Petrographic and isotopic constraints on cooling history:** The low-temperature portion of 76535's cooling history has been addressed using multiple approaches yielding nuanced results. The "annealed" texture of the plagioclase supports the initial characterization of 76535 as deep-seated intrusive rock perhaps requiring $10^8$ years to fully cool, an interpretation reinforced with x-ray precession photography and the compositions of coexisting Fe-Ni metal phases associated with symplectites at the boundaries between olivine and plagioclase [5]. Cooling rates of 1.5-3.9 degrees per million years are suggested by combining ages representing closure of various isotopic systems for the 825 to 650 $^oC$ temperature range [6,7]. On the basis of Fe-Mg ordering in orthopyroxene, cooling at 0.04 degrees per year (26,000 times faster than the high-temperature cooling rate) is posited through the 500 $^oC$ isotherm, suggesting that deep-seated materials were excavated from depth while still warm [8]. In contrast to the subsolidus history, cooling rates at magmatic temperatures are unresolved, and thus the timing of magma emplacement in the lower crust is unknown to within ~100 million years (Fig. 1).

**Methods:** We studied two regions of interest (ROI) in thin section 76535,52 using polarizing light microscopy (PLM), x-ray element intensity mapping and wavelength-dispersive spot analysis by electron probe microanalysis (EPMA). X-ray element maps (Al and P in olivine; Na in plagioclase) were modeled using simple assumptions about the initial distributions and concentrations of diffusing elements, and we solve Fick's second law in 2D using finite difference methods [9]. The olivine model incorporates anisotropy of diffusivities [10] and utilizes crystal orientation determined with EBSD.

**Results.** ROI-1 is a multiphase cluster of olivine, plagioclase, orthopyroxene, symplectite, and interstitial minerals (Fig. 2). Aluminum x-ray element mapping (not shown) reveals no intra-olivine variation, whereas spatial variation in P concentration occurs within the olivine and at its margin (Fig. 2b). The latter concentration zones are interpreted to be the result of dissolution-precipitation, but the former are far more likely to have formed during the initial growth of the olivine crystal from silicate melt [11–13]. The diffusion modeling yields P concentration distribution similar to that in the natural sample (Fig. 3). Either 250-300 y, 2.5-3 ky, or 25-30 ky are needed to broadly match the P and Al data for diffusion at 1300, 1100, or 900$^oC$, respectively.

ROI-2 contains a single euhedral (igneous) plagioclase crystal completely surrounded (within section) by orthopyroxene. X-ray mapping reveals Mg-rich blebs ~1μm in diameter, as well as concentric variation in Na concentration. Taking into account the presence of local enrichment in Na associated with pyroxene exsolution, the concentration profile is matched after 15 ky at 1300 $^oC$, 4.8 My at 1100 $^oC$, or (physically impossible) 11 Gy at 900 $^oC$. We have not attempted to find the combination of temperature and time that satisfies all three data sets, but note that similar duration-temperature pairings resolve both the P and Al in olivine data reasonably well.

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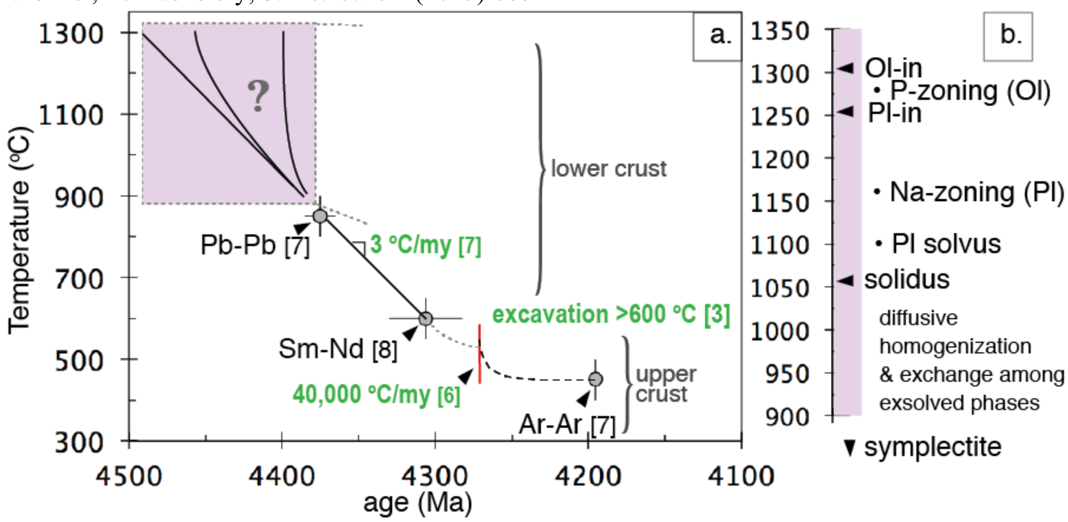


**Figure. 1 Constraints on the thermal history of 76535 below ~900 °C highlight the relative scarcity of information about its high-temperature history.**

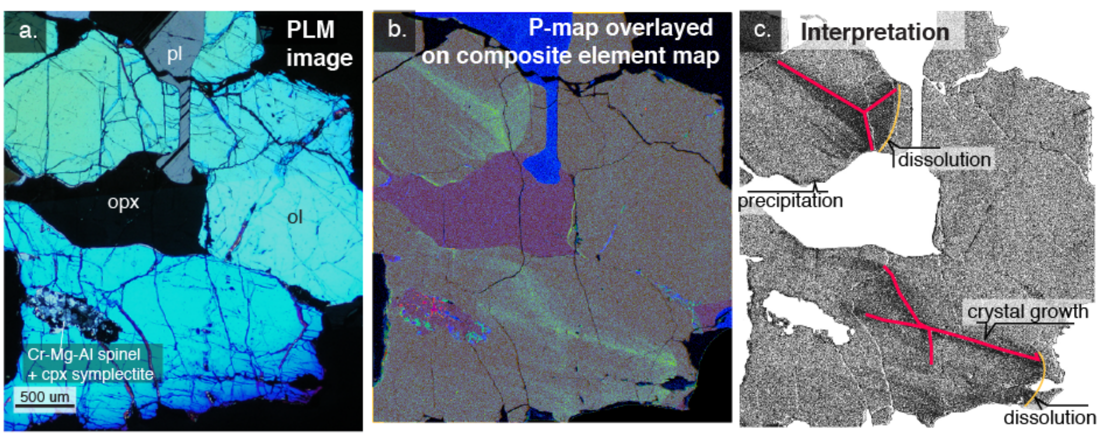


**Figure 2. ROI-I as imaged in cross-polarized light (a), by x-ray mapping (b) and provisionally interpreted (c).**

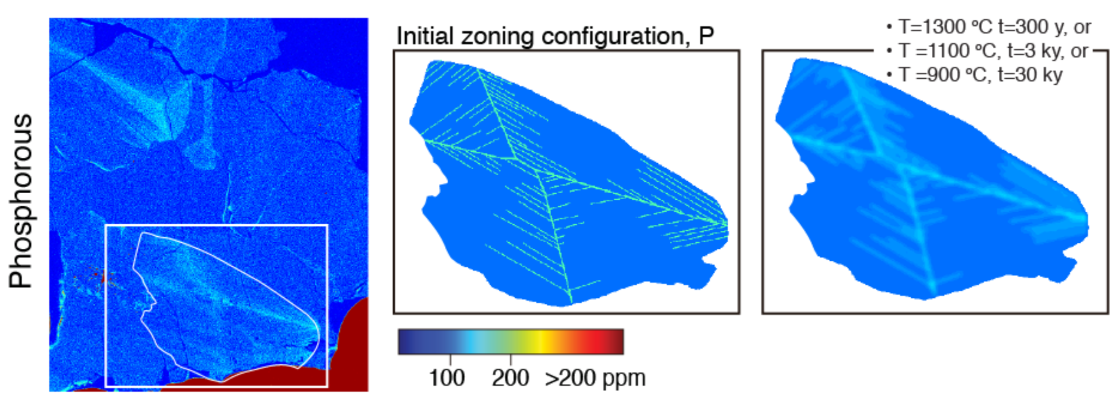


**Figure 3. Numerical simulation of phosphorus diffusion in olivine of *ROI-1*.**