Phosphorus and aluminum partitioning during olivine growth: both sides of the story

THOMAS SHEA[1], JULIA E. HAMMER[1], ERIC HELLEBRAND[1], ADRIEN MOUREY[1], EMILY FIRST[2], KENDRA LYNN[2], FIDEL COSTA[3]

[1] Department of Geology & Geophysics, SOEST, University of Hawai'i at Mānoa, Honolulu, HI 96822 (tshea@hawaii.edu)
[2] DEEPS, Brown University, Providence, RI 02912
[3] Dept. of Geological Sciences, University of Delaware, Newark, DE 19716
[4] Earth Observatory of Singapore, Nanyang Technological University, Singapore 639798

Ferromagnesian olivine typically contains trace amounts of P and Al (<0.1 wt.%). Both elements display striking fine-scale enrichment patterns within crystals from various geological settings (OIB, MORB, komatiites, arc andesites, and meteorites). These zoning patterns are interpreted as blueprints of rapid olivine crystallization, where intrinsic factors (e.g., changing growth rates) rather than external forcings (e.g., repeated magma mixing) lead to strong variations in incorporation of P or Al. These findings forced petrologists to reassess canonical ideas about the formation of phenocrysts and the interpretation of element zoning in olivine: phenocrysts do not necessarily form via concentric addition of growth layers (i.e., the 'tree ring' model), but by skeletal growth. Two end-member mechanisms for enrichment of P and Al are usually proposed: (i) the 'boundary layer' model (BL) of element enrichment, whereby a high rate of crystal growth relative to component mobility in the melt results in enrichment according to equilibrium partitioning (e.g. Lasaga 1982), or (ii) the 'growth entrapment' (GE) model, whereby anomalous enrichment, tolerated within a distinct surface layer of the crystal, is buried by rapid growth (Watson and Liang 1995). In both cases, the growth rates required to form large boundary layers or preserve trapped concentration anomalies are very high, at least 10^{-7} m/s. By coupling simple crystallization experiments involving a Hawaiian basalt with numerical simulations of diffusion-controlled growth, we show that: (1) P and Al display contrasting partitioning behavior, yet form similar enrichment patterns consistent with skeletal growth; (2) The degree of undercooling required to produce a skeletal P-Al blueprint is ≤ 25 ºC; (3) the BL model explains Al but not P enrichment, the latter likely requiring GE or, as we propose, growth-rate dependent partitioning.