THE MARTIAN OLIVINE GLOSSARY: COMMON TEXTURES AND ZONING PATTERNS, AND IMPLICATIONS FOR ASCENT OF MARTIAN MAGMAS AND THEIR PLUMBING SYSTEMS. M. M. Jean[1], M. McCanta[1], G. H. Howarth[2], L. A. Taylor[1], [1]Planetary Geosciences Institute, Dept. Earth and Planetary Sciences, University of Tennessee, Knoxville. [2]Dept. Geological Sciences, University of Cape Town, South Africa. (*mjean1@utk.edu*)

Introduction: The chemical zoning and textural features of minerals lies at the heart of petrologic studies investigating the plumbing dynamics of magmatic systems. Apropos, olivine (Ol) has long been valued as a geochemical and petrological tracer of physico-chemical processes. Therefore, Ol may be used to reconstruct the history of crystals and their host magma, which can testify to and record otherwise inaccessible early crystallization histories [1].

A successful and relatively new tool that may provide insight into the evolution of magma properties is phosphorous (P) zoning in Ol [2]. Within the last decade, the study of P-zoning in Ol has been extended from terrestrial igneous rocks to extraterrestrial samples [3,4]. It has been recorded that P-rich zones in Ol reflect incorporation of P during rapid Ol growth and that the zoning patterns primarily record crystal-growth-rate variations [2, 5]. Phosphorus diffuses extremely slowly in Ol [6] and therefore, undergoes minimal modification under many geologic conditions [2]. Thus P-zoning can be preserved over 1–100 k.y. time scales, long after traces of other incompatible elements have been erased under magmatic conditions [7-11].

The construction of the martian magmatic plumbing system(s) have long been speculated upon [12-20]. In particular, the ascent of martian magmas is poorly understood, but thought to be much like the magmatic plumbing-systems found on Earth. Adding to current debates, we also lack information regarding the depths and temperatures at which magmas are stored prior to eruption.

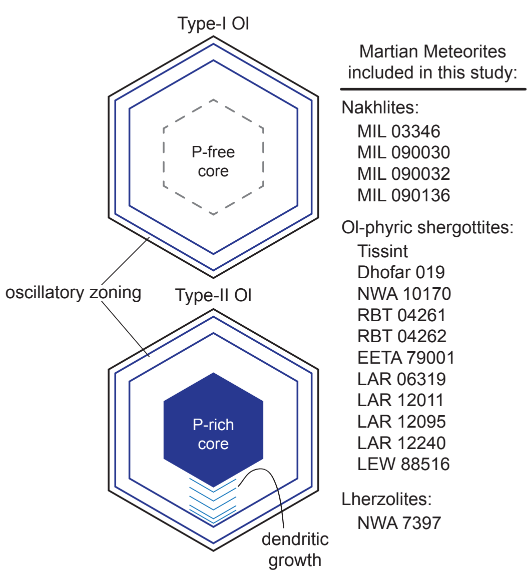


Figure 1. Primary Ol P-zonation patterns. Type-I (Megacryst and Type-II (Groundmass).

Clues to unraveling magma storage conditions are quantified here via the compositions, textures, and zoning patterns of P in Ols from a variety of Martian rocks (Fig. 1). We also compile Ol zoning patterns published in the literature. All Ols reported here fall into two primary designations, as revealed from *(i)* composition; *(ii)* habits (e.g., skeletal, hopper, or euhedral); and *(iii)* P-zoning patterns (e.g., P-rich cores, oscillatory and sector zoning, and dendritic). Combined, they reveal previous histories of complex crystal, in what otherwise appear to be relatively featureless crystals. These observations suggest a petrologic process that has been hidden from examination until now, thereby performing an important role in the magmatic evolution of this Earth-like planet.

Methods: Olivine (plus pyroxene and plagioclase) was analyzed for major- and minor-element compositions with a Cameca SX-100 electron microprobe at the University of Tennessee. Chemical mapping of Ols was conducted using a 15 kV acceleration voltage, 200–300 nA beam current, 1–3 μm step size, and 200–800 ms dwell time.

Results: All Ols from meteorites investigated in this study fall into two primary designations, as revealed from their size and P-zoning patterns (Fig. 1).

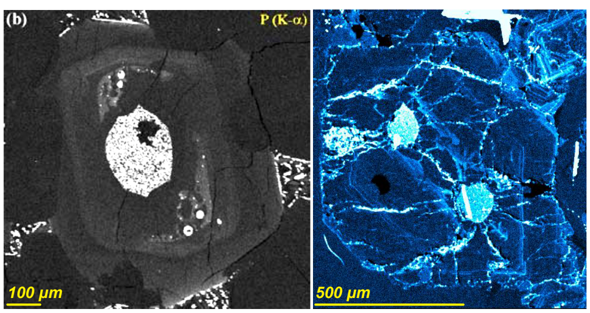
Type-I: Type-I Ols, typically the megacrysts, have P-free cores, with strong oscillatory zoning near the rims that mostly parallel Ol edges (Fig. 1). The origins of megacrysts have been interpreted as phenocrysts [21-24] and hypothesized to represent the primary melt composition, however, megacryst cores in this study exhibit variable forsterite contents (Fo_{70-85}) that partly overlap groundmass Ol compositions.

Type-II: Type-II Ols are typically found as groundmass, with P-rich cores (< 1700 ppm), surrounded by oscillatory or dendritic zoning (Fig. 1). The P-rich core is observed as either a nuclei that matches current ol edges or as an hourglass-shaped 'spine.' The groundmass Ol typically have ≤ Fo_{65}.

Discussion: The oscillatory zoning of P in Ol has been ascribed to result from either *extrinsic* or *intrinsic* parameters [25]. Extrinsic mechanisms such as magma mixing, crystal settling, eruption, T/P changes, or P_{H2O}, are those processes that impose a physical or chemical change to the system as a whole. Intrisic mechanisms, however, link crystal growth to purely local phenomena, such as crystal growth rate, solute trapping, undercooling, coupled substitutions, or cooling.

The crystallization sequence of martian meteorites could potentially reveal which mechanism is dominant in martian plumbing systems [12-20]. The petrography and chemical relationships of Ol-phyric shergottites suggest that megacrysts (Fo_{77-71}) are the early-crystallizing phase, followed by co-crystallization of the groundmass Ol ($\leq Fo_{70}$) with Pyx (~Mg# 70). Continued crystallization of pyroxene evolves toward high-Mg augite, and Ol becomes more Fe-rich (~Fo_{50}). Crystallization continues with plagioclase as a major constituent, until the end of silicate crystallization.

Nakhlites and lherzolites, however, offer new evaluations of the martian crystallization process. Nakhlites are olivine-augite cumulates that formed in lava flows or shallow intrusions of basaltic magma [26] and have experienced post-igneous processes to varying degrees. Lherzolites, conversely, are considered to represent cumulate rocks crystallized at depth within the martian crust [27, 28]. *Preserved P-zoning in these rocks potentially alters these interpretations* (Fig. 2).



Nakhlite (NK17) Lherzolite (NWA 7397)

Figure 2. Observed P zoning for Ol in martian nakhlites (Nakhla; Ref. 27) and lherzolites (NWA 7397)

The preservation of fine-scale zoning in phenocrysts suggests a brief interval between Ol crystallization and eruption, e.g., within a few months [5]. Longer durations at near-liquidus temperatures would result in pronounced "dampening" of fine-scale zoning (Fig 1, 2). The implication is that (1) Ol phenocrysts grew very shortly before eruption, or (2) Ols were not held at magmatic temperatures for long after growth; supported by the preservation of Cr-zoning [29].

Implications: The petrogenesis for shergottites favors a multi-stage model [Fig. 3: 28, 30]. *Stage 1:* primary melts from the martian crust-mantle boundary, crystallized P-poor Ol megacrysts (Type-I) via early-stage fractionation in a staging chamber or feeder conduit at depth. *Stage 2:* a (final?) magma pulse entrains Ol megacrysts, which undergo further crystallization of P-rich Ol (Type-II) and pyroxenes, in a staging chamber or discharging conduit, prior to extrusion/intrusion.

Stage 3: the magma is erupted as a thin lava flow, so as to form ferroan rims of Ol and pyroxenes and minimal crystallization of plagioclase.

The determination of cooling rates (a proxy for ascent rate) through diffusion calculations supports this interpretation. Phosphorus-based diffusion calculations [6] yield rapid cooling rates, ~ 3 °/yr. Megacrysts, as they represent well-equilibrated phases, are typified by slow cooling rates [31, 32]. This contrast in the ascent rate of magmas in the martian crust illustrates the complexities currently debated and only furthers the application of the zoning of minor elements in Ol as a true indication of the storage conditions of magma within Mars.

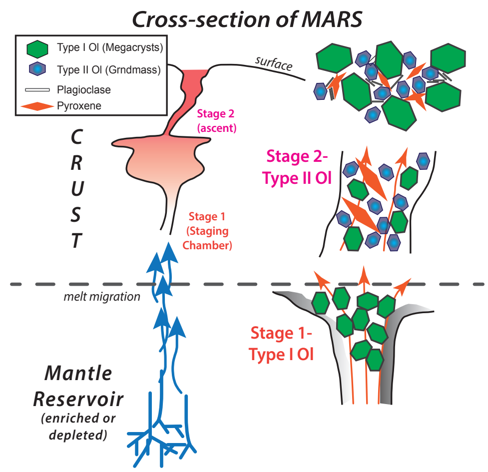


Figure 3. Cross-section of Mars; modified after 3 and 30.

References: [1] Sobolev A.V et al. (2007) *Science* 316, 412-417; [2] Milman-Barris M. et al. (2008) *CMP* 155, 739-765; [3] Shearer C.K. et al. (2013) *GCA* 120, 17-38; [4] Elardo S.M. and Shearer C.K. (2014) *GCA* 99, 355-368; [5] Watson E.B. (2015) *AmMin* 100, 2053-2065; [6] Spandler C. et al. (2007) *Nature* 447, 303-306; [7] Nicholls J. and Sout M.Z. (1998) *JPetrol* 29, 81-100; [8] Petry C. et al. (2004) *GCA* 68, 4179-4188; [9] Coogan L.A. et al. (2005) *GCA* 69, 3683-3694; [10] Welsch B. et al. (2014) *Geology* 42, 867-870; [11] Shea T. et al. (2015) *Geology* doi: 10.1130/G37082.1; [12] Usui T. et al. (2008) *GCA* 72, 1711-1730; [13] Basu Sarbadhikari A. et al. (2009) *GCA* 73, 2190-2214; [14] Basu Sarbadhikari A. et al. (2011) *GCA* 75, 6803-6820; [15] Filiberto J. et al. (2010) *Meteor. Planet. Sci.* 45, 1258-1270; [16] Peslier A.H. et al. (2010) *GCA* 74, 4543-4576; [17] Balta J.B. et al. (2013) *Meteor. Planet. Sci.* 48, 1359-1382; [18] Liu Y. et al. (2013) *GCA* 108, 1-20; [19] Balta J.B. et al. (2015) *Meteor. Planet. Sci.* 50, 63-85; [20] Treiman A.H. and Filiberto J. (2015) *Meteor. Planet. Sci.* 50, 632-648; [21] Greshake A. et al. (2004) *GCA* 68, 2359-2377; [22] Ikeda Y. (2004) *Antarct. Meteorite Res.* 17, 35-54; [23] McKay G. et al. (2004) *Lunar Planet. Sci. XXV.* Lunar Planet. Inst., Houston #2145 (abstr.); [24] Mikouchi T. et al. (2004) *Antarct. Meteorite Res.* 17, 13-34; [25] Shore M. and Fowler A.D. (1996) *Canadian Mineralogist* 34, 1111-1126; [26] Treiman A.H (2005) *Chemie der Erde* 65, 203-270; [27] Goodrich C.A. et al. (2010) *Lunar Planet. Sci. XLI.* Lunar Planet. Inst., Houston #1387 (abstr.); [28] Howarth G.H et al. (2014) *Meteor. Planet. Sci.* 49, l812-1830; [29] Ito M. and Ganguly J. (2006) *GCA* 70, 799-809. [30] Usui T. et al. (2009) *GCA* 74, 7283-7306; [31] Taylor L.A. et al. (1977) *Lunar Planet. Sci. VIII.* Lunar Planet. Inst., Houston 1581-1592 (abstr.); [32] Costa F. et al. (2008) *RIMG* 69, 545-594.