The Origin of Oscillatory Zoning of Major and Minor Elements in Pyroxene Phenocrysts in Lunar Basaltic Meteorite NWA 032/479

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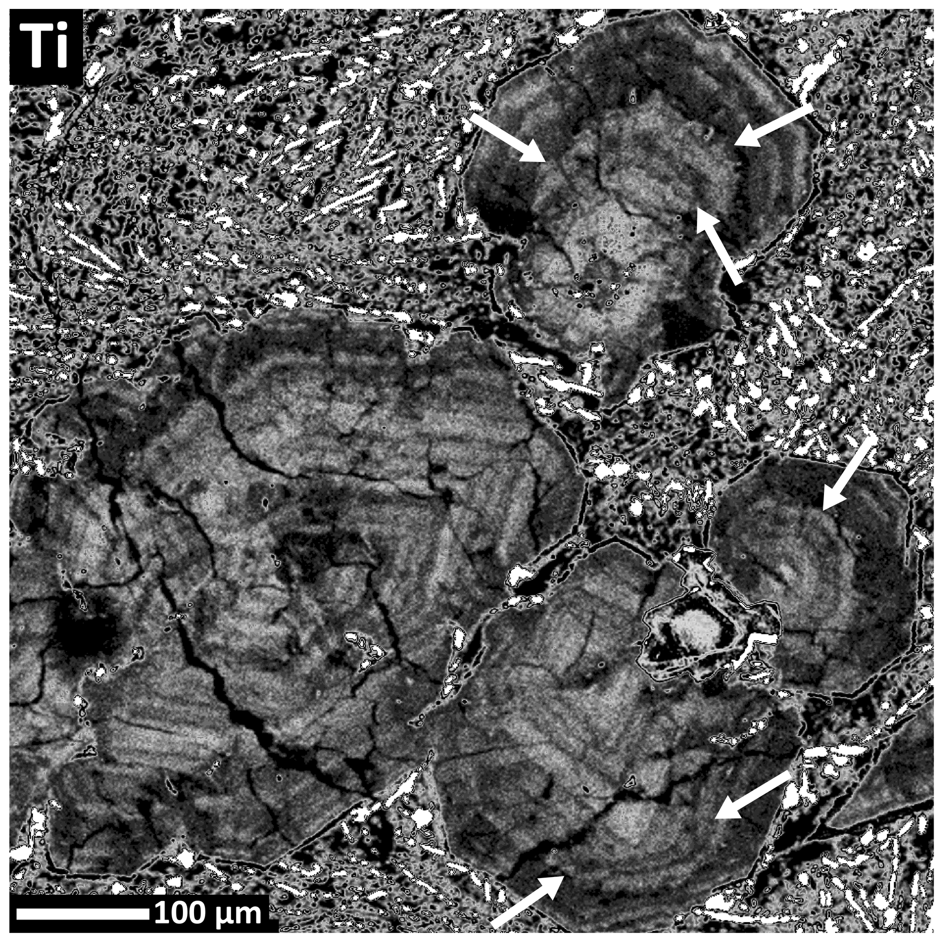
1. Introduction

Lunar basaltic meteorite Northwest Africa (NWA) 032/479 is currently the youngest known igneous sample from the Moon [2.93 Ga; see 1]. Previous workers have shown that NWA 032/479 sampled a low-Ti basaltic flow that is distinct from those sampled during the Apollo and Luna missions. NWA 032/479 contains ~17% chromite, olivine, and pyroxene phenocrysts set in a fine-grained groundmass [2] that formed upon eruption on the lunar surface. Fagan et al. [2] argued NWA 032/479 underwent a relatively simple cooling history. However, Burger et al. [3] initially identified the presence of oscillatory zoning patterns in pyroxene phenocrysts, although the origin of this zoning was not determined. In this study, we present analyses of pyroxene phenocrysts in NWA 032/479 to constrain the thermal history of a young mare basalt. The zoning patterns in its phenocrysts record the cooling history of a basalt that passed through the lunar crust at a time when the elastic lithosphere had thickened significantly [4-7].

Models for oscillatory zoning fall into two categories: intrinsic and extrinsic [8-10]. Intrinsic models are typically based in crystallization kinetics. A rapidly growing crystal depletes a boundary layer in compatible growth components and incorporates a greater than expected amount of incompatible components (i.e. "solute trapping"). Growth then slows, the boundary layer is destroyed, and the process repeats. Extrinsic models call upon an external forcing such as magma recharge events or magma chamber convection [9, 11]. Here we assess this range of models to better interpret the cooling history of the youngest igneous sample from the Moon.



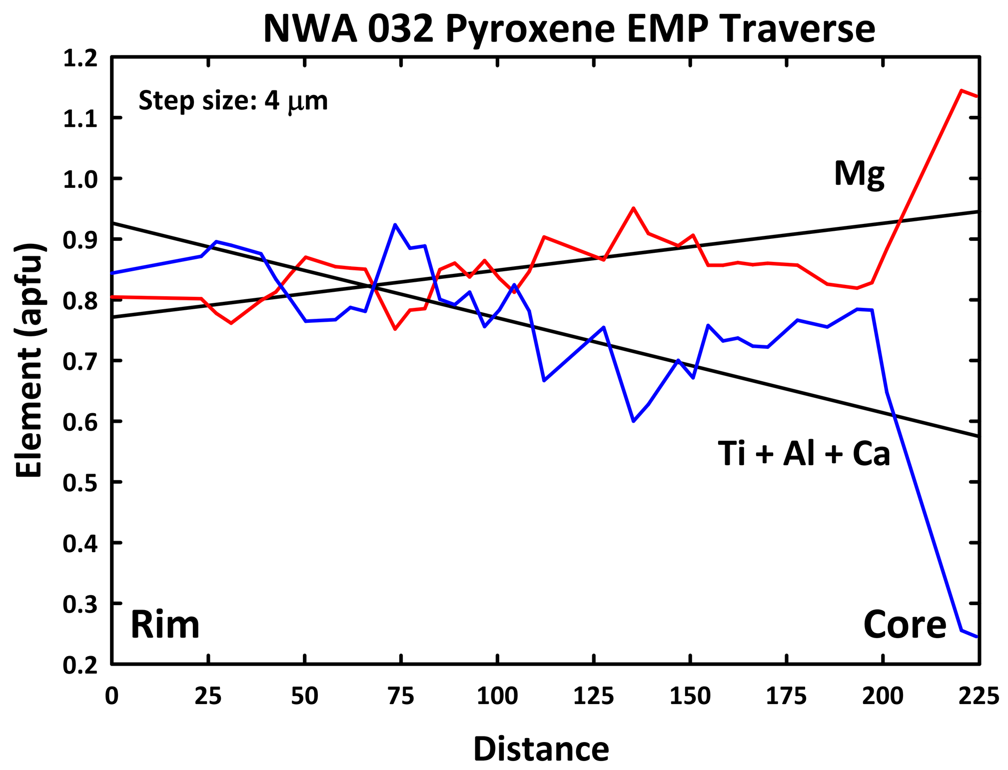
Qualitative WDS map of Ti in pyroxene. Bright shades are high concentrations, darker shades lower concentrations.

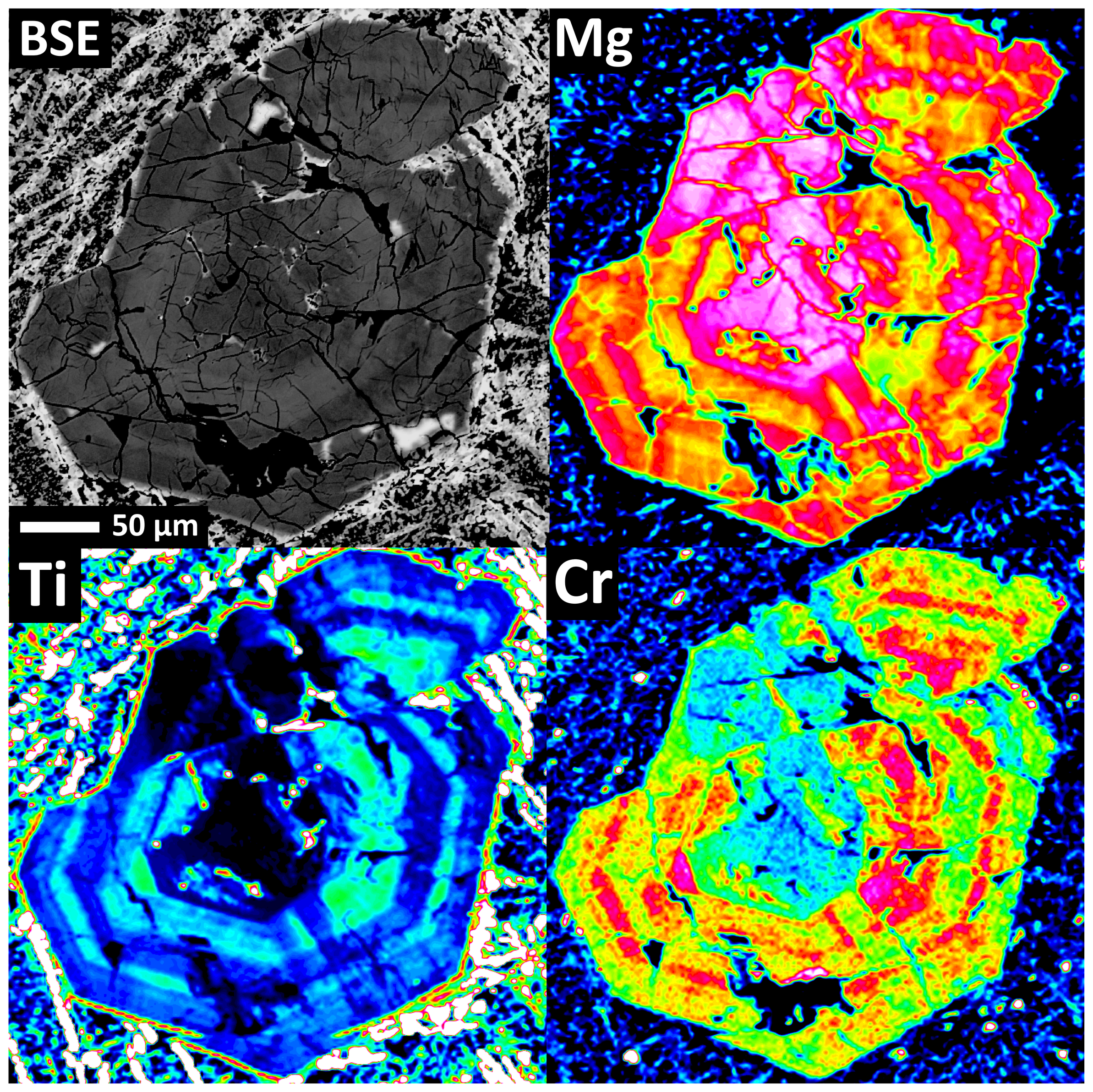
3. Resorption Surfaces

The gray-scale WDS map of Ti concentrations at left shows that although most oscillatory bands in pyroxene phenocrysts are euhedral and have sharp edges, some have rounded, diffuse, or uneven edges. Examples are indicated by arrows. These rounded and uneven edges are interpreted as resorption surfaces. Similar resorption features have been noted by other authors and are associated with coarse banding in plagioclase and pyroxene. Resorption surfaces would not be expected for instances of oscillatory zoning that form due to kinetically controlled non-linear crystal growth. Rather, resorption surfaces indicate that the crystals experienced variable temperatures and liquid compositions during crystallization. Both magma recharge events and crystal convection in the magma chamber could be causes of variable temperature, and variable liquid compositions.

4. Long-Scale Magmatic Zoning

The plot at right shows the B - B+231 µm section of the traverse below and represents a core to rim traverse. The elemental concentration of Mg and the sum concentration of Ca, Ti, and Al are shown with linear regressions of the concentration profiles. The decrease in Mg and increase in Ca, Ti, and Al are indicative of crystallization from pigeonite to augite in lunar magmas. These data show that while the short scale zoning in pyroxene is oscillatory, it is overprinted on longer scale normal magmatic zoning patterns. This argues for crystallization of a single magma body as opposed to repeated replenishment of the magma chamber.

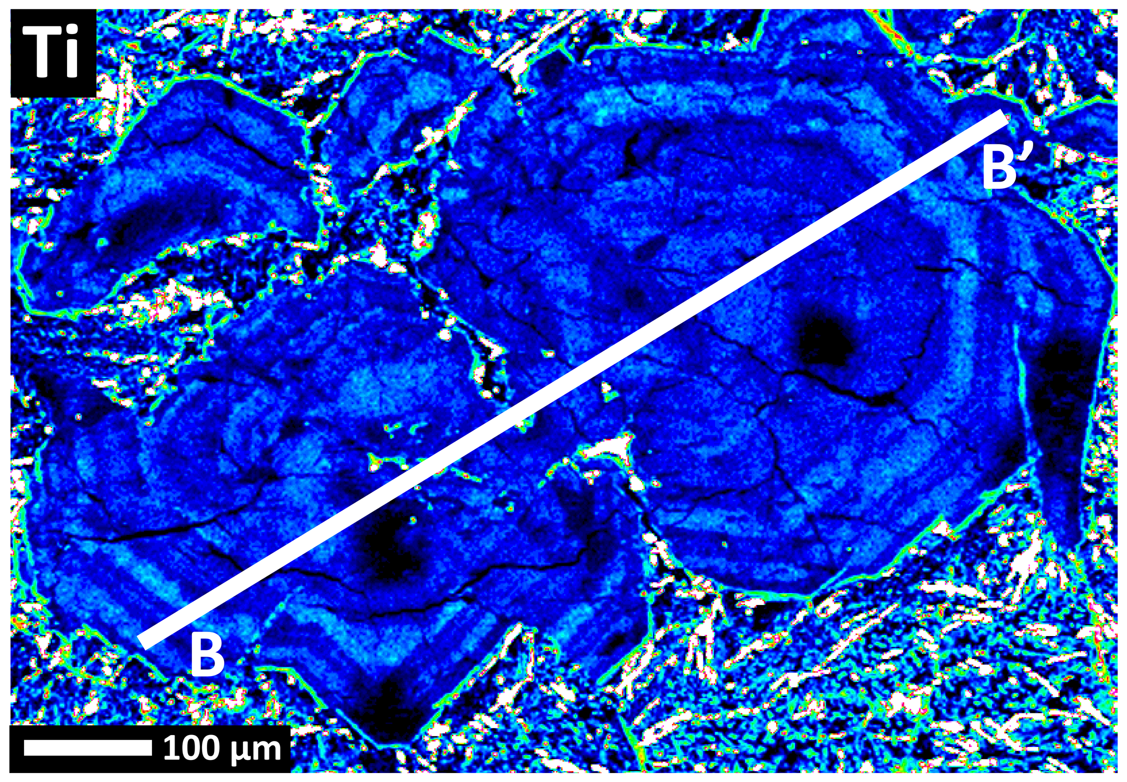


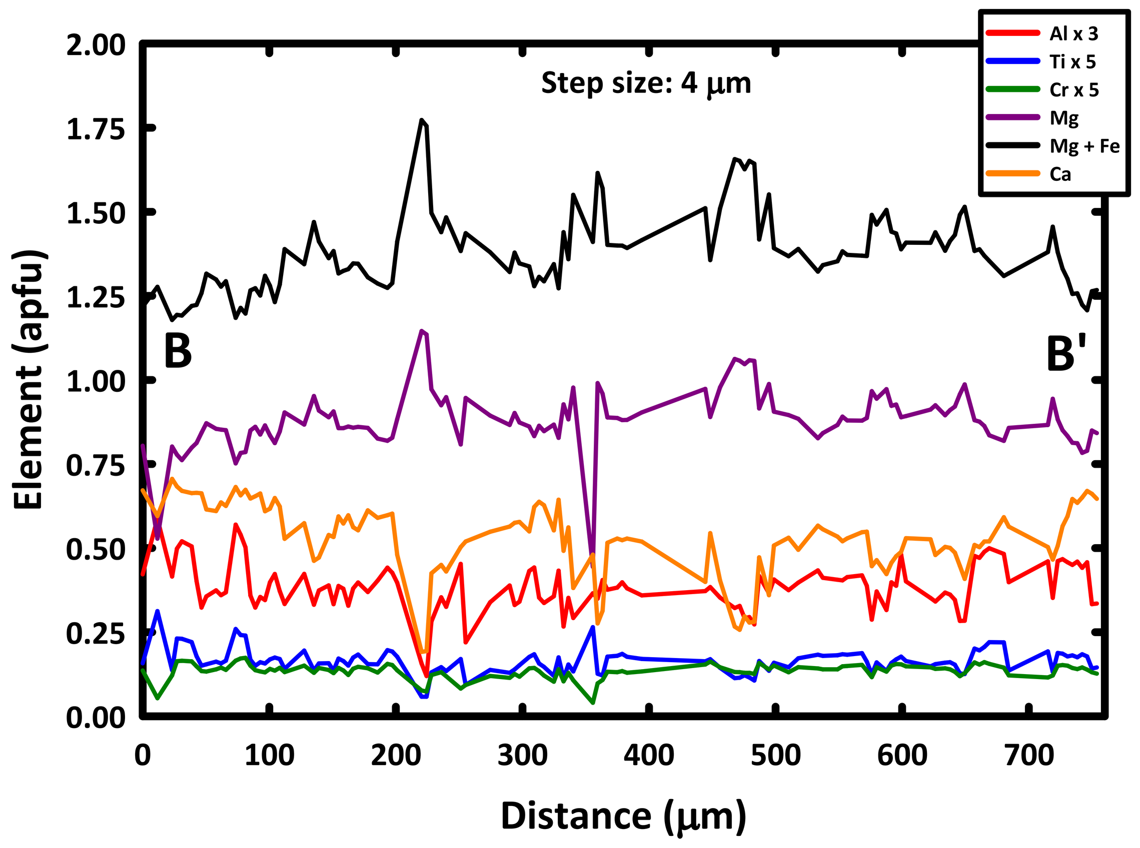


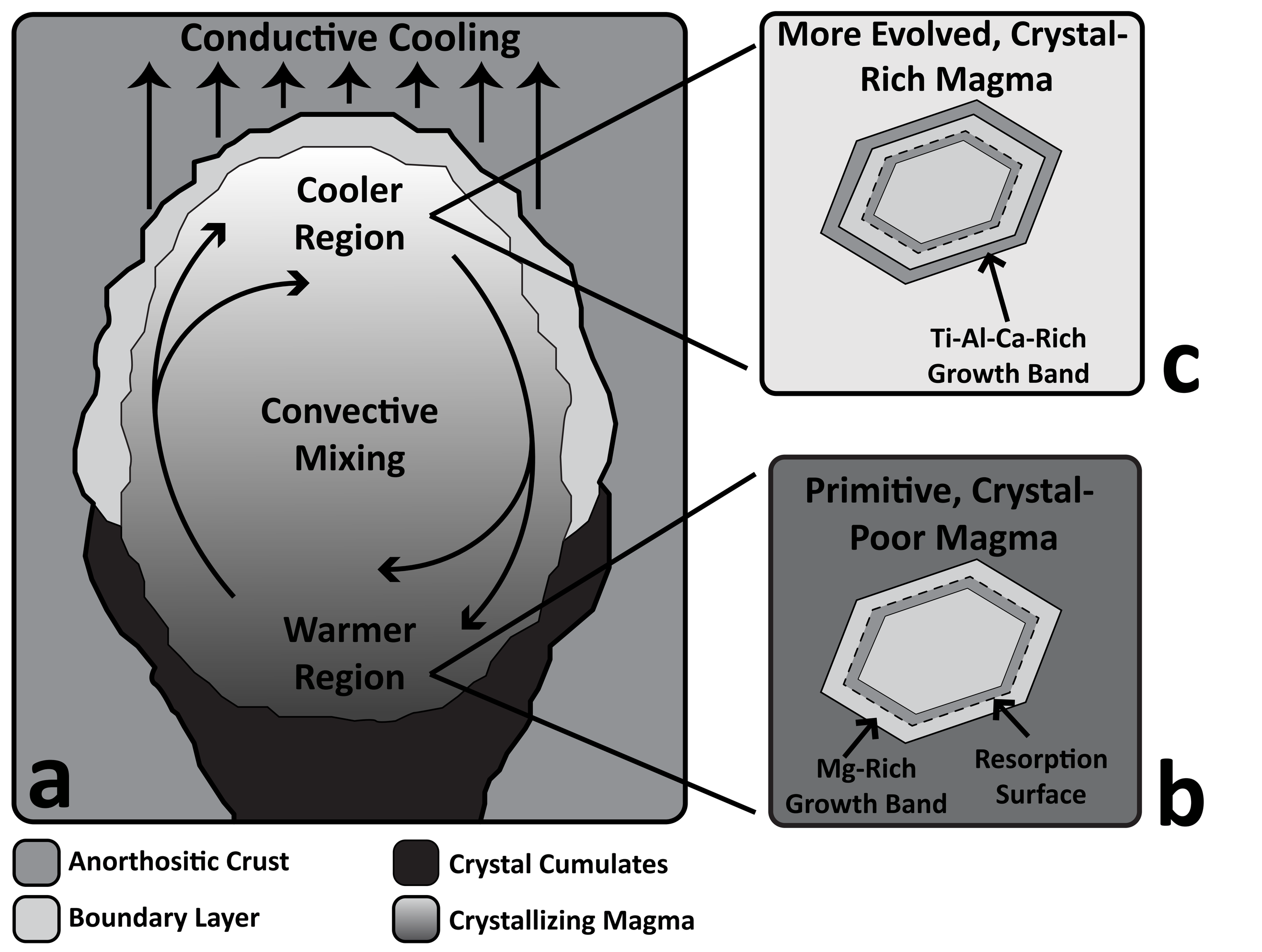
Qualitative WDS Maps. Hot colors are high concentrations, cool colors low concentrations.

2. Characteristics of Oscillatory Zoning in Pyroxene

A) Pyroxenes show oscillatory zoning in Mg, Ca, Fe, Cr, Ti, and Al.
B) Mg-rich bands antithetical to Ca-Ti-Al-Cr-rich bands.
C) Bands range from ~3-5 µm to ~60 µm in thickness. Typically bands are ~10 - 20 µm thick.
D) Bands have variable widths over short distances.
E) Bands are typically euhedral and parallel to crystallographic planes, indicating constant euhedral crystal growth.







5. Magma Chamber Convection Model

Oscillatory of pyroxene is consistent with convection in a differentially cooling magma chamber. A schematic model is shown above. The magma chamber loses heat more efficiently at the top, and this creates a thermal gradient that results in a compositional gradient in the chamber. As phenocrysts are cycled through warmer, more crystal-poor regions by convection, some resorption of more evolved pyroxene growth bands may occur. However, the magma is still pyroxene saturated so this results in the growth of Mg-rich oscillatory bands. As the crystals are cycled through the cooler, more crystal-rich regions, no resorption occurs and the new growth bands are more Ca, Ti, and Al-rich. Because layer growth is a response to the liquid composition in different regions of the chamber rather than availability of growth components in a boundary layer, coarse bands of variable thickness are permitted to form. Also, the longer scale normal magmatic zoning will be a reflection the evolution of a single magma.

References: [1] Borg et al. (2009) GCA 3963-3980, [2] Fagan et al. (2002) MAPS 371-394, [3] Burger et al. (2009) LPSC #2043, [4] Hess (2000) JGR-P 4347-4360, [5] Wieczorek and Phillips (2000), JGR-P 20,417-20,430 [6] Hess and Parmentier (2001), JGR-P 28,023-28,032 [7] Spohn et al. (2001), Icarus, 54-65 [8] Shore and Fowler (1996) Can. Min., 1111-1126 [9] Pearce (1994) Nato Adv. Sci. Inst. Se. 421, 313-349, [10] Milman-Barris et al. (2008) Contrib. Min. Pet. 739-765, [11] Ginibre et al. (2002) Contrib. Min. Pet. 436-448. Funding: NASA NESSF Fellowship to S.M.E #NNX12AO15H and NASA Cosmochem. to C.K.S. #NNX10AI77G.