# CERAMIC VOLCANISM ON REFRACTORY WORLDS: THE CASES OF IO AND CHONDRITE CAIs.

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**Background/Overview:** Most differentiated rocky worlds in our Solar System have mantles of olivine, pyroxene, spinel, and calcic plagioclase (or equivalent high-pressure phase assemblages). Earth's mantle peridotite and similar rocks in other silicate planets and asteroids normally melt to form basaltic magma, komatiite, or other olivine-normative melts. Details of planetary mantle compositions and magma petrogenesis may lead to departures of magma compositions from olivine-normative liquids, e.g., the silicic trend of magmas derived from Earth's subduction-watered mantle. However, magma genesis on inner Solar System bodies produces melts that are generally less refractory (in melting and volatility senses) than the mantle source was to begin with. There are hints that a very different process might occur on Io and some asteroids, resulting in ultrarefractory, silica-deficient Ca-Al-rich lava compositions that would make a ceramic engineer proud. In the extreme, volatilization of very hot lavas could produce unsilicated, nonmagnesian, non-ferroan residues of simple refractory oxides.

**Lava volatilization & melting phase relations**: According to the vapor pressures of basaltic and komatiitic lavas, the first major metallic elements lost by thermal evaporation are Na and K [1-3]. This is evident around some terrestrial volcanoes, where sodic condensates, such as thenardite ($Na_2SO_4$) are found. At temperatures similar to those found in some Ionian eruptions (near or above the liquidus of komatiite e.g., 1870 K, [4]), thermal evaporation of Fe, Mg, and Si (in overlapping sequence) can also become significant. Na, K, Fe, Mg, and Si are here termed subvolatiles to distinguish them from supervolatiles, particularly elemental sulfur and volatile compounds of S. The total vapor pressures of Fe, Mg, and Si and their oxides attains a microbar at ~1900 K [1-3].

So long as a lava surface is often refreshed (as at boiling lava lakes), cumulative evaporation can be significant. Effects of evaporation processes on solid-liquid melting relations may be profound so long as condensates and refractory residues are not efficiently remixed. Some possible effects of fractional volatilization on melting phase relations of the refractory residue of an initial komatiite type lava are shown in Figures 1 and 2. The vapor calculations for fractional distillation represented in Figure 1 are explained in [3]. The solid-liquid phase equilibria used to calculate lava liquidus temperatures and liquidus solid phase in Figure 2 are from [5].

**The case of Io:** Volcanic volatilization of alkalis occurs on Io, where Na, K, and Cl, and recently NaCl have been seen in emissions [6-7]. On Io, however, some lava temperatures are so extreme—as hot or hotter than the liquidus of komatiite [2, 4]—that Fe, Mg, and Si can be volatilized [1-3]. The absence of a dense atmosphere and presence of a strong Jovian magnetic field would tend to allow these materials to be swept away over time, though the continued presence of alkalis and sulfurous volatiles indicates that surface-based cold trapping is effective. The apparent absence or deficiency of FeO on Io's volcanic surface [8] could be explained by condensation and sinking to the core of Fe and Fe-oxide. Io has recycled its entire crust and mantle mass at least 80 times at recent rates of volcanism [9]. This activity allows many opportunities to evaporate iron. This process can be effective if just 1% of the iron in each lava flow is both lost from the lava and condensed in a stable location, where it accumulates and eventually drains into the core.

Magnesium and silicon are both more refractory and more abundant than iron, but a significant fraction could be volatilized over time. Minerals that may be produced in refractory residues and condensates have widely differing densities. If distillation and fractional crystallization are effective processes on Io, these mineral phases are apt to form segregated masses as well as unique rock types. Some could end up in the core, and others in the lower mantle, in the upper mantle, in low-lying plains, and in segregated buoyant crustal blocks. Figure 3 shows the hypothesized fates of selected minerals and constituent elements. Of course, none of this segregation would occur if Io has efficient means of remixing condensates and residues. We suggest, however, that Io's prominent peaked massifs are made of rock and mineral types, such as melilite, that are both refractory and buoyant.

**The case of CAIs:** The residues of extreme evaporation lack Fe, are deficient in Si and Mg, and are strongly enriched in Ca, Al, and Ti oxides. An initial basaltic or komatiitic lava produces a refractory residue very similar to common meteoritic Ca-

Al-rich inclusions (CAIs). In extreme cases these residues can be completely outside the usual phase stability fields familiar to igneous petrologists. We speculate that prolonged, intense heating of the asteroid parent bodies of CAIs may have caused an early period of volatilization and "ceramic volcanism" like that inferred for Io, but possibly more extreme.

The cases of Io and CAIs may offer two complementary views of the same phenomenon. On Io, we see evidence of the high temperatures that can be accounted for by active ceramic volcanism. In CAIs we see the lithic and geochemical evidence of possible ceramic volcanism that occurred over 4.5 billion years ago.

**Conclusions:** When ultramafic Fe-Mg-Si-rich lavas are subjected to temperatures close to their liquidus under vacuum conditions, there can be significant selective evaporation and loss of certain metals and simple oxides, with metals lost in amounts or in the sequence Na and K > Fe > Mg > Si [3]. If the lava is boiling or convecting vigorously, evaporation can be considerable, causing the residual lava to evolve to a more refractory state. Io, due to its intense tidal heating and vigorous volcanic history and its tenuous atmosphere, may currently exhibit this process. Some meteoritic Ca-Al-rich inclusions (CAIs) may be due to similar activity over 4.5 billion years ago. Since Io may be at an earlier stage of evaporation-driven fractionation, the study of CAIs may give insights into Ionian volcanism. Ceramic volcanism may be common also on excessively tidally or radiatively heated moons and planets of other solar systems.

**References:** [1] Schaefer, L. and Fegley, B., Jr., (2002) *BAAS, 34(3)*, 904. [2] Kargel, J.S. et al. (2003) *EOS*, submitted. [3] B. Fegley, Jr. et al. (2003) abstract, this volume. [4] Davies, A.G. et al. (2001) *J. Geophys. Res,. 106*, 33,079-33,103. [5] Fegley, Jr., B. and Zolotov, M. Yu. (2000) *Icarus, 148,* 193–210. [6] Lellouch, E. et al. (2002) *Nature, 421,* 45-47. [7] Osborn, E.F. et al. (1954) *Jour. Metals, 6*, 3-15. [8] Geissler, P.E. et al. (1999) *Icarus, 140*, 265-282. [9] Keszthelyi, L. and McEwen, A. (1997) *Icarus, 130*, 437-448.

**Figure captions** (from top to bottom).

**Fig. 1**. Fractional vaporization model for an initial Barberton-like komatiite lava at 1900 K showing composition of residual refractory liquid with progressing evaporation.

**Fig. 2**. Evolution of liquidus temperature and liquidus solid phase corresponding to the evolving vapor-distilled liquid compositions plotted in Fig. 1. Quaternary phase equilibria from [7]. Thermodynamic calculations due to Fegley et al. [3].

**Fig. 3**. Hypothetical/speculative fates of major mineral and lithic products of fractional vaporization and fractional crystallization of initial basaltic or komatiitic liquids on Io.