USING MODERATELY VOLATILE ELEMENTS TO PROBE PLANETARY ACCRETION. F. Nimmo[1], R.A. Fischer[2] and T. Kleine[3], [1]University of California Santa Cruz (fnimmo@ucsc.edu), [2]Harvard University (rebeccafischer@g.harvard.edu), [3]University of Muenster, Germany (thorsten.kleine@uni-muenster.de)

Introduction: The relative concentrations of elements in the silicate mantles of planetary bodies provide clues to their accretion history. Moderately volatile elements (MVEs) are depleted relative to refractory elements with similar chemical affinities, suggesting either loss or incomplete condensation [1]. However, there is no consensus on when this difference arose: in the nebular phase [2]; during planetesimal growth [3]; or after accretion was mostly complete [4].

Evaporative loss of MVEs during planetesimal growth is consistent with small excesses of isotopically heavy Mg and Si in the Earth [5,6]. The absence of K isotopic fractionation [7] is explained by total loss followed by late delivery of chondritic K [5].

However, the pattern of MVE depletion in planetary bodies does not in general resemble that expected from experimental measurements. Sossi et al. [8] suggested that the depletion patterns are the result of mixing between depleted and undepleted reservoirs; below we provide a quantitative analysis of this suggestion in the context of N-body accretion simulations.

MVE Depletion Patterns: Figure 1 below shows the elemental depletion patterns relative to chondritic for different planetary mantles. The order of elements is approximately that of their 50% condensation temperatures, showing that more volatile elements are more depleted. We focus below on lithophile elements because siderophile elements suffer from the additional complication of removal to the core [9].

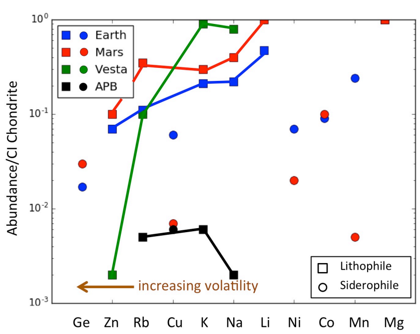

Figure 1. Selected elemental depletion patterns for different bodies (APB=angrite parent body). Sources:[10]-[13].

Modeling Evaporative Loss: Sossi et al. [8] carried out experiments tracking the evaporative loss of elements from silicate melts at different temperatures *T*. Figure 2a reproduces their results and shows that the fraction of element remaining is a very strong function of temperature: to a good approximation, at a particular temperature elements are either completely retained or almost entirely depleted. A similar result holds true if oxygen fugacity (fO_2) rather than *T* is varied.

This experimental result, however, is very different from what is observed in planetary mantles. Rather than a sharp cutoff, for Earth and Mars there is instead a relatively gradual decrease in concentration with increasing volatility (Fig 1). [8] explain this disagreement by appealing to a *mixture* of two precursor materials with different degrees of volatile depletion.

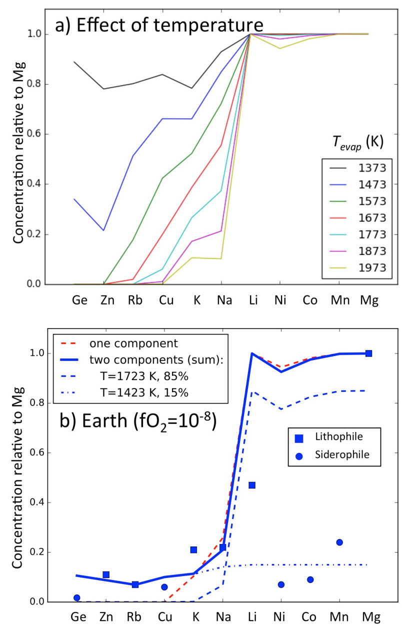

Figure 2. a) Predicted fraction of element remaining as a function of temperature using the method of [8] and with fO_2 fixed to QFM. b) Comparison of observed bulk silicate Earth concentrations (Fig 1) with one- and two-temperature fits at fixed fO_2. For the single-temperature fit *T*=1573 K.

To investigate this idea, we adopt the methods of [8] and find the combination of *T* and fO_2 which provide the best fit to the Earth's lithophile element concentrations (Fig 1). Fig 2b shows the result (red dashed line): the single-temperature fit fails to reproduce the more volatile MVEs. This result agrees with [8].

We next investigated a two-temperature fit. This provides a much better match to the observations (blue line) and consists of 85% of a high-T material and 15% of a low-*T* material. A recent study of Mg and Si isotopes concluded that the Earth consisted of ~25% low-*T* material [6].

Figure 3a shows the result of a similar exercise for Mars, again demonstrating the failure of the single-*T* model. In this case, the low-*T* material comprises 20%

of the total. In contrast, for Vesta (Fig 3b) a single-*T* model provides a good match to the observations. This makes sense: Vesta, being much smaller, probably accreted material from a restricted region while Mars and Earth acquired material from a variety of sources.

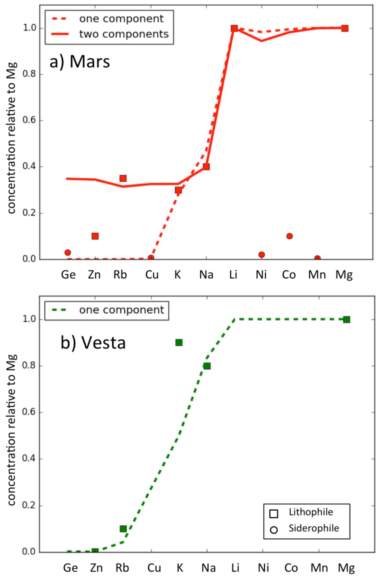

Figure 3. a) As for Fig 2b but for Mars with an fO_2 of 10^{-8}. Best-fit two-component model has T_1=1423 K, T_2=1623 K and a low-*T* fraction of 20%. b) As for a) but for Vesta. Single-component fit has *T*=1523 K and $fO_2 = 3 \times 10^{-8}$. Elemental concentrations are from Fig 1.

Of course, assuming that there are only two reservoirs, each characterized by a single effective evaporation temperature *T* is an oversimplification. Furthermore, fO_2 is also likely to vary between reservoirs. Nonetheless, this very simple model provides a starting point for testing the Sossi et al. hypothesis with N-body accretion models.

N-body Simulations: Although not the only possibility, it seems likely that the precursor material volatile content is controlled by initial distance from the Sun. For a two-*T* model we can then just assume a critical distance separating these two reservoirs. This allows us to use N-body accretion codes to track how the two reservoirs are mixed into the final planets. Such mixing studies have been done before, e.g. for oxygen isotopes [14] and Mo/Ru isotopes [15].

Figure 4a shows the evolution of planetary mass and fraction of low-*T* material as a function of time for an Earth-analog planet from the simulations of [16]. Here the high-*T*/low-*T* boundary is set at 1.8 AU. The low-*T* fraction increases over time, because in these models the feeding zone of the planet expands outwards with time [15]. The final low-*T* fraction of 20% resembles that found for the Earth in Fig 2b.

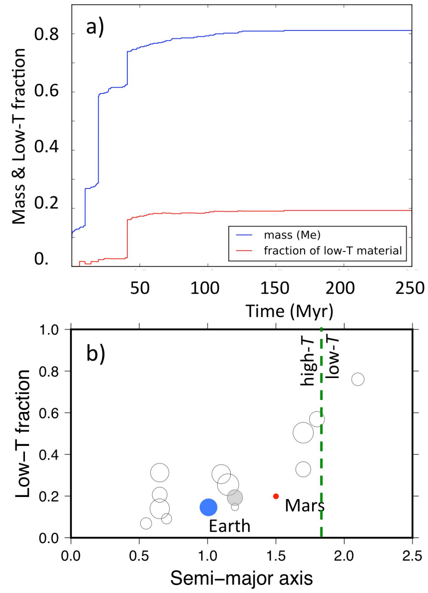

Figure 4. a) Evolution of planet mass and fraction of low-T material as a function of time. N-body simulation is CJS1 from [16]. Boundary between high-*T* and low-*T* material set at 1.8 AU. b) Final planet semi-major axis and low-*T* fraction from four CJS simulations (open circles), compared with inferred values for Earth and Mars. Gray-shaded circle is planet from Fig 4a. Circle size scales with the square root of planet mass.

Figure 4b shows the outcome for planets in multiple simulations, compared with the inferred Earth and Mars values. As expected, the larger the final semi-major axis of the planet, the higher the fraction of low-*T* material, although there is considerable scatter. A boundary location inwards of 1.8 AU results in planets with too large a fraction of low-*T* material.

Conclusions: This preliminary work shows that radial mixing of a low-*T* and a high-*T* component can explain the MVE patterns in Earth and Mars. For the CJS accretion models, the boundary between these two components is at 1.8 AU or more, suggesting volatile-rich planetesimals only survived beyond this distance. Future work includes exploring other accretion scenarios (e.g. the Grand Tack [17]) and incorporating the effect of core partitioning.

References: [1] Palme, *Meteorites & the early solar system*, pp. 436-461, 1988. [2] Siebert+, *EPSL*, 2018. [3] Pringle+, *EPSL*, 2017. [4] Albarede, *Nature* 2009. [5] Hin+, *Nature*, 2017. [6] Young+, *Icarus* 2019. [7] Humayun & Clayton, *GCA*, 1995. [8] Sossi+, *GCA*, 2019. [9] Braukmuller+, *Nature Geosci.* 2019. [10] Mittlefehldt+, *MAPS* 2007. [11] Palme & O'Neill, *Treat. Geochem.* 2014. [12] Wang & Becker, *GCA* 2017. [13] Steenstra+, *Icarus* 2019. [14] Kaib & Cowan, *Icarus* 2015. [15] Fischer+, *EPSL* 2018. [16] O'Brien+, *Icarus* 2006. [17] Walsh+, *Nature* 2011.