Steam-Atmosphere Driven Element Fractionations in Planets

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Introduction: We recently modeled chemical equilibria between silicate magmas and steam atmospheres for Si, Mg, Fe, Ca, Al, Na, K, and Ni [1,2]. The rocky elements dissolve mainly as hydroxides in steam; but halides are also important for Na, K, Ca, and Al. The relative fractionation of the rocky elements by steam is quite different from the vaporization of rock into a highly reduced solar nebula gas, or within a dry, oxygen-rich outgassed atmosphere at magmatic temperatures. The results indicate that the bulk composition, density, heat balance, and interior structure of rocky planets can be altered significantly by fractional vaporization and subsequent loss of the “rock-loaded” atmosphere. The steam-magma interactions thus provide a novel fractionation mechanism that should be considered for wet planets with magma oceans. We also note that this mechanism can have significant effects on crustal evolution of rocky planets and on interior rocky cores of gas-rich planets, including exoplanets.

Steam-Magma Partition Coefficients kD: We derived steam-magma partition coefficients for rocky elements between 2000-3000K at two total pressures, 270 bar, and 1100 bar. The magma composition was either bulk silicate earth (BSE) or continental crust (CC). The mass-fractions of magma are quite large in each system, (> 98%) yet fractionations can easily be achieved.

Terrestrial Si/Mg Ratio: The molar Si/Mg ratio in the BSE from various geochemical tabulations is about 0.82 ± 0.03; about 15% smaller than the solar value. The explanations for this include different Si/Mg ratios for upper and lower mantle (unlikely), sequestering up to about 7% Si in the core (unlikely), or loss of Si and Mg via fractional vaporization (plausible). Since Si shows the highest solubility in steam we suspected that the Si/Mg ratio could be decreased by extraction of Si into steam and subsequent atmospheric loss by impact erosion or UV driven hydrodynamic escape. The upper temperature limits for producing the sub-solar Si/Mg ratio are about 2590K (270bar) and 2920K (1100bar). At 270 bars and 2000K, a steam atmosphere with 1.3% of the BSE mass results in the observed Si/Mg ratio in the BSE. This is about 30 K above the magma liquidus temperature, and about 7-8 times the Earth’s current water for a steam atmosphere. At 1100 bars and 2000 K loss of a steam atmosphere with about 5.5% of the BSE mass (nearly 40 times present Earth’s water inventory) is needed to match the Si/Mg ratio.

Under the same conditions at 270 bar, the calculated CI-normalized ratios of Si/Na (1.4) and Si/K (4.0) are also of the right order of magnitude compared to the observed ratios of Si/Na (3.9) and Si/K (4.2) in the BSE. Vaporization into and subsequent loss of a steam atmosphere at 1100 bar gives Si/Na = 3.4 and Si/K = 9.5. This requires that most Cl & F remain in solution in the magma ocean and the loss of Na and K can be 10-20 times higher if most Cl & F are in the steam atmosphere. We did not model Fe loss in our initial work.

Further Studies: The present work will be extended to other elements that could be dissolved in steam. However, the major obstacle for these calculations is the sparsity of well-defined thermodynamic data for (oxy)hydroxide gases. These preliminary calculations show it is possible to match the Si/Mg ratio in the BSE. More detailed modeling is required to determine the optimal conditions (P, T, mass fraction lost) that give the best match to the observed ratios of lithophile elements in the bulk silicate Earth.

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References: [1] Fegley, Jr., B. & Lodders K. 2016, this meeting. [2] Fegley, B. Jacobson, N.S., Williams, K.B., Plane, J.M.C., Schaefer, L., Lodders, K. 2016, Astrophysical Journal, in press.