MAGMATIC CONTRIBUTION OF SURFACE WATER TO ANCIENT MARS. L. G. Bellino1 and C. Sun1, 1Department of Earth and Planetary Sciences, Jackson School of Geosciences, University of Texas at Austin (lucia.bellino@utexas.edu).

Introduction: Extensive geomorphological and mineralogical evidence has been observed supporting the presence of sustained liquid water on the Martian surface [1] with volumes corresponding to a ~100–1,500 m global equivalent layer (GEL) [2], [3]. Yet, the origin of surficial water on Mars remains uncertain. Considering that fluvial activity and volcanism were coeval during the Noachian and Hesperian (~3–4 billion years ago [Ga]), it is possible that magmatic processes played an important role in maintaining liquid water by extracting water from the interior. Notably, previous models regard volcanism as a negligible contributor to water on Mars (2.4–61 m GEL; Fig. 1) [4], [5], [6]. We suggest that previous estimates likely overlooked the magmatic contribution as they did not fully consider the roles of redox conditions, degassing pressures, magmatic generation and differentiation, and magma production rates.

Degassing of multi-component C-H-O-S volatiles is strongly dependent on volatile solubility. As vapor species are sensitive to redox conditions (fO2), it is expected that higher fO2 yields degassing of oxidized species (e.g., H2O, CO2, SO2), whereas lower fO2 causes degassing of reduced species (e.g., H2, CO, H2S, CH4). Note that the reduced H species, H2, is prone to thermal escape instead of condensing as liquid water. Therefore, we explore volcanic contribution of H2O through C-H-O-S degassing with shergottite-derived fO2 (= iron-wüstite mineral buffer (IW)–IW+3) [7], [8], estimated mantle H2O abundance (30–300 ppm) [9], and pressures relevant to the Martian crust and paleoatmosphere (5 kbar–103 bars) [10], [11].

Methods: In this study, we assess the contribution of H2O from magmatism through petrological modeling of C-H-O-S degassing with the thermodynamic modeling software, Magma and Gas Equilibrium Calculator (MAGEC) [12]. MAGEC employs laboratory thermochemical data, redox reactions, and mass balance calculations to assess the stability of eight volatile species in gas and melt phases. Conditions reflective of the shergottite mantle source encompass fO2 = IW–IW+3 [8]. There have been no rigorous constraints on mantle H2O content, so we consider a range (H2O ≈ 30–300 ppm) to explore volcanic H2O input [9]. Pressures tested range from the base of the Martian crust to estimates for the ancient atmosphere (5 kbar–103 bars). We estimate H2O contribution from degassing with the extent of degassing, the percentage of degassed H2O, and calculated volcanic mass for each period.

A crucial control on the amount of H2O produced through volcanism is the extent and evolution of magma generation. Employing rates of volcanism, as opposed to total volume of volcanism, allows for assessment of magmatic H2O contribution on a temporal scale. Rates of volcanism utilized for the Noachian, Hesperian, and Amazonian were 0.75 km3/yr, 1 km3/yr, and 0.1 km3/yr, respectively [13]. Previous models that calculate volcanic H2O contribution use the estimated volume of post-Noachian volcanism on Mars (~ 5 km GEL), derived from Martian surface observations and terrestrial ratios of intrusive to extrusive volcanism [14]. Ultimately, the pressures that we test extend beyond this “volcanic layer” to the base of the Martian crust (50 km ≈ 5 kbar) [10]; however, the pressure associated with the base of this volcanic layer (5 km ≈ 0.5 kbar) represents an intrusive magmatism scenario and minimum volcanic H2O contribution. In contrast, Martian paleoatmospheric pressures (~1–103 bars with a preferred atmospheric pressure of 0.5 bars) [11] correspond to extrusive volcanism and maximum H2O contribution. This volcanic layer also informs Martian petrologic evolution: we consider a primary magma generated by 10% partial melting of the mantle [15] that then undergoes 90% fractional crystallization to form the crustal volcanic layer. We employ a basaltic shergottite composition, as shergottites represent a long-lived magmatic source active through the Noachian and Hesperian [7]. Specifically, the magmatic contribution utilized is that of the evolved Los Angeles basaltic shergottite with a temperature of 1100°C [16].

Fig. 1: Estimates of H2O on the Martian surface and volcanic contribution. The total H2O abundance on the Martian surface is 100–1500 m GEL [2], [3]. Previous studies [4], [5] calculate a volcanic contribution from 3.8 Ga – present equal to 2.4–61 m GEL H2O. This study estimates a volcanic H2O contribution from 4.1 Ga – present of 0.17–799 m GEL H2O.
Results: Our results indicate that H₂O is a dominant vapor species degassed from Martian volcanism. Expectedly, lower $f_{O_2}$ yields higher proportions of reduced gas species over oxidized ones; thus, more oxidized conditions indicate greater surface emission of H₂O. If the early Martian mantle was reduced ($f_{O_2}$ at 1 bar = IW) with 150 ppm H₂O, volcanic degassing may have released a maximum volume of ~175 m GEL H₂O since 4.1 Ga. For a more oxidized mantle (1W+3 at 1 bar) with 150 ppm H₂O, volcanic degassing could have released a maximum of ~390 m GEL H₂O since the early Noachian. The source redox condition of early Mars, which has been recorded by basaltic shergottites to span three orders of magnitude, has a substantial impact on the H₂O emitted from magmatic processes.

For all tested $f_{O_2}$ and mantle H₂O abundances, our results indicate that H₂O is a dominant species degassed at pressures relevant to the Martian paleoatmosphere. Our simulations suggest that the minimum degassed H₂O abundance (mantle H₂O = 30 ppm; $f_{O_2}$ = IW; $P = 5$ kbar) is 0.17 m GEL and the maximum degassed H₂O abundance (mantle H₂O = 300 ppm; $f_{O_2}$ = IW+3; $P = 0.5$ bar) is 799 m GEL. Our maximum surficial H₂O estimates are significantly greater than previous estimates (40–61 m GEL). In addition to dominating vapor emission, H₂O is also prominent in the melt. H₂O and S²⁻ are the most abundant volatile species dissolved in the melt under all pressure and volatile conditions at IW to IW+3. Under degassing pressures relevant to the crust, magmas could contain 0.1–1 wt% H₂O and S²⁻.

Discussion: Magmatic degassing processes could deliver H₂O to the Martian surface and hydrate the Martian crust. Degassing could be sub-aerial, submarine, or sub-crustal. Extrusive volcanism (sub-aerial) would most efficiently cycle volatiles from the interior of Mars to the surface and yields maximum magmatic H₂O estimates ($P = 0.5$ bars). Submarine degassing, with added hydrologic pressure, would inject volatiles into fluid to potentially contribute to hydrothermalism. Intrusive magmatism most conservatively transports volatiles to the Martian surface; therefore, intrusive volcanism in the upper portion of the crust ($P = 0.5$ kbar ≈ 5 km depth) produces minimum magmatic H₂O.

This range in pressures contributes to the variation in estimated H₂O abundances, as do poor constraints on mantle H₂O content. Moderate mantle H₂O (150 ppm) and $f_{O_2}$ (IW+1.5) yield 29.1–324.5 m GEL of magmatic H₂O. The lower bound agrees with prior volcanic H₂O estimates (2.4–61 m GEL), but the upper bound of our result is enough water to align with total H₂O estimates for early Mars. The full range of mantle H₂O concentrations (30–300 ppm) at $f_{O_2}$ = IW+1.5 result in 0.02–665 m GEL H₂O. Furthermore, H₂O contents in Martian magma = 0.1–1 wt. % suggest that intrusive magmatism may have contributed to crustal hydration.

Our consideration of magmatic resurfacing during the Noachian provides greater abundances than previous studies that have utilized estimates of post-Noachian volcanism. Since 4.1 Ga, the greatest amount of water on Mars was emitted during the Hesperian. Inclusion of magmatic activity during the Noachian represents a volume of magma equivalent to a ~2 km GEL. Consideration of only volcanism during the Noachian and Hesperian yields volumes of H₂O ranging from 0.17–615 m GEL. The magmatic volumes from 4.1–present sum to a crustal layer ~9 km GEL, ~1/5 of the present-day crustal thickness. Such volumes of volcanism align with studies that propose rapid formation of the Martian crust at ~4.4 Ga [e.g., 15]. If pre-Noachian volcanic activity were considered, magmatic contribution of H₂O would be much greater. Regardless, our models indicate that volcanism could have been a substantial contributor of H₂O to the Martian surface. Additionally, intrusive magmatism may have aided in hydration of the Martian crust.

Our simulation results also indicate that CO₂ emitted from volcanism at 3–4.1 Ga is equivalent to $P_{CO_2} = 0.67–3.8$ bars, assuming no carbonation or atmospheric escape of the degassed CO₂. As it is greater than our preferred atmospheric pressure of 0.5 bars and slightly higher than the range of possible Martian atmospheric pressures [1], this apparent overestimation likely suggest significant loss of CO₂ to atmospheric escape and/or drawdown of CO₂ by weathering and carbonation processes. Nonetheless, our results suggest that volcanism could also have provided sufficient CO₂ to compose much of the ancient Martian greenhouse gas paleoatmosphere.