WHY THE MARTIAN MANTLE IS (MOSTLY) "WET." Sean C. Solomon[1], Oded Aharonson[2], Steven A. Hauck, II[3], Bruce M. Jakosky[4], Roger J. Phillips[5], and Maria T. Zuber[6]. [1]Dept. of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015; [2]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125; [3]Dept. of Geological Sciences, Case Western Reserve University, Cleveland, OH 44106; [4]Laboratory for Atmospheric and Space Physics and Dept. of Geological Sciences, University of Colorado, Boulder, CO 80309; [5]Dept. of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130; [6]Dept. of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139.

Introduction. The question of the water content of the mantle of Mars is an important one for reasons ranging from the composition of the objects from which the planet was assembled, to the melting conditions and transport properties of Martian mantle material, to the history of outgassing of water to the surface and its implications for geological and biological processes. One source of information on this question is the water content of the magmas from which Martian meteorites were formed, and Jones [1,2] has recently argued that those magmas "were effectively dry" and by implication "there is no compelling reason…that the Martian mantle should contain a significant amount of water" [1]. A broader view of water in the Martian mantle, which we take here, demonstrates that the water content of the Martian mantle likely depended on time and location, that "wet" and "dry" depend on one's perspective, and from many important perspectives the bulk of the Martian mantle is likely "wet."

Early Mars. Scenarios for the formation of the terrestrial planets, and Mars in particular, support the notion that the earliest Martian mantle contained some water. Whether water was incorporated in the growing terrestrial planets as a result of the accretion of objects formed outside of Mars's orbit [3] or of hydrated planetesimals formed within the inner solar system [4], geochemical arguments favor the addition of hydrous material throughout the planet formation process [4], an inference consistent with dynamical constraints, particularly if the gas giant planets formed early [5]. Accretion simulations suggest water mass fractions for Mars of 10^{-4} to 10^{-3} [6].

Isotope systematics in Martian meteorites [e.g., 7-9] and dynamical accretion simulations [e.g., 6] point to global differentiation on Mars within a few tens of millions of years after solar system formation, a process that likely included a global magma ocean incorporating most or all of the silicate fraction of the planet [10]. Cooling and fractionation of that magma ocean would have incorporated some water in the earliest solidifying phases [e.g., 11] as well as in any intercumulus liquid in the lower mantle, but much of the water would have been retained in the late-stage liquid that experienced some combination of outgassing of volatiles to the atmosphere and final solidification at shallow levels [10]. Overturn of the convectively unstable product of magma ocean solidification would have brought more water-rich upper layers to the lower mantle [10].

Crustal Formation. Most of the crust on Mars formed in the Early Noachian, on the basis of the time of formation of distinct silicate reservoirs [e.g., 8-9] and the density of large impact features [12]. By the Middle Noachian, crustal magmatism on Mars was concentrated in the Tharsis province, and by the beginning of the Late Noachian much of the magmatic additions to Tharsis had been completed [13]. Both of these aspects of Martian crustal history bear on the mantle water content.

Convective thermal history models that incorporate melting and crustal formation are sensitive to the assumed ductile flow law for mantle material. In particular, a mantle flow law appropriate to anhydrous material leads to high viscosities, inefficient convective heat transport, and substantial mantle melt production too late in Martian history to be consistent with early crustal formation [14]. In contrast, sufficient mantle water leads to a weaker flow law [15], more efficient convection, and an absence of large-scale melt production after the Early Noachian [14]. The difference in behavior is controlled by the pressure-dependent concentration of water in olivine, but mass fractions of water from 10^{-5} to 10^{-4} are sufficient to reduce the viscosity by requisite factors [16]. The thermal evolution models therefore point to mantle water concentrations of at least those levels for much of Martian history.

The history of Tharsis and of strong water-surface interaction on Mars hints at an additional constraint on mantle water. On the basis of both the strain field recorded in tectonic features [17] and the flow directions of Martian valley networks [13], most of the magmatism that contrib-

uted to the construction of the Tharsis rise occurred prior to the Late Noachian. The well-developed valley networks [e.g., 18] and extensive denudation of large areas of the highlands [e.g., 19] during the Late Noachian are suggestive that at least some of the water involved in these processes was added to the Martian atmosphere and hydrosphere by degassing from Tharsis magmas [13]. This connection has not been demonstrated conclusively, but the volume of material added to the crust at Tharsis would have contributed a volume of water equivalent to a global layer 10 to 100 m thick for magmatic water contents of 10^{-3} to 10^{-2} by weight [13].

Martian Meteorites. The most direct constraints on the water content of the Martian mantle come from the concentrations of water and other volatiles in Martian meteorites, all of which are igneous rocks derived from magmas produced by mantle partial melting. A wide range of estimates has been offered. Direct measurements of water in Martian meteorites yield contents of hundreds of ppm [e.g., 20], but McSween and others inferred pre-eruptive water contents as high as 1-2% from zoning of soluble trace elements in shergottite pyroxenes and from hydrous and anhydrous crystallization experiments [21]. The latter arguments and the inferred high magmatic water contents have both been challenged by Jones [1]. Nonetheless, estimates for the water weight fraction of the mantle source region of Chassigny by Jones [1] and of the shergottites by McSween and others [21] are both of order 10^{-4}.

There are reasons to believe, however, that inferences derived from Martian meteorites may not apply generally to the bulk of the Martian mantle. All but one of the Martian meteorites identified to date have igneous ages of 1.3 Ga or less [22] and sample the Middle to Late Amazonian epochs [23]. Volcanic units spanning such ages are primarily restricted to areas within the Tharsis and Elysium provinces [24,25], both long-lived volcanic centers within which the majority of magmatism occurred much earlier in Martian history. To the extent that the Martian mantle has not been well mixed over its history, an inference supported by the longevity of isotopically distinct mantle reservoirs [7-9], the mantle beneath Tharsis and Elysium may have been a sustained source of magmas from the Noachian to the Amazonian. If so, then the extensive magmatism during the Noachian may have substantially depleted the source regions of volatiles, with the result that inferences from Amazonian-aged Martian meteorites pertain only to that volatile-depleted mantle rather than the Martian mantle as a whole.

Concluding Discussion. Geophysical arguments suggest that the Martian mantle, from the period following global differentiation to the Late Amazonian, has been sufficiently "wet" that flow laws for mantle material are strongly influenced by water-weakened olivine. The requisite water contents are not contradicted either by expectations from planetary accretion scenarios or by what can be inferred from the water and volatile contents of Martian meteorites.

Given the extended history of magmatism at Tharsis and Elysium, and the likelihood that most of the Martian meteorites in our current collections were derived from young magmas in these regions, the Noachian magmas that contributed to the construction of Tharsis and Elysium likely were richer in volatiles than the parent magmas of nearly all Martian meteorites. The inference that outgassing of H_2O and CO_2 from the magmas that built up Tharsis and Elysium contributed significantly to the Martian atmosphere and hydrosphere during the Noachian [13] is therefore fully consistent with what is known about water in the Martian mantle.

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