

extent. It is possible that these bins could be dominated by data from the Argyre and Hellas Basins, which are within the two longitude wedges represented at these times; further study of the data in these  $L_s$  bins will be needed to resolve this question.

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**WATER ON MARS: INVENTORY, DISTRIBUTION, AND POSSIBLE SOURCES OF POLAR ICE.** S. M. Clifford, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058, USA.

Theoretical considerations and various lines of morphologic evidence suggest that, in addition to the normal seasonal and climatic exchange of  $H_2O$  that occurs between the martian polar caps, atmosphere, and mid- to high-latitude regolith (e.g., [1,2]), large volumes of water have been introduced into the planet's long-term hydrologic cycle by the sublimation of equatorial ground ice, impacts, catastrophic flooding, and volcanism. Under the climatic conditions that are thought to have prevailed on Mars throughout the past 3–4 b.y., much of this water is expected to have been cold-trapped at the poles. In this abstract the amount of polar ice contributed by each of the planet's potential crustal sources is discussed and estimated. The final analysis suggests that only 5–15% of this potential inventory is now in residence at the poles.

Recent estimates of the inventory of water on Mars suggest that the planet has outgassed the equivalent of a global ocean at least several hundred meters deep. Evidence for such a large inventory is provided by a long list of martian landforms whose morphology has been attributed to the existence of subsurface volatiles [3–6]. In particular, it is supported by the existence of the martian outflow channels, whose distribution, size, and range of ages suggest that a significant body of groundwater was present on Mars throughout much of its geologic history [4,5,7,8]. Based on a conservative estimate of the discharge required to erode the channels, and the likely extent of their original source region, Carr [4,5] estimates that Mars may have outgassed the equivalent of a global ocean of water 0.5–1 km deep.

On Mars there are essentially three reservoirs in which water can reside: the atmosphere, perennial polar caps, and near-surface crust. Of these, the atmosphere is known to contain ~15 precipitable micrometers of water averaged over the planet's surface, while the quantity of water stored as ice in the polar caps is equivalent to a global layer approximately 10 m deep. This leaves more than 98% of the suspected

global inventory of water on Mars unaccounted for—virtually all of which is thought to reside as ground ice and groundwater beneath the surface.

Although mean annual surface temperatures are below freezing everywhere on Mars, observations made by the Viking Orbiter Mars Atmospheric Water Detectors (MAWD) indicate a globally averaged frost point temperature of ~198 K. Therefore, given the present latitudinal range of mean annual surface temperatures (~154–218 K), any subsurface  $H_2O$  is unstable with respect to the water vapor content of the atmosphere at latitudes equatorward of  $\pm 40^\circ$  [9].

The survival of ground ice at equatorial and temperate latitudes was considered in detail by both Clifford and Hillel [10] and Fanale et al. [11]. They found that, for reasonable values of porosity and pore size, the near-equatorial crust has probably been desiccated to a depth of 300–500 m over the past 3.5 b.y., assuming that our present knowledge of the quasiperiodic changes in martian obliquity and orbital elements is accurate (e.g., [12–14]). However, because the sublimation of  $H_2O$  is sensitively dependent on temperature, the quantity of ice lost from the regolith is expected to decline with increasing latitude, falling to perhaps a few tens of meters at a latitude of  $35^\circ$  [10,11].

By integrating the the likely pore volume between the martian surface and the desiccation depths discussed above, Fanale et al. [11] have estimated that over the course of martian geologic history as much as  $2.7\text{--}5.6 \times 10^6 \text{ km}^3$  of  $H_2O$  (equivalent to a global ocean ~20–40 m deep) may have been sublimed from the equatorial regolith and cold-trapped at the poles. However, as mentioned at the outset of this discussion, the sublimation of equatorial ground ice is just one of several potential processes that may have episodically introduced large volumes of water into the atmosphere.

Perhaps the clearest evidence that the martian crust has been a major source of atmospheric water are the outflow channels. The abrupt emergence of these features from regions of collapsed and disrupted terrain suggests that they were formed by a massive and catastrophic release of groundwater [7,8,15]. Channel ages, inferred from the density of superposed craters, indicate at least several episodes of flooding—the oldest dating back as far as the Late Hesperian (~2–3 b.y. ago), while the youngest may have formed as recently as the Mid-to-Late Amazonian (i.e., within the last 1 b.y.) [16–20]. Based on a conservative estimate of how much material was eroded to form the channels (~ $5 \times 10^6 \text{ km}^3$ ) and the maximum sediment load that the flood waters could have carried (40% by volume), Carr [5] has estimated a minimum cumulative channel discharge of  $7.5 \times 10^6 \text{ km}^3$  of  $H_2O$  (the equivalent of a global ocean ~50 m deep).

Impacts into the ice-rich crust may have been another important source of atmospheric water. Assuming that the thickness of permafrost on Mars averages about 2.5 km and has an ice content of 20%, the volume of water excavated

and/or volatilized by an individual impact will range from  $\sim 34 \text{ km}^3$  for a crater 10 km in diameter to in excess of  $2.8 \times 10^5 \text{ km}^3$  for a major impact basin like Hellas ( $D \sim 2000 \text{ km}$ ). Given a global crater size-frequency distribution equivalent to that preserved in the cratered highlands (e.g., [21]), the resulting total volume of water that may have been injected into the atmosphere by impacts over the course of martian geologic history is roughly  $1.5 \times 10^7 \text{ km}^3$  ( $\sim 105 \text{ m}$ ). Note that, because the crater statistics of [21] do not include any correction for obliteration or erosion, this estimate is likely a lower bound.

Finally, as discussed by Greeley [22] and Plescia and Crisp [23], volcanism has probably also introduced large volumes of water into the martian atmosphere. For example, if the water content of martian magmas is comparable to that of terrestrial mafic to ultramafic lavas ( $\sim 1\%$  by weight), Plescia and Crisp [23] estimate that the formation of the volcanic plains in southeastern Elysium ( $5^\circ\text{N}$ ,  $195^\circ\text{W}$ ) may have alone exsolved between  $10^3$ – $10^4 \text{ km}^3$  of  $\text{H}_2\text{O}$ . Greeley [22] has taken a more global perspective, calculating the total volume of juvenile water released from the planet's interior by estimating the extent and thickness of all volcanic units visible on the planet's surface. However, the estimate of extrusive magma production on which Greeley's [22] calculation is based has recently been revised by Greeley and Schneid [24]. Substituting this revised figure into Greeley's [22] analysis suggests that volcanic processes have injected  $\sim 2.3 \times 10^6 \text{ km}^3$  ( $\sim 16 \text{ m}$ ) of  $\text{H}_2\text{O}$  into the atmosphere. It should be noted, however, that in light of our inability to accurately assess both the extent of plutonic activity and the magnitude of ancient ( $>4 \text{ b.y. old}$ ) volcanism, this estimate is probably a minimum. Note also that, unlike water derived from other crustal sources (which simply undergoes an exchange from one volatile reservoir to another), water released by volcanism represents an actual addition to the planet's outgassed inventory of  $\text{H}_2\text{O}$ . However, once this water has been introduced into the atmosphere, its fate is governed by the same processes that affect water derived from any other crustal source—leading to a slow but inexorable transfer of water from equatorial and temperate latitudes to the poles [10,11].

Indeed, even if we consider only those sources of atmospheric  $\text{H}_2\text{O}$  for which there is unambiguous evidence (i.e., volcanism and catastrophic floods), it suggests that Mars should possess a polar inventory of  $\text{H}_2\text{O}$  roughly an order of magnitude greater ( $\sim 1 \times 10^7 \text{ km}^3$ ) than that which is presently observed in the caps. If the potential contribution from impacts and the sublimation of equatorial ground ice is also included, it could easily increase this disparity by an additional factor of three.

Potential solutions to this mass balance problem include (1) the amount of water released to the atmosphere by volcanism, catastrophic floods, and other processes may have been significantly smaller than presently believed; (2) the

geographic location of the spin axis of Mars has wandered over geologic time due to changes in the planet's moment of inertia, thereby redistributing ice cold-trapped at the poles over a much larger area of the planet [25]; or (3) the bulk of the ice deposited in the polar regions has been reintroduced into the crust through the process of basal melting [26]. A more detailed discussion of polar deposition, basal melting, and the polar mass balance is contained in Clifford [27].

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**RHEOLOGY OF WATER-SILICATE MIXTURES AT LOW TEMPERATURES.** William B. Durham, Lawrence Livermore National Laboratory, Livermore CA 94550, USA.

Our laboratory studies of the effects of hard particulates on the rheology of ice have been mainly directed at the evolution of the Galilean satellites, but yield results that may be applicable to the rheology of the martian polar caps. Our experiments have explored the ductile rheology as well as brittle behavior of water + particulate (mainly quartz) mixtures in particulate volume fractions  $\phi$  ranging from 0.001 to 0.56, particulate sizes 1–150  $\mu\text{m}$ , temperatures 77–224 K, and deformation rates  $3.5 \times 10^{-7}$  to  $3.5 \times 10^{-4} \text{ s}^{-1}$ , under confining pressures of 50–100 MPa. Particulates act mainly to strengthen the material in the ductile field, although work by others has shown that very close to the melting temperature hard particulates can actually cause softening (possibly by impeding grain growth). So-called dispersion hardening by

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