WATER ON MARS: EVIDENCE FROM MINERALS AND MORPHOLOGY. P. R. Christensen[1] [1]Arizona State University, Department of Geological Sciences, Tempe, AZ 85287-6305; phil.christensen@asu.edu.

Introduction: A wealth of recent remote measurements of the mineralogy, elemental abundance, and morphology of the martian surface have greatly improved our view of the history of water on Mars. Mineralogic data from orbital spectroscopy reveal a volcanic planet that lacks extensive aqueous weathering or carbonate formation, but which has undergone significant localized aqueous mineralization. Mid- to high-latitude hydrogen abundances and unusual morphologies suggest extensive deposits of water ice with localized, recent melting to form gullies. The upper surface of Mars appears to have an extensive water inventory, but this water may have existed in a frozen state throughout much of martian history.

A Dry Mars: Global mineral mapping using Mars Global Surveyor Thermal Emission Spectrometer (TES) data has shown that Mars is dominated by volcanic minerals and volcanic rocks [1-3]. Rocks classified as basaltic on the basis of their mineralogy and inferred chemistry are found in the ancient cratered terrains of Mars and appear to be representative of the early martian crust. Detailed mapping using TES data has revealed the presence of olivine in abundances of 10-15% in basalts in isolated regions [4-6]. These rocks have been exposed to martian environmental conditions over long periods of time, yet show no unequivocal evidence for aqueous weathering products [1, 7].

Mars Odyssey Thermal Emission Imaging System (THEMIS) multi-spectral infrared data have revealed the presence of a layer of olivine-rich basalt exposed in the walls near the floor of Ganges Chasma [8]. This layer is 50-100 m thick, occurs beneath 4.5 km of overlying rocks, and extends over an area at least 30 by 100 km in size. The composition of the Ganges floor material determined from individual TES spectra is basaltic; the wall unit is similar but contains ~10-15% olivine with an Mg/(Mg+Fe) ratio of 68 (Fo68) [8]. The olivine-rich layer could have been; (1) emplaced as an olivine-enriched lava flow, followed by deposition of 4.5 km of overlying units; (2) injected as sill; (3) formed as a cumulate layer in layered intrusive body; or (4) deposited as a sedimentary layer in which olivine was enriched during transport or deposition. In any case, this ancient layer was once buried to a depth of at least 4.5 km and subsequently exposed at the surface. The preservation of olivine, which is unstable in aqueous conditions, indicates that (1) significant weathering did not occur deep beneath the surface in this particular region, and (2) significant surface weathering has not occurred since this layer was exposed.

Carbonates in the regolith have long been proposed to play an important role in the CO_2 exchange cycle, acting as a reservoir for sequestering large amounts of CO_2 from the ancient martian atmosphere [e.g. 9, 10-12]. Thus, the presence, or absence, of carbonates has important implications for the evolution of the martian atmosphere, placing constraints on the abundances, reaction chemistry, and history of H_2O and CO_2. To date, neither TES nor THEMIS data have revealed any evidence for carbonate rock units on Mars, and it is possible to conclude that large-scale (>10's km sized) carbonate deposits are not currently exposed at the surface of Mars [1]. It remains possible that carbonate deposits are buried by younger deposits or UV dissociated to calcium oxide [13]. However, the detection of unusual, and presumably rare, mineralized hematite units shows that either carbonates are less common than mineralized hematite, or the processes by which they remain "hidden" are more efficient.

Recent analysis of the spectra of Mars bright regions in which the atmospheric contributions have been rigorously removed [14] have detected the occurrence of minor (<5%) abundances of carbonates in the fine-grained dust of Mars [15, 16]. The low carbonate abundance and its occurrence on dust-covered surfaces with high surface-area-to-volume ratios are consistent with carbonate formation by interaction between the current Mars atmospheric CO_2 and water vapor and surface mineral grains as proposed by Booth and Kieffer [9, 15]. While it is possible that these carbonates formed by erosion and dissemination of extensive carbonate rock units, a more likely scenario is their formation *in situ* in the current atmosphere [15, 16]. Thus, the detection of carbonates, rather than suggesting an ancient period of a warm, wet Mars, instead argues for minor carbonate formation in a cold, dry Mars. Furthermore, the detection of carbonates by TES argues against UV dissociation or difficulties in detecting carbonates from thermal IR spectra as the explanation for the lack of detection of widespread carbonate units. It appears that carbonate rock layers may never have formed, and Mars may never have experienced a period of extensive interaction between large amounts of liquid water and a thick CO_2 atmosphere.

A Wet Mars: While much of the mineral evidence from TES, THEMIS, and other spectroscopic observations argues against extensive, global aqueous miner-

alization, there are examples of localized deposits that are suggested to have formed through aqueous processes. The TES data have revealed unique deposits of crystalline gray hematite exposed at the martian surface in Sinus Meridiani, Aram Chaos, and in scattered locations throughout Valles Marineris. The Sinus Meridiani material is an in-place, rock-stratigraphic sedimentary unit characterized by smooth, friable layers composed primarily of basaltic sediments with ~10-15% crystalline gray hematite. This unit has outliers to the north that appear to have formed by stripping and removal. The hematite within Aram Chaos occurs in a sedimentary layer within a closed basin that was likely post-dates the formation of associated chaos and outflow terrains. This unit appears to be exposed by erosion and may be more extensive beneath the surface. The Valles Marineris occurrences are closely associated with the interior layered deposits, and may be in place within the layers or eroded sediments. Overall, crystalline gray hematite is extremely uncommon at the surface, yet in all observed locations it is closely associated with layered, sedimentary units.

Formation modes for gray hematite detected by TES have been grouped into two classes: (1) chemical precipitation and (2) thermal oxidation of magnetite-rich lavas [17, 18]. Chemical precipitation models include (1a) low-temperature precipitation of Fe oxides/ oxyhydroxides from standing, oxygenated, Fe-rich water, followed by subsequent alteration to gray hematite, (1b) low-temperature leaching of iron-bearing silicates and other materials to leave a Fe-rich residue (laterite-style weathering) which is subsequently altered to gray hematite, (1c) direct precipitation of gray hematite from Fe-rich circulating fluids of hydrothermal or other origin, and (1d) formation of gray hematitic surface coatings during weathering [17, 18]. Models (1a) and (1b) require an oxidative alteration process (e.g., burial metamorphism) to convert Fe-oxide/oxide assemblages (e.g., red hematite, goethite, ferrihydrite, goethite, and siderite) to coarse-grained (>10 μm), gray hematite.

Although none of these models can currently be excluded, the geologic setting of the martian hematite deposits suggest they formed by chemical precipitation from aqueous fluids, under either ambient or hydrothermal conditions [18, 19]. All three hematite sites are sedimentary environments, and the hematite-bearing units in Aram and Valles Marineris occur in closed sedimentary basins consistent with deposition in water. Sub-surface water was clearly present in Aram Chaos as evidenced by collapse and outflow features, and the hematite-bearing unit in Ophir/Candor is associated with layered, friable deposits that may be of aqueous origin [20-22]. The primary argument against thermal oxidation of magnetite-rich lavas (model 2) is the absence of distinct morphological evidence for lava flows or constructs, and the presence of evidence for material more friable than primary lava in the Sinus Meridiani hematitic unit [18, 23].

Thus, the TES mineralogic data provide evidence that liquid water was stable near the surface, probably for extensive periods of time, in specific locations on early Mars.

An Icy Mars: Mars Odyssey Gamma Ray and Neutron Spectrometer observations have shown that water ice is abundant at latitudes poleward of ~50° in both hemispheres [24-26]. It has also been suggested that extensive deposits of unusual materials that mantle the martian mid-latitudes are ice-rich deposits [27-29]. A model has been proposed in which the recent martian gullies that are found in the mid-latitudes are related to these mid-latitude, ice-rich mantles, and that the gullies were eroded recently through melting of these overlying deposits [30]. In this model: (1) Water is transported from the poles to mid-latitudes during periods of high obliquity, forming a water-rich snow layer [31-34]. (2) Melting occurs as mid-latitude temperatures increase, producing liquid water that is stable beneath an insulating layer of overlying snow; (3) Gullies form on snow-covered slopes through erosion by meltwater or as a result of meltwater seeping into the loose slope materials and destabilizing them; (4) Gullies incised into the substrate are observed where the snow layer has been completely removed; (5) Patches of snow remain today where they are protected against sublimation by a layer of desiccated dust/sediment [27]; and (6) Melting could be occurring at the present time in favorable locations in these snowpacks [30].

While melting snow provides an interesting possible explanation for the formation of recent gullies, the more important outcome of this model is the evidence that the gullies provide that the mid-latitude mantles are not simply volatile rich, but must be primarily water ice. Ice that enters the regolith and fills the pores through vapor exchange during periods when the mid-latitude temperatures are relatively low [27, 35], will most likely exit in the same manner when the climate warms. Therefore, it is unlikely that ice-rich soils will produce the melting necessary to erode gullies. On the other hand, snow deposits are capable of producing meltwater due to the solid-state greenhouse effect of ice that contains minor amounts (~1,000 parts per million, mass) of dust [36]. Thus, the formation of gullies by melting snow provides evidence that the mid-latitude deposits are dirty ice, rather than icy dirt.

This model suggests that at least some mid-latitude mantles were deposited directly on the surface with

(very) high ice-to-soil ratios. The high (>50% volume) water-ice abundances inferred in the upper few meters at high-latitudes from Odyssey Neutron and Gamma-Ray Spectrometer data [24-26], suggest that the ice in these regions was also deposited on the surface rather than in pores. A common surface texture found from 30-50° latitude in both hemispheres has been interpreted to be the result of devolatilization and erosion of ice-cemented soils that are up to several meters thick [27]. Mustard et al, [27] suggested that the ice was recently emplaced through vapor diffusion into the pore space [27, 37]. However, these eroded mantles transition poleward into continuous mantles, and the boundary of this transition corresponds to the sharp increase observed in near-surface ice abundance [38]. This correlation suggests that the equatorward portion of this mantle may be the same ice-rich material whose upper few meters have been thoroughly desiccated [30]. In this case the high-latitude ice-rich materials observed by the Odyssey Neutron/Gamma-Ray spectrometers, the poleward continuous mantles, the dissected mid-latitude mantles, and the gully-forming snow deposits may all have been formed by deposition of atmospheric condensates onto the surface, and may all have high (70-100%) water-ice abundances. If this model is correct, then these surface mantles would have substantially more water than previously suggested [27].

Summary: The available remote measurements of martian mineralogy and morphology suggest a complex and diverse set of states of martian water. Near-surface water ice appears to be more abundant than previously considered. Aqueous processes have occurred locally to produce hematite mineralization in isolated regions. However, the lack of extensive carbonates (and clays?) and the presence of ancient olivine suggests that liquid water has been rare at or near the surface over time. Together these observations suggest a relatively water-rich surface layer in which water is primarily in a frozen state expect for isolated, and very interesting, events.

References:

[1] Christensen, P.R., et al. (2001), *J. Geophys. Res., 106*. 23,823-23,871. [2] Bandfield, J.L., et al. (2000), *Science, 287*. 1626-1630. [3] Hamilton, V.E., et al. (2001), *J. Geophys. Res., 106*. 14,733-14,747. [4] Clark, R.N. and T. Hoefen (2000), *Bull. Am. Astron. Soc., 32(3)*. 1118. [5] Hoefen, T.M. and R.N. Clark (2001), *Lunar and Planetary Science Conference, XXXII*. abstract #2049 (CD-ROM). [6] Hamilton, V.E., et al. (submitted), *Meteoritics and Planetary Science*. [7] Bandfield, J.L. (2002), *J. Geophys. Res., 107*. 10.1029/2001JE001510. [8] Christensen, P.R., et al. (submitted), *Science*. [9] Booth, M.C. and H.H. Kieffer (1978), *J. Geophys. Res., 83*. 1809-1815. [10] Fanale, F.P. and B.M. Jakosky (1982), *Planet. Space Sci., 30*. 819-831. [11] Kahn, R. (1985), *Icarus, 62*. 175-190. [12] Fanale, F.P., et al., *Epochal climte change and volatile history*, in *Mars*, H.H. Kieffer, et al., Editors. 1992, University of Arizona Press: Tucson, AZ. [13] Mukhin, L.M., et al. (1996), *Nature, 379*. 141-143. [14] Bandfield, J.L. and M.D. Smith (2003), *Icarus, 161*. 47-65. [15] Bandfield, J.L., et al. (2003), *Lunar and Planet. Sci., XXXIV.* Abstract #1723 (CD-ROM). [16] Bandfield, J.L., et al. (submitted), *Science*. [17] Christensen, P.R., et al. (2000), *J. Geophys. Res., 105*. 9623-9642. [18] Christensen, P.R., et al. (2001), *J. Geophys. Res., 106*. 23,873-23,885. [19] Hynek, B.M., et al. (2002), *, J. Geophys. Res., 107*. 5088, doi:10.1029/2002E001891. [20] McCauley, J.F., *Geologic Map of the Coprates Quandrangle of Mars, scale 1:5,000,000.* 1978, U.S. Geol. Surv. Misc. Inv. Series Map I-897. [21] Lucchitta, B.K. (1982), *Reports of Planetary Geology Program, NASA TM-85127*. 233-234. [22] Nedell, S.S., et al. (1987), *Icarus, 70*. 409-441. [23] Arvidson, R.E., et al. (in press), *J. Geophys. Res.* [24] Boynton, W.V., et al. (2002), *Science, 297*. 81-85. [25] Feldman, W.C., et al. (2002), *Science, 297*. 75-78. [26] Mitrofanov, I., et al. (2002), *Science, 297*. 78-81. [27] Mustard, J.F., et al. (2001), *Nature, 412*. 411-414. [28] Malin, M.C. and K.S. Edgett (2001), *J. Geophys. Res., 106*. 23,429-23,570. [29] Carr, M.H. (2001), *J. Geophys. Res., 106*. 23,571-23,595. [30] Christensen, P.R. (2003), *Nature, 422*. 45-48; doi:10.1038/nature01436. [31] Toon, O.B., et al. (1980), *Icarus, 44*. 552-607. [32] Jakosky, B.M. and M.A. Carr (1985), *Nature, 315*. 559-561. [33] Jakosky, B.M., et al. (1995), *J. Geophys. Res., 100*. 1579-1584. [34] Haberle, R.M., et al. (2001), *J. Geophys. Res., 106*. 23,317-23,326. [35] Costard, F., et al. (2002), *Science, 295*. 110-113. [36] Clow, G.D. (1987), *Icarus, 72*. 95-127. [37] Mellon, M.T. and B.M. Jakosky (1995), *J. Geophys. Res., 100*. 11,781-11,799. [38] Tokar, R.L., et al. (2002), *J. Geophys. Res., 29*. 1904, doi:1029/2002GL015691.