high emission angles, i.e., near the planetary limb. The atmosphere is assumed to be optically thin in this model, so optical depths greater than 0.2 are not modeled using this formulation. Hapke's bidirectional reflectance function is used to model the surface scattering, assuming a phase function of the form $P(a) = 1 + b\cos(a)$, where a is the phase angle. Dust was assumed to be responsible for all the atmospheric scattering in this model (Rayleigh scattering in the martian atmosphere is insignificant in visible light).

The effects of turbulence in the terrestrial atmosphere ("seeing") upon groundbased Mars images were simulated by convolving a smearing function similar to that used by Lumme [5] with theoretical profiles. The results of this convolution indicate that changes in optical depth of 0.1 can be observed from Earth even with 2 arcsec seeing if the atmosphere is optically thin (small changes in opacity cannot be distinguished in the optically thick case). The shape of the photometric profile is not diagnostic of scattering in all cases, but the absolute reflectance can be used to infer the optical depth of dust in the atmosphere. Therefore, it should be possible to determine the optical depth of aerosols in an optically thin martian atmosphere using well-calibrated groundbased images of Mars. To test the viability of this method, we are comparing Viking data with nearly simultaneous groundbased photographs of Mars taken during the 1977–1978 apparition. The results of this comparison will be reported at the workshop.

References: [1] Martin L. J. and Zurek R. W. (1993) *JGR, 98,* 3221. [2] Zurek R. W. and Martin L. J. (1993) *JGR, 98,* 3247. [3] Arvidson R. E. et al. (1989) *JGR, 94,* 1573. [4] Herkenhoff K. E. and Murray B. C. (1990) *JGR, 95,* 1343. [5] Lumme K. (1976) *Icarus, 29,* 69. [6] Thorpe T. E. (1978) *Icarus, 36,* 204. [7] Thorpe T. E. (1982) *Icarus, 49,* 398. [8] Gierasch P. J. and Goody R. M. (1972) *J. Atmos. Sci., 29,* 400. [9] Haberle R. M. et al. (1982) *Icarus, 50,* 322. [10] Barnes J. R. (1990) *JGR, 95,* 1381. [11] Murray B. C. et al. (1972) *Icarus, 17,* 328. [12] Cutts J. A. et al. (1976) *Science, 194,* 1329. [13] Cutts J. A. (1979) *JGR, 84,* 2975. [14] Squyres S. W. (1979) *Icarus, 40,* 244. [15] Toon O. B. et al. (1980) *Icarus, 44,* 552. [16] Carr M. H. (1982) *Icarus, 50,* 129. [17] Howard A. D. et al. (1982) *Icarus, 50,* 161. [18] Plaut J. J. et al. (1988) *Icarus, 75,* 357. [19] Thomas P. et al. (1992) in *Mars* (H. H. Kieffer et al., eds.), 767–795, Univ. of Arizona, Tucson. [20] Martin L. J. et al. (1991) *Bull. A.A.S., 23,* 1217. [21] Clancy R. T. (1992) personal communication. [22] Ingersoll A. P. and Lyons J. R. (1991) *Bull. A.A.S., 23,* 1217. [23] Zurek R. W. (1982) *Icarus, 50,* 288. [24] Esposito L. W. et al. (1990) *Bull. A.A.S., 22,* 1076. [25] Thorpe T. E. (1977) *JGR, 82,* 4151. [26] Jaquin F. et al. (1986) *Icarus, 68,* 442. [27] Hillier J. et al. (1991) *JGR, 96,* 19203.

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MARS ATMOSPHERIC LOSS AND ISOTOPIC FRACTIONATION BY SOLAR-WIND-INDUCED SPUTTERING AND PHOTOCHEMICAL ESCAPE. B. M. Jakosky[1], R. O. Pepin[2], R. E. Johnson[3], and J. L. Fox[4], [1]Laboratory for Atmospherics and Space Physics, University of Colorado, Boulder CO 80309, USA, [2]School of Physics and Astronomy, University of Minnesota, Minneapolis MN 55455, USA, [3]University of Virginia, Charlottesville VA 22908, USA, [4]State University of New York, Stony Brook NY 11794, USA.

We examine the effects of loss of Mars atmospheric constituents by solar-wind-induced sputtering and by photochemical escape during the last 3.8 b.y. Sputtering is capable of efficiently removing all species from the upper atmosphere including the light noble gases; N is removed by photochemical processes as well. Due to diffusive separation (by mass) above the homopause, removal from the top of the atmosphere will fractionate the isotopes of each species with the lighter mass being preferentially lost. For C and O, this allows us to determine the size of nonatmospheric reservoirs that mix with the atmosphere; these revervoirs can be CO_2 adsorbed in the regolith or H_2O in the polar ice caps. We have constructed both simple analytical models and time-dependent models of the loss from and supply of volatiles to the martian atmosphere.

Both Ar and Ne require continued replenishment from outgassing over geologic time. For Ar, sputtering loss explains the fractionation of $^{36}Ar/^{38}Ar$ without requiring a distinct epoch of hydrodynamic escape (although fractionation of Xe isotopes still requires very early hydrodynamic escape). For Ne, the current ratio of $^{22}Ne/^{20}Ne$ represents a balance between loss to space and continued resupply from the interior; the similarity of the ratio to the terrestrial value is coincidental. For Ni, the loss by both sputtering and photochemical escape would produce a fractionation of $^{15}N/^{14}N$ larger than observed; an early, thicker CO_2 atmosphere could mitigate the N loss and produce the observed fractionation as could continued outgassing of juvenile N. Based on the isotopic constraints, the total amount of CO_2 lost over geologic time is probably of order tens of millibars rather than a substantial fraction of a bar. The total loss from solar-wind-induced sputtering and photochemical escape, therefore, does not seem able to explain the loss of a putative thick, early atmosphere without requiring formation of extensive surface carbonate deposits.

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SNC METEORITES AND THEIR IMPLICATIONS FOR RESERVOIRS OF MARTIAN VOLATILES. J. H. Jones, Mail Code SN4, NASA Johnson Space Center, Houston TX 77058, USA.

The SNC meteorites and the measurements of the Viking landers provide our only direct information about the abundance and isotopic composition of martian volatiles [1,2]. Indirect measurements include spectroscopic determinations of the D/H ratio of the martian atmosphere [3]. Here I present a personal view of volatile element reservoirs on Mars, largely as inferred from the meteoritic evidence. This view is that the martian mantle has had several opportunities for dehydration and is most likely dry, although not completely degassed. Consequently, the water contained in SNC meteorites was most likely incorporated during ascent through the crust. Thus, it is possible that water can be decoupled from other volatile/incompatible elements, making the SNC meteorites suspect as indicators of water inventories on Mars.

Multiple Reservoirs of Volatiles on Mars: The covariation of $^{129}Xe/^{132}Xe$ with $^{84}Kr/^{132}Xe$ among the members of the SNC suite strongly implies that there are at least two volatile element reservoirs on Mars [4]. The first, best associated with the Chassigny meteorite, has a solar $^{129}Xe/^{132}Xe$ ratio of ~1 [4]. The second, best associated with shock glasses from the EETA79001 shergottite, has $^{129}Xe/^{132}Xe$ ~2 [4] and is within error of the Viking measurement of martian air [1]. Because Chassigny is a cumulate igneous rock that appears to have experienced minimal weathering [5,6] and interaction with crustal materials [7] (but see below!), it is assumed here that Chassigny's anhydrous, volatile-element component is derived from the martian mantle. Conversely, the volatiles contained within the shock glasses of EETA79001 are thought to be derived from the martian atmosphere. The simplest alternative to this scenario is that the different subsets of SNC meteorites did not originate from the same planet [8].

The Mantle Reservoir: I advocate that the martian mantle has had little input from crustal or atmospheric sources and is most likely dry. The mantle of Mars is probably more depleted than the MORB mantle of the Earth [ε_{Nd} (Mars) = +20–25 vs. ε_{Nd} (MORB) = +10–12]. I also believe that the chemical and isotopic characteristics of the martian mantle were established very early. A corollary of this perspective is that most of the water contained in SNC meteorites is crustal.

A final (and more model-dependent) inference is that the martian mantle is relatively homogeneous and has been so over most of the planet's history. The logic, as presented by Jones [7], is somewhat convoluted: (1) Long-lived parent-daughter pairs, such as ^{238}U-^{206}Pb, ^{87}Rb-^{87}Sr, and ^{147}Sm-^{143}Nd, indicate that the ~180-m.y. shergottites [9] were produced from a mantle chemically similar to that which produced the nakhlites (and Chassigny) at ~1.25 b.y. (2) The crucial assumption behind this extrapolation from 1250 m.y. to 180 m.y. is that the parent-daughter ratio of the martian mantle that pertained between 4.5 aeons and 1.25 aeons also pertains subsequently. (3) The simplest way for this assumption to be true is if there was an early differentiation event that produced (a) enriched crust; (b) a homogeneous, highly depleted mantle; and (c) a metallic core. This depleted mantle was then tapped at various times, producing basalts over the history of the planet.

(Although the complexities arising from short and intermediate-lived nuclei, such as ^{146}Sm and ^{235}U, indicate that this model is somewhat oversimplified [7,10], it can nevertheless explain the ~4.5-aeon shergottite whole-rock Rb-Sr isochron [7]. And, as indicated above, the model can also isotopically relate the various SNCs to a common mantle source region, regardless of their individual crystallization ages.)

The large difference between the $^{129}Xe/^{132}Xe$ ratios of the crust and mantle is most plausibly attributed to the decay of ^{129}I ($t_{1/2}$ = 16 m.y.). If so, this iodine must have been "degassed" very early in the planet's history, consistent with the model given above, which was based on long-lived nuclei. There has presumably also been insignificant transport of Xe from the crust (or atmosphere) to the mantle, since mantle (Chassigny) Xe is isotopically indistinguishable from solar. This is consistent with the inference from Viking imaging that terrestrial-style plate tectonics and slab subduction has not been active on Mars for ~4 b.y. [11]. Consequently, it is inferred that the martian mantle and its volatiles have remained effectively isolated over most of the history of the planet. Accordingly, transport of volatiles has been chiefly from mantle to crust. The exception to this rule is water, since the martian mantle is thought to be dry.

Desiccation of the Martian Mantle: The SNC meteorites contain significant water [2] and it has often been assumed that that water is mantle-derived [12]. There are at least three reasons to suspect that this is not so: (1) Initially, before the formation of a core, there was presumably excess metal [13,14], which should have quantitatively reacted with oxidized phases, such as water or hydroxyl ions. (2) Following core formation, there was an early episode of crust formation. Consequently, the martian mantle should be depleted in incompatible, crust-forming elements, including water. (3) The water in terrestrial magmas is most probably not juvenile, but subducted, recycled water [15]. Since subduction does not appear to be an important process on Mars and since the Xe isotopic ratio of the mantle has remained unchanged relative to solar, it seems unlikely that volatile transport from crust to mantle has been significant (but see below).

An important piece of evidence in support of this view is the recent measurement of the D/H ratios of hydrous minerals in the SNC meteorites. At this writing, all measurements of water in SNCs are compatible with a single, isotopically heavy source with a D/H ratio of +4000‰ [16,17]. This value is so large that relatively massive loss of H from the planet, relative to D, is implied. Also, since this D/H ratio is in agreement with spectroscopic measurements of the martian atmosphere [3], the most likely source of SNC water is the crust or the atmosphere, which could have lost H to space.

Again, these inferences also imply that there has probably been a decoupling between water and other volatile/incompatible elements. For example, in the case of Chassigny, water is inferred to have been acquired during passage through the crust without addition of other volatiles such as Xe. Consequently, it seems difficult, using the SNCs, to make meaningful deductions about the water inventory of Mars.

Oxidation of the Martian Mantle: Has there been absolutely no cycling of water into the martian mantle over geologic time? Probably not. The phase assemblages of SNC meteorites imply that the redox state of the martian mantle is ~QFM, much like that of the Earth [5]. This O fugacity is considerably higher than is inferred from most models of core formation [13]. Consequently, the addition of small amounts of oxidized materials to the martian mantle have probably raised the mantle's O fugacity over geologic time. The lever arm here is quite large, as small amounts of such oxidants go a long way. Only 10 ppm of material with an intrinsic fo_2 of 10^{-3} is required to change a reduced mantle, with an fo_2 of 10^{-12}, to an oxidized one ($fo_2 = 10^{-8}$).

Atmospheric/Crustal Reservoir: The inferences from the Viking measurements and those based on the shock glasses of EETA79001 are amazingly consistent [18]. Consequently, it appears that we know the chemical and isotopic composition of the martian atmosphere quite well. This is in stark contrast to the convoluted and torturous machinations that have been required to decipher the SNCs and the story they have to tell. In brief, the martian atmosphere is dominated by CO_2, has a very large $^{40}Ar/^{36}Ar$ ratio of ~3000 (vs. ~300 for the Earth), a $^{129}Xe/^{132}Xe$ ratio of ~2 (vs. 0.98 for the Earth), a $^{15}N/^{14}N$ ratio of +600‰ (relative to terrestrial air), and a D/H ratio of ~+4000‰ (~5 times that of terrestrial ocean water). Thus, the atmosphere appears to be enriched in radiogenic components (^{40}Ar and ^{129}Xe), as well as in the heavier isotopes of stable elements (^{15}N and D). The enrichment of heavy stable isotopes is not well understood, although various atmospheric loss processes are likely to be responsible [19]. However, the enrichment of radiogenic isotopes is most plausibly attributed to crustal degassing over geologic time. Mantle degassing will presumably only dilute the effect of the crust-derived component. Thus, if the present atmosphere can be used as a guide, it appears that crustal degassing has dominated mantle degassing over the history of the planet.

Summary: There is currently evidence for two ancient, isolated, and quite distinct volatile element reservoirs on Mars. One is attributed to the martian mantle and is believed to be dry. The second has been shown to be much like the martian atmosphere and/

or the martian crust and is likely to be much wetter. SNC meteorites have probably gained their water by assimilation of crustal materials, and thus are probably poor indicators of the abundance of water on Mars.

References: [1] Bogard D. D. and Johnson P. (1983) *Science, 221,* 651–654. [2] Karlsson H. et al. (1992) *Science, 255,* 1890–1892. [3] Bjoraker G. L. et al. (1989) *Proc. 4th Intl. Conf. on Mars,* 69–70. [4] Ott U. (1988) *GCA, 52,* 1937–1948. [5] McSween H. Y. Jr. (1985) *Rev. Geophys., 23,* 391–416. [6] Treiman A. H., personal communication. [7] Jones J. H. (1989) *Proc. LPS 19th,* 465–474. [8] Ott U. and Begemann F. (1985) *Nature, 317,* 509–512. [9] Jones J. H. (1986) *GCA, 50,* 969–977. [10] Harper C. L. Jr. et al. (1993) *Science,* in press. [11] Phillips R. J. and Ivins E. R. (1979) *Phys. Earth Planet. Inter., 19,* 107–148. [12] Johnson M. C. et al. (1991) *GCA, 55,* 349–366. [13] Treiman A. H. et al. (1987) *Proc. LPSC 17th,* in *JGR, 92,* E627–E632. [14] Wänke H. and Dreibus G. (1988) *Phil. Trans. Roy. Soc. London, A325,* 545–558. [15] Sheppard S. M. F. (1977) *Stable Isotopes and High Temperature Geological Processes* (J. W. Valley et al., eds.), 165–183, *Rev. of Mineralogy, 16.* [16] Watson L. L. (1993) Presentation to the 56th annual Meteoritical Society meeting. [17] Kerridge J. F. (1988) *LPS XIX,* 599–600. [18] Pepin R. O. (1985) *Nature, 317,* 473–475. [19] Pepin R. O. (1992) *Annu. Rev. Earth Planet. Sci., 20,* 389–430.

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THE NORTHERN PLAINS MSATT MEETING, AND A CALL FOR A FIELD-ORIENTED SUCCESSOR TO MSATT.

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The Workshop on the Martian Northern Plains: Sedimentological, Periglacial, and Paleoclimatic Evolution (August 9–15, 1993) formally was devoted to a review of our knowledge of the martian northern plains and presentation of recent ideas pertaining to the geologic and climatic evolution of this interesting region. The meeting was held in Fairbanks to allow easy access to Mars-like terrains in central and northern Alaska. There is no place on Earth that is a close analog of the martian northern plains, but parts of Alaska come reasonably close in some respects, so we may expect that some of the processes occurring there are similar to processes that have occurred (or are hypothesized to have occurred) on Mars. The meeting was sited in Fairbanks because of (1) the accessibility of Mars-like landscapes, (2) the availability of logistical support facilities, and (3) the willingness of knowledgeable faculty at the University of Alaska to lead field trips.

The meeting organizers invited the participation of four scientists (T. Péwé, J. Begét, R. Reger, and D. Hopkins) with expertise in Alaskan geology, cold-climate geomorphology, and cold-climate physical processes. These scientists actively participated in the workshop and led us in two major field trips and a low-altitude overflight. Field Trip I (2 days) was to the Alaska Range and interior Alaska between Fairbanks and the Alaska Range; Field Trip II (1 day) was in the Fairbanks area; and the overflight (1 day) took us to Barrow (where we stopped and engaged in a brief field excursion), the Prudhoe Bay area, and the Brooks Range. The formal part of the meeting (2 days) was capped by an informal evening discussion, principally by the "terrestrial experts," that focused around a small selection of Mars slides that had engendered considerable discussion and controversy. A synopsis of this important discussion and of the field trips and overflight have been presented in the formal meeting summary [1].

Approximately 20 cameras recorded our field activities and the highlights of our overflight, resulting in some remarkable images of thermokarst, pingoes, ice-wedge polygons, sorted stone stripes and stone circles, gelifluction sheets, ice-cored moraine, eskers, alpine glaciers, the Arctic coast, and many other periglacial and glacial landforms. Field trip participants were introduced to some landforms that they had never observed previously (many had not even heard of them), most notably the nivation hollow and the cryoplanation terrace, both of which are periglacial features that are produced through the action of melting snow packs over permafrost, and both of which may have Mars analogs. The interaction of eolian, glacial, and periglacial processes, the results of which were observed in the the field, left indelible images in the minds and on the films of many participants. For instance, classic ventifacts on the summit of a moraine, and thick deposits of loess composed of dust that was originally derived from outwash plains, attested to the importance of wind modification or eolian genesis of many landforms and rock units that are an integral part of the regional glacial geologic assemblage. This series of observations of the interplay of wind and ice processes became a sharply imprinted reminder that multiple processes are likely to have operated in concert on Mars as well.

The involvement of Earth scientists was a major factor in the success of this field-oriented workshop. Many participants left the meeting with the conviction that interaction between the Mars and Earth science communities, as exhibited at the northern plains meeting, should continue, and that the combination of formal workshops with field studies is the nominal way for the deepest interaction to occur.

Call for Future Field-oriented Meetings of the Mars Science Community: It is widely acknowledged that Mars is an Earth-like planet (relative to other objects in the solar system). Accordingly, virtually all geomorphological interpretations of Mars are based, in part, on analogical inferences drawn directly from (or modified from) observations and interpretations of terrestrial geologic features. This is a justifiable basis from which to proceed in our studies of martian geological history, climate evolution, and atmospheric evolution, because there are insufficient data to build a geology of Mars from a totally "martian" perspective.

Some of the most dynamic recent controversies in Mars science have centered on geologic (or geomorphologic) interpretations of features that seem to speak differently to different observers. The controversies and the interpretations, of course, are in the minds of the observers, not in the rocks of Mars! The rocks surely have their stories to tell in all their fine detail, and it is the planetary geologists' job to decipher these stories. A roughly consistent geologic explanation of the martian surface has eluded Mars geologists, as a group, thus far. The problem is that, with the data we have, there are too many processes on Earth that might have formed many of the varied martian landforms. One can excuse the physical modelers when they sieze on the geologists' consistent descriptions of a very few types of landforms (e.g., sand dunes and volcanos) and frame very specific, and sometimes overly conservative, models around these limited observations and interpretations. Many geologists consider much of the recent Mars modeling to have very little relevance to the most dynamic episodes in martian geologic history; this is perhaps inevitable until the Mars geologists reach a consensus on a few of the major issues, and this is not likely to happen until new types of data, especially "ground truth," are obtained.