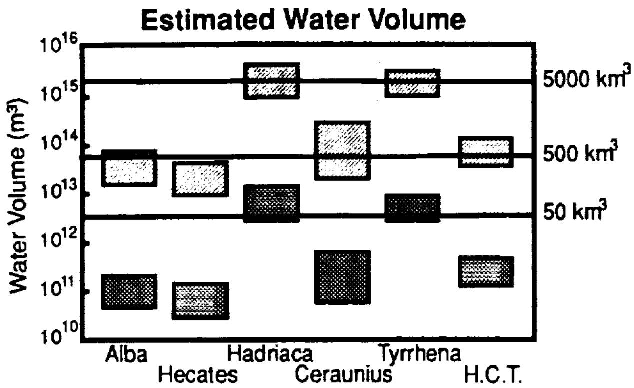

Fig. 2.

geologic unit [3]. A uniform, globally higher heat flow should not produce such localized sapping valleys. It is for these reasons that we invoke localized hydrothermal systems for martian valley genesis. Such hydrothermal systems would be localized in surface extent, yet (as the simulations suggest) draw groundwater from great distances while focusing outflow into relatively small regions. The hydrothermal discharge would also preferentially produce landforms associated with groundwater outflow—the sapping valleys. However, snowfall melting in hydrothermal areas and sublimating elsewhere might also play a role in producing such a distribution [3].

The principle finding of our numerical model is that magmatic intrusions of several 10^2 km^3 provide sufficient volumes of groundwater outflow over the timescales (several 10^5 yr or more) needed to form fluvial valleys [8]. Calculated discharges are robust. Subsurface inhomogeneities, local impermeable caps, and uncertainties in porosity all affect the discharges at the 20% level or less. The parameter with the single greatest effect on the calculated discharges is the subsurface permeability. Permeabilities between 10 and 1000 darcy provide sufficient quantities of groundwater outflow to form fluvial valleys. Lower permeabilities require larger intrusion volumes to produce the same discharge. However, in the range of permeabilities expected for basaltic rock, there is no difficulty in producing significant groundwater outflow.

We have estimated the eroded volumes of two of the best-developed valley networks (Parana and Warrego Valles) in the heavily cratered terrains. These values (H.C.T) are compared with our estimated valley volumes on martian volcanos in Fig. 1. Estimates of martian valley erosion can be combined with terrestrial fluvial erosion rates to obtain estimates of the total volume of water required to form each set of martian valleys. Some ratios of water volume to eroded volume for Mars are as low as 2 or 3 to 1 [9]. However, based upon our own study of fluvial erosion on volcanic landscapes, we find ratios as large as 1000:1. The total water volume using each ratio is shown for each valley group in Fig. 2. For each locality the lower bar represents the uncertainty due to valley side-wall slopes while using a water-to-eroded-volume ratio of 3:1, the upper bar using a ratio of 1000:1. Horizontal lines in Fig. 2 illustrate the cumulative discharge of hydrothermal systems associated with 50-, 500-, and 5000-km^3 igneous intrusions. Therefore we conclude that hydrothermal systems can provide the volumes of groundwater outflow needed to form martian valley networks and can provide an alternative to rainfall from a warm, wet early Mars.

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A MODEL FOR THE EVOLUTION OF CO_2 ON MARS.

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There are several lines of evidence that suggest early Mars was warmer and wetter than it is at present [1]. Perhaps the most convincing of these are the valley networks and degraded craters that characterize much of the ancient terrains. In both cases, fluvial activity associated with liquid water is believed to be involved. Thus, Mars appears to have had a warmer climate early in its history than it does today. How much warmer is not clear, but a common perception has been that global mean surface temperatures must have been near freezing—almost 55 K warmer than at present.

The most plausible way to increase surface temperatures is through the greenhouse effect, and the most plausible greenhouse gas is CO_2. Pollack et al. [2] estimate that in the presence of the faint young Sun, the early martian atmosphere would have to contain almost 5 bar of CO_2 to raise the mean surface temperature up to the freezing level; only 1 bar would be required if the fluvial features were formed near the equator at perihelion at maximum eccentricity. However, these calculations now appear to be wrong since Kasting [3] has shown that CO_2 will condense in the atmosphere at these pressures and that this greatly reduces the greenhouse effect of a pure CO_2 atmosphere. He suggested that alternative greenhouse gases, such as CH_4 or NH_3, are required.

In this paper, we approach the early Mars dilemma from a slightly different point of view. In particular, we have constructed a model for the evolution of CO_2 on Mars that draws upon published processes that affect such evolution. Thus, the model accounts for the variation of solar luminosity with time, the greenhouse effect, regolith uptake, polar cap formation, escape, and weathering. We initialize the model 3.8 G.y. ago with a specified CO_2 inventory and then march it forward in time to the present epoch. The model partitions CO_2 between its various reservoirs (atmosphere, caps, regolith, carbonates, and space) according to the thermal environment predicted by a modified version of the Gierasch and Toon [4] energy balance climate model. The goal is to determine if it is possible to find an evolutionary scenario that is consistent with early fluvial activity, and that arrives at the present epoch with the initial CO_2 partitioned into its various reservoirs in plausible amounts. Our early fluvial activity criterion is that global mean temperatures must be at least 240 K at the beginning of the simulation; our current reservoir criteria is that the atmosphere must hold about 7 mbar of CO_2, the caps several millibars, and the regolith 300 mbar. We do not constrain the final size of the rock reservoir.

We find no evolutionary scenario that satisfies these criterion when using published estimates of the processes involved. The main

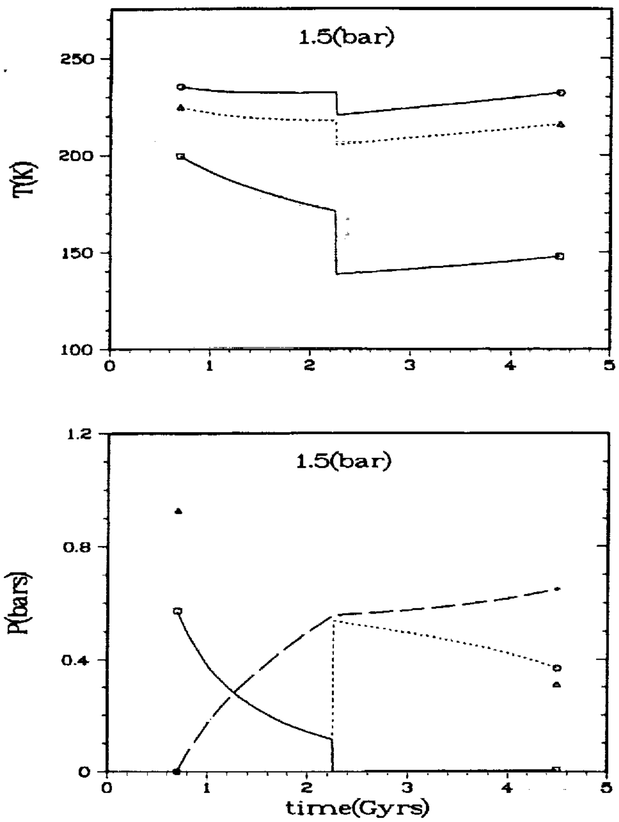

Fig. 1. Temperature (top) and pressure evolution (bottom) for total initial abundance of 1.5 bar. The temperatures shown are for the surface at equator (solid line with circles), pole (solid line with squares), global mean (dashed line with triangles), and frost point (dotted). The CO_2 reservoir pressures are atmosphere (solid line with squares), caps (dashed line with circles), regolith (dotted line with triangles), and carbonate (chain dotted line with plus sign).

difficulty is making Mars warm early on. As Kasting has pointed out, only a stronger greenhouse or a brighter early Sun can help in this regard. However, we have found that if the greenhouse were stronger or if the Sun were brighter, then massive permanent caps would form as a result of a collapse in the climate system sometime between 1.5 and 3.5 b.y. ago. An example of this collapse and the thermal history associated with it is shown in Fig. 1.

The collapse is a result of an unstable feedback between the poleward transport of heat by the atmosphere, the greenhouse effect, and surface pressure. As surface pressure falls, heat transport and the greenhouse effect are reduced, the polar caps cool, surface pressure falls further, and so on. Gierasch and Toon [4] discuss this instability in detail. In our model, the instability is set off by weathering that removes CO_2 from the atmosphere at a rate that is exponentially proportional to temperature. Thus, the warmer early Mars is, the more likely collapse will occur. As much as 600 mbar goes into the caps when collapse occurs with the CO_2 coming from the atmosphere and the regolith. More importantly, at least 300 mbar survives to the present epoch—much more than appears to reside in the south residual cap.

Collapse can be avoided if the polar albedo is significantly lower than the value we have assumed (0.75), or if the actual poleward heat flux is greater than that given by our simple parameterization. However, in either case, the implication is that if global mean surface temperatures were at or above 240 K on early Mars, then a minimum total inventory of 2 bar of CO_2 is required, and at least 70% of it has been sequestered as carbonate in near-surface materials. On the other hand, if the fluvial features in the ancient terrains do not require global mean temperatures near 240 K and can be explained by phenomena that are not climate related, such as an elevated geothermal heat flux, then our model favors an initial CO_2 inventory near 600 mbar. Of this initial CO_2, most has gone into the regolith (300 mbar), modest amounts into carbonates (130 mbar), even smaller amounts into the atmosphere (7 mbar) and caps (3 mbar), with the remainder having escaped into space (160 mbar). Thus, it is crucial that we obtain better constraints on the thermal regime required to form the fluvial features on early Mars.

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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 Atmospheric and Space Physics, University of Colorado, Boulder CO 80309-0392, USA, [2]School of Physics and Astronomy, University of Minnesota, Minneapolis MN 55455, USA, [3]Department of Nuclear Engineering and Engineering Physics, University of Virginia, Charlottesville VA 22903, USA, [4]Department of Mechanical Engineering, State University of New York–Stony Brook, 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 also is removed by photochemical processes. Due to the 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 reservoirs can be accounted for by exchange with CO_2 adsorbed in the regolith and with H_2O in the polar ice deposits. We have constructed both simple analytical models and time-dependent models of the loss of volatiles from and supply to the martian atmosphere. Both Ar and Ne require continued replenishment from outgassing over geologic time.

For Ar, sputtering loss then explains the fractionation of $^{36}Ar/^{38}Ar$ without requiring a distinct epoch of hydrodynamic escape (although fractionation of Xe isotopes still requires a 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 N, the loss by both sputtering and photochemical