the fractionation in dissociative recombination is to incorporate the higher electron temperatures that have been indicated by a recent analysis of Viking RPA data [5]. Higher electron temperatures provide more energy for the ^{15}N atoms released in dissociative recombination of $^{15}N/^{14}N$ at the exobase, and thus the escaping fraction is larger than that computed by Wallis [6]. Luhmann et al. [7] have computed the sputtering rates of atmospheric O and C by O^+ ions picked up by the solar wind. The addition of sputtering as a loss process for N_2 greatly exacerbates the problem with overfractionation of $^{15}N/^{14}N$ [8]. We find that even a dense, early atmosphere cannot inhibit the enormous escape rates and subsequent fractionation implied by the Luhmann et al. fluxes.

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FLUVIAL VALLEYS IN THE HEAVILY CRATERED TERRAINS OF MARS: EVIDENCE FOR PALEOCLIMATIC CHANGE?

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Whether the formation of the martian valley networks provides unequivocal evidence for drastically different climatic conditions remains debatable. Recent theoretical climate modeling precludes the existence of a temperate climate early in Mars' geological history [1]. An alternative hypothesis [2] suggests that Mars had a globally higher heat flow early in its geological history, bringing water tables to within 350 m of the surface. While a globally higher heat flow would initiate groundwater circulation at depth, the valley networks probably required water tables to be even closer to the surface. Additionally, we have previously reported that the clustered distribution of the valley networks within terrain types, particularly in the heavily cratered highlands [3], suggests regional hydrological processes were important. In this abstract, we summarize the case for localized hydrothermal systems and present estimates of both erosion volumes and of the implied water volumes for several martian valley systems.

Sustained groundwater outflow requires that hydraulic gradients be maintained. On Earth, rainfall or melting snow or ice eventually infiltrate into the subsurface and maintain these gradients. Thus on Earth, groundwater outflow and surface runoff are intimately connected and such a connection is reflected in the formation of fluvial systems. In locations where sapping valleys do form they are associated with runoff-dominated systems, regardless of lithologic or climatic conditions [3].

On Mars, however, it is not clear how hydraulic gradients were maintained, particularly in the southern highlands, where most fluvial valleys exhibit a sapping morphology. In these regions, sapping valleys generally do not form together with runoff valleys, but instead form as isolated systems. Thus, groundwater outflow does not seem closely linked to an atmospheric hydrological cycle. In the heavily cratered terrains, evidence for fluvial erosion is found on the ejecta blankets of impact craters, on some volcanos, and in intercrater plains regions. Many valleys in the intercrater plains are associated with dark units that have been interpreted as igneous sill intrusions [4]. An asymmetric distribution of valleys around impact craters is common on Mars, unlike drainages situated around terrestrial impact craters that tend to be more uniformly distributed. While most martian valley networks are attributed to formation by groundwater outflow processes [5–7], the distribution of these networks is unlike that formed by terrestrial sapping valleys.

Lacking an atmospheric hydrologic cycle, subsurface energy sources must maintain hydraulic gradients. Two possibilities are a global, uniformly higher heat flow and localized energy sources, such as magmatic intrusions. Although a global, higher heat flow would produce vertical temperature gradients, it would not produce anomalously large, localized horizontal temperature gradients in the groundwater by itself. Such gradients are necessary to produce lateral flow and recharge of aquifers. However, the addition of vigorous, localized hydrothermal circulation to a uniformly higher heat flow overcomes this problem. Such systems would naturally be associated with igneous intrusions, volcano formation, and large impact craters, all of which are locales for valley formation on Mars, particularly in the heavily cratered terrains. Depending on the volume of the associated magmatic intrusion, martian hydrothermal systems can circulate groundwater into the surface environment for several million years; such systems are thus able to maintain hydraulic gradients sufficient for valley formation. Rather than replenishing groundwater through rainfall and infiltration, our numerical modeling demonstrates that a martian hydrothermal system replenishes itself by continually drawing in colder, denser groundwater radially from more distant parts of the aquifer. The total quantity of groundwater that passes through the modeled hydrothermal system over its lifetime is comparable to that needed to form a single outflow channel. Hence, subsurface aquifers of the required magnitude to form fluvial valleys must have existed on Mars.

The clustered distribution or localization of sapping valleys on Mars and their isolation from runoff valleys strongly suggests localized, subsurface sources of water. In short, a rainfall genesis should produce associated runoff valleys and a more uniform distribution of fluvial valleys within a given terrain type or surface

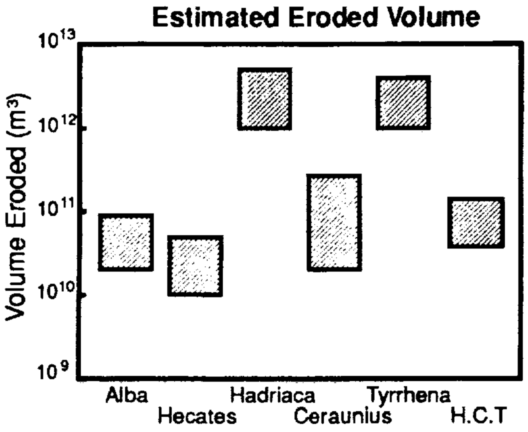

Fig. 1.

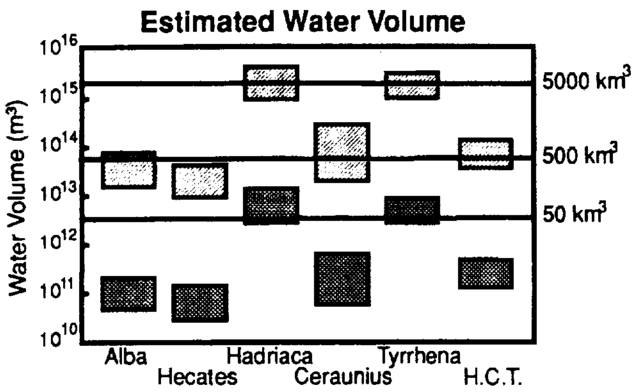

Fig. 2.

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 sidewall 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