

major volcanic centers such as Tharsis and Elysium). Note that, with the exception of active geothermal areas, the flow velocities associated with these processes are likely to be orders of magnitude smaller than those that characterize precipitation-driven systems on Earth.

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THE EARLY MARTIAN ENVIRONMENT: CLUES FROM THE CRATERED HIGHLANDS AND THE PRECAMBRIAN EARTH. R. A. Craddock and T. A. Maxwell, Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington DC 20560, USA.

There is abundant geomorphic evidence to suggest that Mars once had a much denser and warmer atmosphere than present today. Outflow channels [1], ancient valley networks [2], and degraded impact craters in the highlands [3] all suggest that ancient martian atmospheric conditions supported liquid water on the surface. The pressure, composition, and duration of this atmosphere is largely unknown. However, we have attempted to place some constraints on the nature of the early martian atmosphere by analyzing morphologic variations of highland impact crater populations, synthesizing results of other investigators, and incorporating what is known about the geologic history of the early Earth. This is important for understanding the climatic evolution of Mars, the relative abundance of martian volatiles, and the nature of highland surface materials.

The duration of the martian primordial atmosphere and the interval of time water existed as a liquid on the surface can be estimated from the ages of features thought to have formed by fluvial processes. Formation of the large outflow channels occurred from the late Noachian (e.g., Ma'adim Vallis [4]) until the early Amazonian (e.g., Mangala Valles [5]). Formation of the ancient valley networks [6] and degradation of the cratered highlands [3] also occurred during this period, and the timing of both these processes appears to be dependent upon elevation. Formation of valley networks and degradation of highland impact craters ceased at higher elevations before they shut off at lower elevations. This implies that the highland volatile reservoir became depleted with time or, alternatively, the density of the martian atmosphere decreased with time. In the latter scenario, precipitation would occur throughout the highlands initially fairly independent of elevation. With time and loss of atmosphere, cloud condensation (and thus precipitation) could occur only at progressively lower altitudes. Condensation of the Earth's primordial steam atmosphere occurred ~4.0 b.y. ago [7]. Assuming that the martian primordial atmosphere

also condensed at approximately the same time (perhaps sooner given Mars' distance from the Sun), the maximum interval of time liquid water existed on the surface is either ~1.2 b.y. or ~450 m.y. The differences in these estimates are due to the uncertainties in the absolute ages of the martian periods and are based on two different models of the cratering flux at Mars [8,9 respectively].

Because the early Sun is thought to have had a lower luminosity than today [10], ~5 bar of CO₂ may have been needed to maintain the ancient martian surface temperature above freezing [11]. On the other hand, models incorporating early solar mass loss [12] suggest that early solar luminosities were actually much higher than today. This would allow the early martian atmosphere to be much thinner (~1 bar) and yet warm enough for liquid water. Regardless, the age and elevation relationship of features contained in the cratered highlands suggest that the pressure of the martian primordial atmosphere was never fixed at a high level but steadily decreased to <1 bar at about the beginning of the Amazonian. If sapping and seepage of groundwater were the mechanisms for ancient valley network formation [2] and highland degradation [3], a recharge mechanism is still needed for the aquifer in order to maintain these processes over the interval of time they were operating (tens to hundreds of millions of years at any given elevation). Again, martian atmospheric pressures must have been maintained >1 bar for a long time in order to produce the weather patterns necessary to efficiently recharge the highland aquifer at higher elevations. Based on the amount of time fluvial processes occurred on Mars, a rough estimate of the primordial atmospheric pressure is ~5-10 bar. Possible recharge of the atmosphere through impact-induced CO₂ [13] suggests that highland degradation may have also been periodic, but such a mechanism would have become less efficient with time to correlate with the age/elevation relations of highland features. If the weak Sun paradox is wrong [11], the primordial atmosphere would still need to be between ~5 and 10 bar initially to allow ancient valley network formation and highland degradation to occur over the interval of time observed.

The primordial terrestrial atmosphere and oceans were highly reducing [14]. Similarly, it is probable that Mars also had a primordial, highly reducing atmosphere and surface waters. Possible release of martian water in a CO₂-rich atmosphere by precipitation and channel-forming processes has led numerous investigators to speculate on the creation of massive martian carbonate deposits [e.g., 11]. The formation of such deposits would tend to remove CO₂ from the martian atmosphere and would require a substantially thick primordial atmosphere (~20 bar [11]) for ancient valley network and highland degradation processes to operate for ~450 m.y. or ~1.2 b.y. However, these hypotheses have been based on the assumption that an acidic primordial atmosphere (pH <1-3 [15]) was buffered by cations released through the weathering of rock. Precipitation of calcium carbonate occurs only in water with a high pH (>7.8 [16]). On Earth, precipitation of calcium carbonate did not become a common phenomenon until the Proterozoic (2.5 b.y.) when stable, shallow marine cratons developed, thus allowing weathered cations to concentrate [17]. Simply, terrestrial oceans were in existence ~1.5 b.y. before precipitation of calcium carbonate started to occur, and even then it was in unique circumstances!

On Mars two scenarios exist for standing bodies of water, the extreme being Oceanus Borealis [18]. This large ocean, thought to occupy much of the northern plains, postdates most of the fluvial features on Mars (up to the middle Amazonian), is needed to explain

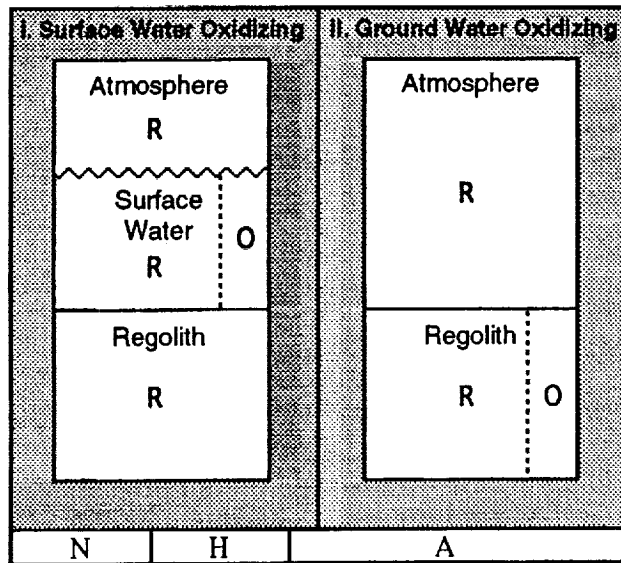


Fig. 1. A two-box model showing the location of reducing (R) and oxidizing (O) conditions on Mars through time. Oxidizing conditions in stage I represent local O oases, which may have developed in small pools formed by precipitation or seepage. Oxidizing conditions in stage II represent buried O oases located where groundwater is enriched by volcanics from an evolved mantle. Based on Fig. 3 in [14].

the formation of putative glacial features in the southern highlands, and probably did not exist (see discussion in [19]). More realistic are the smaller, isolated lacustrine basins proposed for low-lying areas in the northern plains surrounded by outflow channels [20,21] and in the cratered highlands where numerous ancient valley networks terminate [22]. Such basins are supported by geomorphic evidence (e.g., possible wave-cut terraces [20,21]) and occur during the interval that other fluvial features were forming. In addition to these basins, smaller isolated pools may have developed in topographic depressions (e.g., impact craters) if precipitation occurred in the highlands as suggested in [3]. It is especially likely that these smaller pools allowed eroded materials to concentrate, raise the local pH, and induce the formation of carbonates. Such "oases" could be the most likely locations of carbonate deposits on Mars. Other oases may exist underground where oxidizing volcanic gases interact with groundwater to raise the pH, and may help explain the presence of carbonates in the SNC meteorites [23]. Based on this view and the terrestrial example [14], a "two-box" model for the oxidizing stages for Mars is proposed (Fig. 1).

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AN ATTEMPT TO COMPREHEND MARTIAN WEATHERING CONDITIONS THROUGH THE ANALYSIS OF TERRESTRIAL PALAGONITE SAMPLES. C. Douglas¹, I. P. Wright¹, J. B. Bell², R. V. Morris³, D. C. Golden³, and C. T. Pillinger¹, ¹The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK, ²Mail Stop 245-3, NASA Ames Research Center, Moffet Field CA 94035-1000, USA, ³NASA Johnson Space Center, Houston TX 77058, USA.

Spectroscopic observations of the martian surface in the visible to near infrared (0.4-1.0 μm), coupled with measurements made by Viking, have shown that the surface is composed of a mixture of fine-grained weathered and nonweathered minerals. The majority of the weathered components are thought to be materials like smectite clays, scapolite, or palagonite [1]. Until materials are returned for analysis there are two possible ways of proceeding with an investigation of martian surface processes: (1) the study of weathering products in meteorites that have a martian origin (SNCs) and (2) the analysis of certain terrestrial weathering products as analogs to the material found in SNCs, or predicted to be present on the martian surface. Herein, we describe some preliminary measurements of the carbon chemistry of terrestrial palagonite samples that exhibit spectroscopic similarities with the martian surface [2-4]. The data should aid the understanding of weathering in SNCs and comparisons between terrestrial palagonites and the martian surface.

The SNC meteorites contain a variety of weathering products including carbonates, sulphates, and clays of martian and terrestrial origin [5-7]. The C chemistry of SNC meteorites has already been studied extensively so it would seem reasonable to characterize the nature of C in terrestrial palagonites with a view to comparing the data with the results from SNC meteorites [6]. Several mechanisms for the formation of palagonites (which are hydrated and devitrified basaltic glasses) have been proposed: (1) hydrothermal alteration (induced by volcanism, geothermal gradients, or impact), (2) subpermafrost magmatic intrusion, (3) subaerial intrusion above the permafrost layer, and (4) static gas-solid weathering [8].

As a preliminary investigation, two terrestrial palagonite samples have been analyzed for C stable isotopes by the use of stepped combustion and static mass spectrometry. One, PN-9, collected from Mauna Kea, is a palagonitic soil and has been studied extensively because its infrared absorption features closely resemble that of the martian surface [2,5,9]. The C released between room temperature