GEOLOGICAL HISTORY OF WATER ON MARS. V.R.Baker[1,2], [1]Dept. of Hydrology and Water Resources, University of Arizona. Tucson, AZ 85721-0011 baker@hwr.arizona.edu, [2]Lunar and Panetary Laboratory, University of Arizona

Introduction: While it has long been obvious from geomorphological evidence that Mars, like Earth, is a water-rich planet [1], this fact has proven difficult to reconcile with various aspects of Martian geochemistry and geophysics [2]. Indeed, theorization about water on Mars has been highly controversial, with various atmospheric models for early Mars proposing: (a) warm, wet conditions generated by an intense CO_2 greenhouse [3], (b) denial that such a greenhouse is possible [4], so that geothermal heat is necessary to produce temporary water flow for valley formation [5], and (c) that high impact rates early in Mars history explain the release of water for valley formation [6]. There has even been speculation that Martian landforms can be explained without any role for water at all [7]. This debate is made particularly interesting by the stunning confirmation of large quantities of near-surface water (ice) on Mars [8] and the documentation of many water-related Martian landforms that are exceptionally young in age [9].

The landforms that lead to the recognition of a water-rich Mars have long been interpreted to have fluvial, lacustrine, littoral, glacial, wet mass-movement, ice-rich permafrost, and volcano-ice-water origins. Of course, these interpretations have all been intensely debated [2], and alternative, nonaqueous explanations have been proposed for nearly every landform to which aqueous origins have been ascribed. While all these explanations are certainly reasonable for isolated *ad hoc* instances, they do not provide any sense of a unifying theme as to how the Martian landscape works. They are united only by their denial of a significant role for liquid water and/or greatly changed past Martian climates. This view may be partly motivated by a Mars-specific version of the uniformitarian principle, which holds that the present-day, cold-dry Mars conditions (7 millibar atmospheric pressure, mean annual temperature of about -60^0 C and colder) are better postulated for the Martian past than are any speculations about warmer, wetter conditions. Though logically flawed, this mode of reasoning has a long history of influence in geological thinking [10]. A potentially more fruitful approach for interpreting the Martian landscape is somewhat provocatively stated as follows: if this entire assemblage of (apparently) water-related landforms, as manifested both in time and spatial association (these being demonstrated by geological mapping), were observed in some newly discovered region of Earth, there would be absolutely no question in regard to its aqueous origins. It is in this spirit that this brief review is pursued.

In outlining a geological history of water on Mars it is essential to distinguish the "early Mars" (Noachian) epoch during which impacting rates by meteors and comets were much higher than afterward. This early Mars (Noachian) epoch is best recorded in the heavily cratered highlands of the planet, mostly in equatorial and southern latitudes. There is also evidence that the low-lying northern plains of Mars are underlain by large impact basins that were emplaced during this early heavy bombardment period [11], but these are now extensively buried by younger lava flows and/or sediments. Based on a selective interpretation of the Mars fluvial history, a common view, especially among theoreticians, is that nearly all the aqueous activity on Mars was concentrated into this early epoch. For convenience we label this the MIDDEN hypothesis (**M**ars **I**s continuously **D**ead and **D**ry, **E**xcept during the **N**oachian).

Fluvial. The two main varieties of fluvial landforms on Mars are valley networks and outflow channels. A great many of the valley networks occur in the old cratered highlands of Mars, leading to the view that nearly all of them formed during the heavy bombardment, as presumed by the MIDDEN hypothesis. The outflow channels, in contrast, involve the immense upwelling of cataclysmic flood flows from subsurface sources, mostly during post-Noachian periods of Martian history. The transition from a more aqueous phase in the Noachian, with a progressively thickening ice-rich permafrost zone in post-Noachian time, is the basis for theories that explain the outflow channels as products of subsurface water confined by this process [12, 13]. Certainly, there is strong evidence, notably from impact crater morphologies, that much of the Martian surface is underlain by a thick ice-rich permafrost zone, a "cryolithosphere". Nevertheless, the geological record shows that highland valley formation extended into the period after the heavy bombardment [14], and much younger valley networks are extensively developed on some Martian volcanoes [15, 16].

An alternative to the linear model of cryosphere thickening is that outflow channel activity is related to episodic heat flow and volcanism [17]. This hypothesis is now known by the acronym MEGAOUTFLO: **M**ars **E**pisodic **G**lacial **A**tmospheric **O**ceanic **U**pwelling by **T**hermotectonic **F**lood **O**utburst. It envisions long periods (perhaps on the order of 10^8 years) in which Mars has a stable atmosphere that is cold and dry like that of today, with nearly all its water trapped as ground ice and underlying ground water. The stable state is punctuated by relatively short-duration (perhaps 10^4 or 10^5 years) episodes of quasi-stable conditions that are warmer and wetter than those at present. The motivation for MEGAOUTFLO is the observed reality of water-related landforms briefly described in this review, especially those of post-Noachian age. Extensive criticism of the hypothesis by Carr [2] questioned the significance of the water-related landforms and denied that significant epochs of climate change occurred after the heavy bombardment, as presumed by the MIDDEN hypothesis.

The MIDDEN hypothesis is itself under attack for its presumption of warmer atmospheric conditions during the Noachian. Some criticisms arise from the role of internal geothermal heating for valley formation. However, it is clear that extensive geothermal heating will also impact the atmosphere by its injection of water vapor and other gases. Perhaps the strongest argument that early Mars cannot have been continuously cold and dry is that highland craters and basins are extensively eroded, most likely by processes involving rainfall and surface runoff [18]. Prolonged, intense fluvial erosion occurred, with cratering competing with drainage basin development, such that the latter was restricted to localized areas [19]. Relatively high denudation rates are inferred for the Noachian, which are much greater than those of later periods. These observations are consistent with the discovery that the ancient Martian crust of the highlands is layered to considerable depths, probably because sedimentary rocks were emplaced during the intense denudation phase [20]. Imagery from the Mars Orbiter Camera (MOC) of the Mars Global Surveyor (MGS) Mission shows that the Martian highlands do not consist of an initial lunar-like surface, underlain by an impact-generated megaregolith, as presumed in previous hydrogeological models [2]. Instead, cratering, fluvial erosion, and deposition of layered materials probably all occurred contemporaneously, leading to a complex interbedding of lava flows, igneous intrusions, sediments, buried crater forms, and erosional unconformities [21].

Lacustrine and Glacial. Evidence for persistent standing bodies of water on Mars is abundant, but even more controversial than that for fluvial activity. For Mars there is no direct geomophological evidence that the majority of its surface was ever covered by standing water, though the term "ocean" has been applied to temporary ancient inundations of the northern plains, which did not persist through the whole history of the planet. Although initially inferred from sedimentary landforms on the northern plains, inundation of the northern plains has been most controversially tied to identifications of "shorelines" made by Parker et al. [22, 23]. MGS data confirm the initial observations of a regionally mantling layer of sediment, now called the Vastitas Borealis Formation, covering perhaps 3 x 10^7 km^2 of the northern plains [24]. This sediment is contemporaneous with the post-Noachian outflow channels, and it was likely emplaced as the sediment-laden outflow channel discharges became hyperpycnal flows upon entering water ponded water on the plains [25]. In another scenario, Clifford and Parker [13] envision a Noachian "ocean," contemporaneous with the highlands valley networks, and fed by a great fluvial system extending from the south polar cap, through Argyre and the Chryse Trough, to the northern plains.

Numerous lakes, which were temporarily extant on the surface of Mars at various times in the planet's history [26]. The more ancient lakes occupied highland craters during the heavy bombardment epoch, spilling over to feed valleys such as Ma'adim Vallis [27]. Even more abundant crater paleolakes seem to have developed just after the heavy bombardment, and expecially large lakes occupied the floors of the impact basins, Hellas and Argyre. Even younger lacustrine activity is indicated by the finely layered deposits of the Valles Marineris [28]. These are up 8 km thick, which could indicate a very prolonged period of deep-water inundation of this immense tectonic trough.

Considerations of lake mass balances [29] and of likely formation times for observed deltas and wave-eroded terraces [30] suggest that the crater lakes had lifetimes on the order of about 1000 years. Calculations with a general circulation model demonstrate that ice-covered lakes of this duration might be possible in a quasi-stable state for some portions of the Martian surface even under present-day conditions [31]. Of course, the water would first need to be mobilized to liquid form, suggesting that in its present frozen state Mars is merely hydrologically dormant [32].

Evidence for glacial activity though Martian history is also abundant [33] and controversial [2]. Resistance to the idea of ancient glaciers on Mars is especially curious, given that there is a general scientific consensus that Mars displays an immense variety of periglacial landforms, most of which require the activity of ground ice. The periglacial landforms include debris flows, polygonally patterned ground, thermokarst, frost mounds, pingos, and rock glaciers. On Earth most of these landforms develop under climate conditions that are both warmer and wetter than the conditions for cold-based glacial landforms [34]. Because the Mars glacial landforms are all post-Noachian in age, and some are very young, they are completely inconsistent with the MIDDEN hypothesis. Glaciers require substantial transport of atmospheric water vapor to sustain the snow accumulation that generates the positive mass balance needed for glacial growth. There are no known Earth glaciers that develop from water supplied by the melting of ground ice, though this mechanism has been proposed for ancient glaciers on Mars that are hypothesized to have occupied the outflow channels.

The glacial landforms of Mars are erosional (grooves, streamlined/sculpted hills, drumlins, horns, cirques, and tunnel valleys), depositional (eskers, moraines, and kames), and ice-marginal (outwash plains, kettles, and glaciolacustrine plains). Of course, the landform names are all genetic designations, and *ad hoc* alternatives have been suggested for many. What is not *ad hoc*, however, is that all the glacial landforms occur in spatial associations, proximal-to-distal in regard to past ice margins, that would be obvious in a terrestrial setting. Areas of past glaciation on Mars include the Tharsis volcanoes, uplands surrounding Argyre and Hellas [33], and the polar regions, where the ice caps were much more extensive during portions of post-Noachian time [35].

Very Recent Fluvial and Volcano-Ice-Water Activity. One of the most striking recent discoveries is that many water-related landforms on Mars are exceptionally young in age. This fact was prominently demonstrated by MOC images from the MGS orbiter showing numerous small gullies generated by surface runoff on hillslopes [9]. The gullies are most likely formed by debris-flow processes and the melting of near-surface ground ice [36]. Melting can be induced at the appropriate latitude by changes in the solar insolation that would be induced by the immense shifts in Martian obliquity that are retrodicted to have occurred during the past few million years [37, 38]. The gullies are uncratered, and their associated debris-flow fan deposits are superimposed on both on eolian bedforms (dunes or wind ripples) and on polygonally patterned ground, all of which cover extensive areas that are also uncratered [9]. The patterned ground is itself a very strong indicator of near-surface, ice-related processes in the active (seasonally thawed) layer above the Martian permafrost zone [39].

Discussion. Recent discoveries from MOC images show that Mars displays a diverse suite of exceptionally young, globally distributed landforms that are water-related. If observed on Earth these landforms would all be well understood to have aqueous origins that were capable of generating them on relative short time scales (100s to 1000s of years) in a much warmer, wetter, and denser atmosphere than occurs on Mars today. Likewise, in contrast to the MIDDEN hypothesis, the surface of Mars displays older post-Noachian landforms of fluvial, glacial, periglacial, and hydrovolcanic origins. These phenomena are all consitent with the episodic climatic changes envisioned by the MEGAOUTFLO hypothesis.

A much-discussed "conundrum" of Mars science is the problem of the "missing carbonate deposits." The argument made is that in a warm, thick atmosphere [3] reactions of CO_2 gas and water would lead inevitably to weathering of surface rocks and the deposition of extensive carbonate deposits, as occur on Earth [40]. The spectral observations of Mars, however, have failed to detect any carbonates [41, 42]. Moreover, recent data from MGS show that the Martian surface extensively exposes unaltered feldspar and pyroxene in essentially unwearthered basalt outcrops [43]. This lack of weathering is actually to be expected if the post-Noachian history of Mars has nearly always been extremely cold and dry. The MEGAOUTFLO hypothesis envisions only very brief wet episodes, no longer than those of hyperarid and cold-desert regions of Earth, which also preserve essentially unweathered rock outcrops. Weathering in a Noachian wet period might by obscured by burial, and the lack of carbonate spectral signatures could result from suppression of those signatures by processes likely to have occurred on Mars [18]. Alternatively, the carbonates could indeed be absent. They may have accumulated on the floor of a very ancient ocean [44], but this ocean floor could have been subducted during a plate-tectonic regime in the early Noachian [45].

A very early phase of plate tectonics could have generated the Martian highland crust by continental accretion [45, 46]By concentrating volatiles in a local region of the Martian mantle, the early plate-tectonic phase of Mars would have led to a superplume at Tharsis. The resulting immense concentration of volcanism at Tharsis would itself have a great influence on climate change [e.g., 47]. The persistence of this volcanism episodically through later Martian history [e.g., 48] would provide a mechanism for the episodic, short-duration aqueous phases that produced the above-described landforms.

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