

An Examination of Martian Hydrology

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Abstract The climatic history of Mars is briefly presented. Mars has likely lost 80% of its planetary water supply from impacts and solar wind picking. The atmosphere with which it is left is a mere 560 mbar, and its planetary heat flow is only a fraction of what it once was. Because of all of these factors, the Mars of today appears as a cold, dead planet. Over 3.5 Ga, it is thought to have had a warm, wet atmosphere. There was substantial formation of fluvial valley networks, likely from both precipitation and groundwater sapping. Scientists debate over the existence of an ocean at this time, perhaps covering as much as one third of the planet. At that point, the planet went dormant. Clifford and Parker (2001) postulated a global, well connected aquifer, confined by a thick layer of ground ice. When the system would be perturbed, the rock would fracture, and massive flooding would result. A new study by Hanna and Phillips (2005) has shown that this model is overly simplistic, and extremely unlikely. Another model, called MEGAOUTFLO by Baker et al. (1991), appears to describe the hydrologic and climatic behavior of Mars since it became cold and dry. It is tied to the evolution of the Tharsis Magmatic Complex. When it is active, the heat destabilizes clathrates and causes massive pressure driven flooding, and the formation of a short-lived greenhouse. In time, the water and CO₂ return to storage, and the planet has once again become dormant.

I. Introduction

The atmosphere of Mars is presently very thin, barely holding enough water at saturation to cover the surface of the planet with a layer $0.7-1.4 \times 10^{-6}$ m thick. The present day pressure is a mere 560 mbar, with 95% of that being CO₂ (Carr, 1996). Models of impact erosion indicate that between 50-90% of the Noachian Martian atmosphere could have been lost to crater impacts. Stable isotopic data suggests that ~90% of atmospheric species may have been lost to solar wind sputtering (Brain and Jakosky, 1998). What few volatiles that are left are tied up in the polar caps, along with subsurface ice and CO₂ clathrates (Kargel et al., 2000).

The current atmospheric D/H ratio is $(9 \pm 4) \times 10^{-4}$ (Owen et al., 1988). If one assumes that the solar nebula was homogeneous with respect to water isotopes in the inner solar system and that the isotopic fractionation during planetary differentiation was similar for both the Earth and Mars, this would imply that Mars has lost 4/5 of its total planetary water supply. This, among other things, has led most researchers to conclude that early Mars must have had significant amounts of free water. Since 40% of the current Martian surface is Noachian aged crust that has survived (see Figure 2) (Solomon et al., 2005), its geomorphic history is well preserved, and shows abundant evidence for channelized flow (Baker, 2004; Cabrol and Grin, 2001a; Craddock and Howard, 2002; Gulick, 2001; Solomon et al., 2005), paleolakes (Moore and Wilhelms, 2001), and possibly, an ancient ocean(s) (Baker, 2003; Baker et al., 2000; Carr and Head, 2003; Clifford and Parker, 2001; Dohm et al., 2001; Fairén et al., 2004; Phillips et al., 2001). There has been discussion of liquid CO₂ being the primary geomorphic agent in lieu of H₂O, but these have been of limited scope and scale (Musselwhite et al., 2001). One recent study flatly indicated that it was simply “impossible” (Stewart and Nimmo, 2002).

There has been, however, considerable disagreement on what has happened since the end of the Noachian, 3.7 billion years ago. Many researchers have held to the belief that it has since been cold and dry, similar to its present state (Carr, 2002; Clifford and Parker, 2001). Others suggest that this has been the predominant case, with brief punctuations of warmer climates borne of CO₂ cycling (Baker et al., 2000) or changes in the planet’s obliquity (Cabrol and Grin, 2001b; Fanale and Salvail, 1994; Marquez et al., 2004; Tokano, 2003).

In section 2 of this treatment, the Noachian period of Martian history will be briefly examined. The Noachian climate and how it has since changed will be presented. In section 3, the post-Noachian hydrologic history of Mars is examined. The emphasis is not on specific localities, but rather on theoretical possibilities for the observed behavior. While perfect objectivity is not possible, every attempt will be made to do so independently of any theoretical or conceptual model. The primary ones which will be examined are that of Clifford and Parker (2001), Carr (2002), and the 'MEGAOUTFLO' model of Baker et al. (1991, 2000).

II. Noachian Mars

Virtually every aspect of the climatic and hydrological systems of the planet has changed radically in the last 4.5 billion years. The primary reason for this is the small size of the planet, along with its distance from the sun (1.52 AU). Its diameter is a mere 6794 km, while Ganymede, the largest moon in the solar system, has a diameter of 5268 km. For comparison, the Earth has a diameter of 12,756 km (Freedman and Kaufmann, 2005).

Because of its small size, it continued to lose heat rapidly, eventually losing its geodynamo which produced its magnetic field, about 4 Ga (Fairén and Dohm, 2004). Mars was thus left open to the ravages of the solar wind. It has also been heavily bombarded during its early history, and was so again at the Noachian's end. Around ~3.9 Ga, its surface was regularly pummeled by what researchers believe were likely asteroids from the asteroid belt which were perturbed by inward migration on the part of Jupiter (Kring and Cohen, 2002).

Figure 1 shows the heat available at the Martian surface throughout its history. Data on ground heat flux and a model of solar luminosity are plotted for the last 4.5 Ga, and an approximate total is plotted. Due to the huge uncertainties involved, these data should be taken somewhat qualitatively. It shows a theorized heat flux of 820 W/m^2 at 4.5 Ga, and 620 W/m^2 today. Its low of 560 W/m^2 was at approximately 3 Ga. Figure 3 represents the change in atmospheric pressure during the same time period. These data are just here to give a qualitative feel of the climatic evolution of Mars into which this discussion may be placed. A true energy balance would take into account many other variables than just these.

There have been many arguments made that Mars has always been cold and dry, even during the Noachian. Attempts have been made to explain away all the channels, valley networks and even cataclysmic flood tracks with every thing from glacial scour, eolian processes, lava erosion, to gas supported density flows (Carr, 2002; Craddock and Howard, 2002). That view has vanished as recent missions to Mars continue to send back data that were beyond all disputation which prove that water did flow on the Martian surface. The MER Opportunity even landed in a paleo-lake bed! (Squyres et al., 2004) As a side note, those who still believe that Mars always had sub zero temperatures may have just gotten some support. A recent study did k/Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of several different classes of Martian meteorites. They claim that their data (from only three different meteorites) proves that Mars has not been above freezing for all but brief times for the last 4 Ga (Weiss and Shuster, 2005). Their results have not yet been peer reviewed, however.

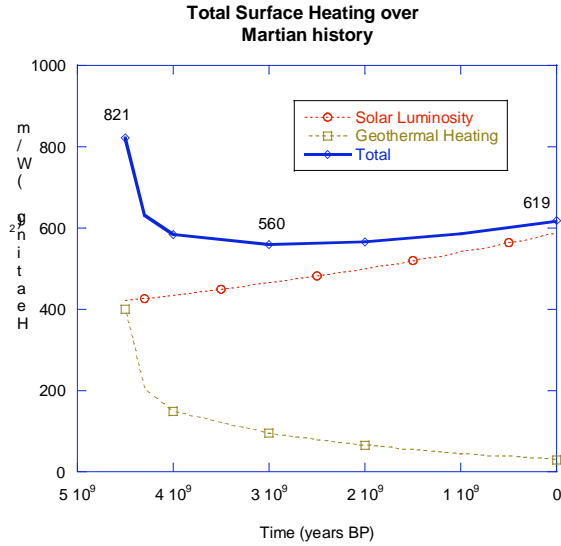


Figure 1 – Total heating on Mars throughout its geologic history. These figures represent global averages and should be considered approximate. Ground flux data are from Clifford and Parker (2001). Solar luminosity is based on a simple analytical model (Fanale and Salvail, 1994; Gough, 1977). Energy is given in W/m²

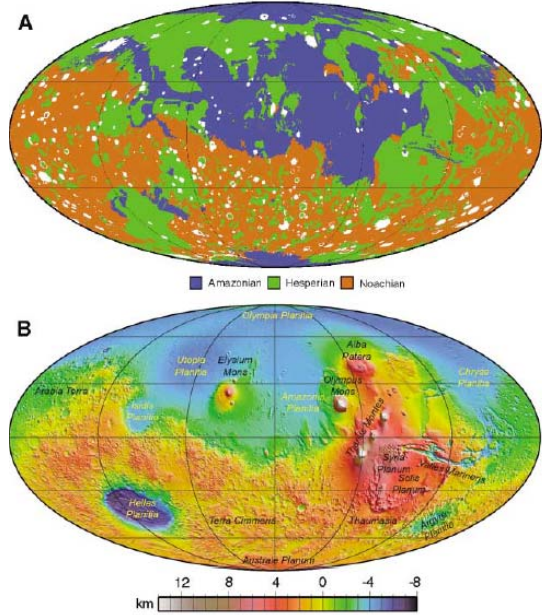


Figure 2 – Panel A shows the different ages of the Martian crust. While 40% of the surface is Noachian in age and is concentrated in the southern highlands, one can see that there has been extensive reworking of much of it in the Hesperian. This would seem to cast doubt on the idea that Mars has been dry and dead since the Noachian. Panel B is MOLA topography presented for comparison. Source: Solomon et al., 2005

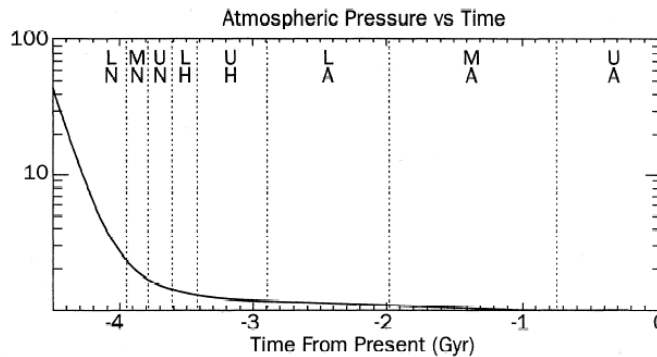


Figure 3 -- (Brain and Jakosky, 1998)

There is a great deal of evidence that there was abundant surface water in the Noachian. This evidence includes fluvial valley networks (Baker and Partridge, 1986; Cabrol and Grin, 2001a; Carr, 2000; Craddock and Howard, 2002; Gulick, 2001) that are generally agreed upon, and a somewhat controversial ocean in the northern plains (Baker

et al., 2000; Baker et al., 1991; Carr, 2000; Carr and Head, 2003; Dohm et al., 2001; Fairén et al., 2004).

Early geomorphic studies of degraded fluvial valleys seemed to show two classes of valleys. One of these was older, and more eroded, while the second one was superimposed upon it and had features which were much more recent (Baker and Partridge, 1986). Based on the evidence it became clear that erosion was decreasing rapidly as the Noachian came to its end, and what was more surprising, many of these valley features were actually quite young. Further work has shown that there was extensive valley incision on the surface of Mars, spanning its entire geologic history, although 60-90% of it was during the Noachian (Carr, 2002). A summary of the different areas which have undergone significant channel and valley incision along with their theorized time of formation are given as Figure 4.

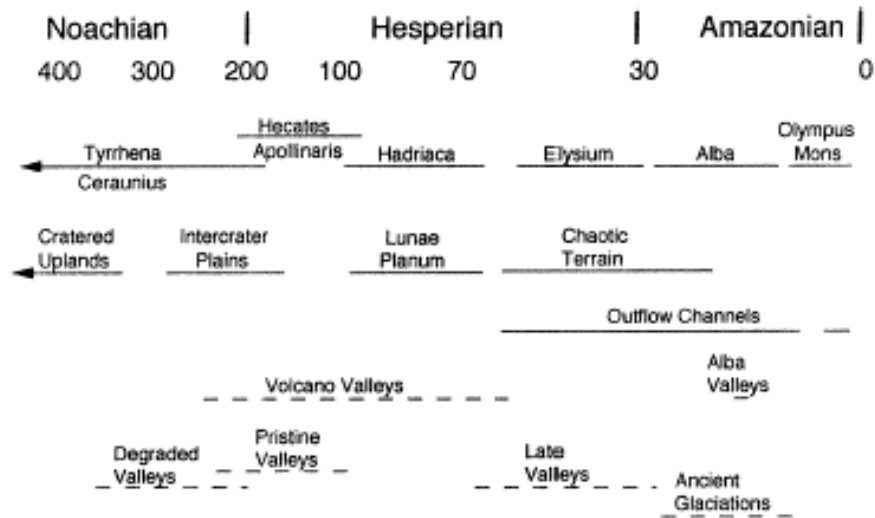


Figure 4 (Gulick, 2001)

Since the degraded valleys which were interpreted to be from the Noachian had slightly higher drainage densities than the pristine ones, it would indicate that there was

more surface runoff available. Indeed, the earliest valleys are found on both the highlands and in inter-crater plains that were only slightly younger. The fact that these formed around the same time, and that during this time there is a high degree of impact crater degradation, has led many to believe that the Noachian was warmer (Gulick, 2001). Others claim that valley formation via sapping could have easily formed in climates similar to the current one, if there was some geothermal heating of the regolith (Goldspiel and Squyres, 2000). Others counter that there is no evidence of significant geothermal heating, and that even if there were, that does not explain the increased erosion of craters (Craddock and Howard, 2002).

There is also a heated debate as to the existence of a Noachian ocean. Based upon their calculations, Clifford and Parker (2003) claim that nearly 1/3 of the planet was covered by such an ocean. While significant work has been done on a Hesperian aged ocean, some believe that it would be extremely difficult to ascertain much about a Noachian ocean because of the degradation which would occur (Carr and Head, 2003). Perfectly illustrating that point is one study examined a series of high resolution MOC imagery in an attempt to locate shoreline features which were said to exist in published literature. They found no such evidence (Malin and Edgett, 1999). Others are quick to counter with the respective areas are so large, and that the number of MOC images was so small (Fairén et al., 2003). To complicate matters even further, a recent study noted that there would be isotopic rebound after the load was removed. The variability introduced by this process could further complicate the scene (Leverington and Ghent, 2004). Figure 5, below, shows the boundary of these hypothesized oceans.

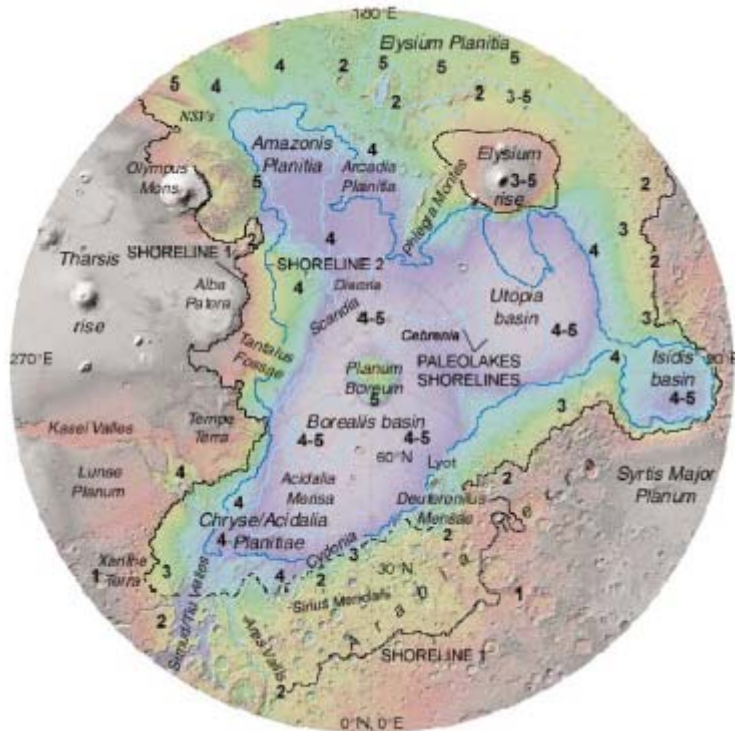


Figure 5 –The hypothesized Noachian ocean of which we have been discussing is the solid black line. The boundary for a later, Hesperian Ocean is shown in dark blue. The potential boundaries of later paleo-lakes are given in light blue. These will be discussed later on. The numbers correspond to the evolution of the Tharsis Magmatic Complex as described in the source. Source: Fairén et al., 2003

III. Post-Noachian Mars

It is generally believed that once Mars had frozen up and become dormant (it is difficult to constrain the exact timing, but likely in the late Noachian or early Hesperian), its climate was roughly the same as it is today. (Baker, 2003) One look at Figure 2 shows that this was hardly the case. Yet, most of the atmosphere was gone and temperatures likely only crept above 273 k on equatorial slopes which faced the sun (Schorghofer et al., 2002).

In addition to the valley formation that was mentioned above, there are huge channels in the circum-Chryse region that were interpreted to be the results of catastrophic flooding (Baker and Milton, 1974). Most have since come to believe

likewise (Carr, 2000; Carr and Head, 2003; Clifford and Parker, 2001). Figure 6 shows the size and scale of the flooding that is presently being discussed. It was these that created the later, Hesperian ocean that was shown in Figure 5, above.

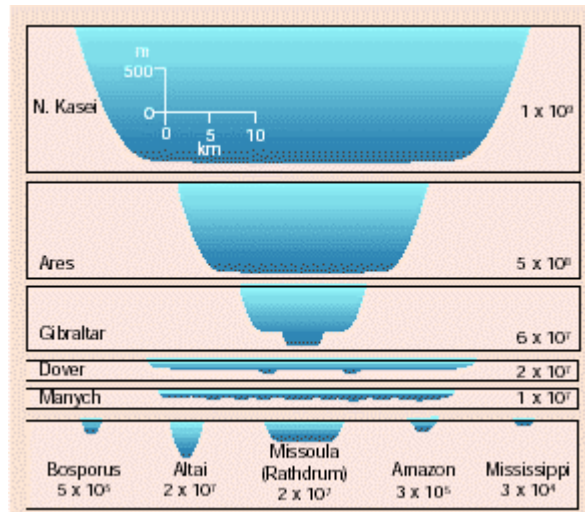


Figure 6 – The relative sizes of different floods on the Earth, compared with cataclysmic flooding on Mars. Gibraltar was the largest known terrestrial flood ever, it was when the Mediterranean sea filled. It is absolutely dwarfed by those of Mars. Source: Baker (2001).

There is, however, disagreement as to the mechanism by which that much liquid water was produced at the surface. Some suggest that meteorite impacts may have caused liquefaction of saturated soils which in turn experienced flow themselves and released all of the groundwater that they were capping (Wang et al., 2005). This hypothesis, and many like it, depends on ideas first proposed in Clifford (1993) and updated in Clifford and Parker (2001). It is that there is a deep, hemispheric scale global aquifer. Clifford first proposed that basal melting at the of the polar caps would infiltrate into this global system, applying a pressure head. It was confined along most of its length under a thick layer of permafrost and ground ice.

At places where there was catastrophic flooding, it was merely the result of something perturbing the system enough to make it so the groundwater could come to the

surface and release the pressure it was under (Clifford, 1993). It has, however, become partially antiquated since MOLA data showed that the North Polar cap is in a 5 km topographic depression. Thus, even if there were sufficient crustal interconnectedness to allow hemispheric scale groundwater circulation to occur, the hydrostatic pressure head produced by basal melting would be insufficient to affect the equatorial regions (Zuber et al., 1998).

The idea was updated in Clifford and Parker (2001). Among other enhancements, they made it so that just the south polar cap would be providing the pressure head on the system. A cartoon of the updated model is shown in Figure 7.

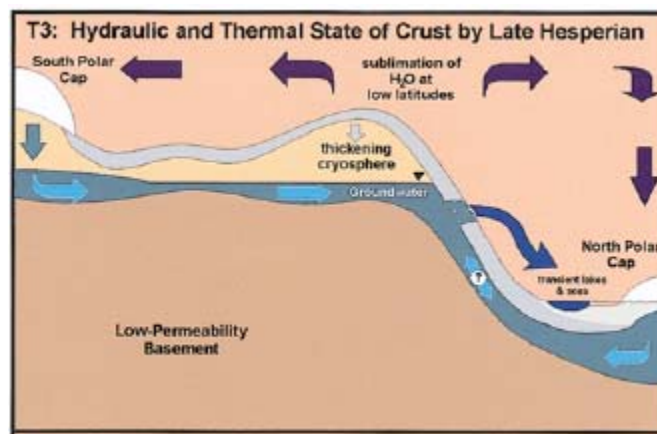


Figure 7 – The Clifford and Parker (2001) model.
Source: Clifford and Parker (2001)

One serious question that arises out of such a theoretical construct is whether there really is a global aquifer. Our current geologic understanding indicates that there should be deep brines in the fissures and basin sediments, down to a point where the pressure from the overburden will eliminate the pore space, which would vary significantly based on different geologic factors. That is likely one of the things the MARSIS instrument on the Mars Express mission will show, if it works. The big question, however, is not if the water is there, but if there is any effective porosity for

these brines to flow through. Clifford (1993) makes a case that because of kilometer scale fracturing and the absence of precipitation, the aquifer would have to be global. His aquifer model is somewhat simplistic, and his terrestrial analogues poor. In spite of that, this model as presented in these two papers has been the most cited treatment of the Martian subsurface, and until recently, nobody seems to have re-evaluated it.

In a thoughtful new study, Hanna and Phillips (2005) have designed an aquifer model that does not categorize the subsurface so simply. They make accommodation for different physiographic terrains, and have a significantly more advanced treatment of porosity, permeability, and compressibility, treating them as independent functions, etc. The main conclusion that they offer is that while rapid cooling would initiate a downward propagating freezing front as Clifford (1993) states, the process would be slow. A real aquifer would not be globally confined as Clifford and Parker (2001) state as one of their primary assumptions, so the pressure that would build up in confined sections of it would therefore be dispersed in unconfined parts. Because of this, and many other factors which come out of the model, the pressure that would build up in specific confined areas would be woefully short of lithostatic.

The fundamental flaws in their aquifer model are not the only problems with their ideas. Carr (2002) notes that there are signs of fluvial erosion at higher elevations, where they could not reasonably be associated with a global aquifer because they were simply above the base level of the polar layered deposits. He also questions why so many floods originate in the Margaritifer region instead of places which were geographically lower, like Chryse.

He proposes three possible solutions to this problem that do not contradict the model. One is that there is volcanic heating. Another is that there were brief warm periods during which there was precipitation (see the MEGAOUTLFO hypothesis below). The last was that another process was involved which generated hydrostatic pressure. Based upon earlier work he surmised that groundwater could be squeezed between the encroaching cryosphere, and impermeable basement rock. As the front propagated downward and water would freeze, it would expand. Thus if the aquifer was confined, pressures would build catastrophically. He himself admits, however that this would only work in cases where there was insufficient room for expansion, which was by no means likely. He frames this idea in terms of a global aquifer, but the process could conceivably work under different circumstances.

Even with these possible explanations, he still is at a loss to explain why the lowest places on the planet, Hellas, Utopia, etc. have not been party to any post-Noachian flooding, and simply calls it, “puzzling”. By virtue of their elevation, the hydrostatic pressures should be the greatest at these locations. This would seem to be another fatal flaw in the Clifford and Parker (2001) model.

In the final words of the Hanna and Phillips (2005) study, it states that, “The work presented here suggests that a more rapid, repeatable, and localized mechanism for pressure generation would be favored as a driving force behind the formation of the outflow channels, such as a magmatic intrusion into the aquifer or a tectonic event.”

While there are many examples of direct magmatic interactions causing flooding to occur (Chapman et al., 2003; Chapman and Tanaka, 2002), it is certainly not always

the case (Carr, 2002). At the very least, what these arguments show is that the global hydrologic system on Mars is poorly understood.

The MEGAOUTFLO (Mars Episodic Glacial Atmospheric Oceanic Upwelling by Thermotectonic Flood Outbursts) hypothesis is a conceptual model which explains Martian climatic and hydrological evolution in a self consistent model. It explains how Mars can go from its normal, cold and dry state, to a planet which has an ocean in the northern planes (Oceanus Borealis), precipitation, glacial formation, and then back again within $\sim 10^4$ - 10^5 years (Baker et al., 2000).

The cycle goes as follows (modified from Baker et al, (2000)):

1. Mars is in a cold, dry epoch which dominates most of its post-Noachian history. These are thought to last for 10^8 years or more.
2. There is magmatic activity in the Tharsis Magmatic Complex, which will release CO_2 and possibly SO_2 .
3. CO_2 clathrate in permafrost zones is destabilized by the thermal flux, and is released from depths of up to 2-3 km.
4. This released gas begins to explode upward
 - a. CO_2 in solution in the groundwater will exsolve.
 - b. This combined pressure exceeds lithostatic, and there is a colossal explosion of gas, water, and rock fragments onto the surface.
5. The heat causes water to continue to circulate and flow onto the surface.
6. Oceanus Borealis is formed.
7. The released CO_2 and water vapor cause a transient greenhouse effect.
8. An Earth like hydrological cycle is in effect and there will be erosion of the surface.
 - a. Glaciers will form at higher altitudes.
 - b. Extensive formation of periglacial features at high latitudes.
 - c. Valley formation
9. Water will return to storage
 - a. Infiltrate into the subsurface
 - b. Be locked up in glaciers and ground ice
 - c. Loss to solar wind sputtering (very small effect)
10. CO_2 will return to storage
 - a. Dissolved gas in infiltrating, acidic waters
 - b. Silicate weathering, burying bicarbonate

- c. Loss to solar wind sputtering (very small effect)
- 11. Decline in planetary heat flux from dissipation of plume
- 12. Ice rich permafrost growth
 - a. traps CO₂ in the subsurface
 - b. Incorporates groundwater
 - c. Once it is thick enough, clathrates will re-form.
- 13. The planet will return to its natural, cold and dry state.
- 14. A new cycle is eventually primed. It will not, however, be as strong as the previous one as:
 - a. Both water and CO₂ will have been redistributed over the planet, away from magmatically active areas.
 - b. The planetary heat flux is constantly decaying
 - c. Small quantities of volatiles have been lost to space.

Only a few of these cycles are seen in the geologic record. One of the primary criticisms of this hypothesis was the apparent lack of carbonate minerals on the Martian surface (Carr, 1996; Carr, 2002). Initially, Baker et al. (2003) defended this by pointing out that there was a preponderance of unaltered feldspars and pyroxene, indicating that the basalt was essentially unweathered. They state that this would be expected since the transient, warm periods were so short. Thus, if you don't have much weathering of basalt, why should you expect to have had a lot of carbonate form either? It has since been shown that there are not any carbonates present at all. The reason for this is that the waters were highly acidic, as evidenced by the presence of the mineral jarosite at the MER Opportunity landing site (Kargel, 2004). Additionally, there has been spectral evidence of sulfates from OMEGA on the Mars Odyssey satellite over much of the planet in places where waters would accumulate (Gendrin et al., 2005).

IV. Conclusions

The Clifford model, as updated in Clifford and Parker (2001), has been shown to be overly simplistic in its treatment of Martian geology, and thus largely invalid. It is possible that the new results may be taken into account and it may emerge in version 3,

hopefully better able to give a framework with which to understand Martian Hydrology. As with the other models described, the MEGAOUTFLO model will, undoubtedly have its flaws as well. As more data becomes available, it will be patched and modified. If our good fortune holds, we will continue to get new data with which to test and try our conceptual understandings.

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