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EVOLUTION OF THE MARTIAN HYDROSPHERE. V. Baker, Department of Geosciences and Department of Planetary Sciences, University of Arizona, Tucson, AZ 85721.

The concept of the hydrological cycle is one of the great achievements in the understanding of nature. Intellectual history's premier hydrologist, Leonardo da Vinci, seems to have held two simultaneous views of the cycle: (a) an external process in which evaporation from ponded areas leads to precipitation and runoff from the land (the prevailing terrestrial view), and (b) an internal process in which subsurface pressures from within the Earth force water upward, as in blood pumped through a human body. After 500 years, a very similar paradox applies to our modern view of the long-term planetary hydrological cycle on Mars. Numerous morphological features, notably the valley network systems of the heavily cratered terrains (1,2,3), imply formation by dynamical cycling of water. The sapping process responsible for most valley networks (4) requires a persistent flow of ground water that can only occur with long-term hydraulic head differentials to drive the flow in subsurface aquifers (5,6). Either endogenetic or exogenetic hydrological cycling is necessary to explain these relationships.

Endogenetic hypotheses for valley genesis on Mars maintain the necessary prolonged ground-water flows by hydrothermal circulation associated with impact cratering (7) or with volcanism (8,9,10). Moreover, the extensive volcanogenetic hydrological systems necessary to explain widespread valleys are consistent with a continuum of processes up to the megascale of Tharsis and Elysium. This observation, plus the discovery of evidence for extensive inundation of the northern plains of Mars (11,12,13,14) and the discovery of evidence for extensive glaciation in the southern hemisphere (15), led to a proposal of episodic ocean formation and related hydroclimatological change throughout Martian history (16,17). The model is consistent with a range of otherwise enigmatic observations, including the formation of Amazonian valley networks (5,18) and the formation of layered deposits in Valles Marineris through repeated lake filling and breaching (19). Continuing work reveals even more detailed consistency with this conceptual scheme, including the extensive glaciation of the Hellas region (20) in Middle Amazonian time (21), further documentation of the glacial landforms used to establish southern hemisphere glaciation (22), and a coincidence of ages (within resolution capabilities) of principal elements in the late-stage global hydrological system (23).

Ocean formation on Mars was episodic. The best evidence for the process is for the latest episodes. Coincident cataclysmic flood discharges to the northern plains, probably triggered by Tharsis volcanism (16), would lead to immense consequences. Potential volumes of ponded water are summarized in Table 1. Regrettably, these figures are highly approximate because of large errors (as great as ±1.5 km) in the existing topographic data set. At various contour levels the modern northern plains geometry permits water bodies up to oceanic proportions, 4.0×10^7 km^2 in area, holding up to 6.6×10^7 km^3 water with an average depth of as much as 1.6 km. Much smaller pondings are possible within the basin, but long-term deformation of the planetary surface precludes meaningful analysis of the inadequate topographic data. Nevertheless, it is interesting that the maximum water volume that might reside in Oceanus Borealis at its theoretical maximum extent is equivalent to a planetwide water layer 450 meters thick. This figure is consistent with other estimates of the Martian water inventory.

The outflow channels have a complex history of multiple flooding events over a prolonged period of planetary history. We hypothesize episodic outbursts of simultaneous discharge triggered by the planetary-scale volcanism. The consequences of such episodes are summarized in Table 2. At total combined discharge rates consistent with the indicated outflow channel dimensions, the various sizes of Oceanus Borealis determined in Table 1 would be achieved in time periods of days to a few years. The potential source zone of Martian upland terrain that could hydraulically provide this water transfer would have to be saturated with water and ice to some thickness. The volumes indicated for various sizes of Oceanus Borealis require saturated thicknesses averaging between 0.5 and 6.6 km over the source region, depending upon the assumed porosity. The elevated region of Tharsis, underlain by porous lava flows, would probably provide unusually thick source regions from which to derive outflow discharges.

The massive transfers of water through the outflow channels, from subsurface storage to Oceanus Borealis, would generate profound changes in climate. The cataclysmic outpouring of subsurface water would rapidly release dissolved CO_2 and evaporated water vapor to the atmosphere. Additional massive amounts of these two greenhouse gases would be generated by inundation of the polar carbon dioxide cap and by evaporation of water and sublimation of ice in the newly formed Oceanus Borealis. As Martian temperatures rose during the resulting transient H_2O-CO_2 greenhouse conditions, additional global change could occur by melting ground ice in the permafrost of the heavily cratered uplands and possibly by releasing adsorbed CO_2 from the previously cold regolith. Modulated by periodic changes of orbital eccentricity and obliquity, the planet would experience a period of maritime climate with exogenetic hydrological cycling from ocean to atmosphere to land by precipitation. Colder regions, such as the south polar latitudes, would receive snow, resulting is the glacial responses described above.

Carbon dioxide is a critical greenhouse gas for driving the modification of Martian climate. Table 3 lists the sources of carbon dioxide that could be associated with massive, cataclysmic water transfers late in Martian history. Although we have not done the indicated radiative transfer calculations, it is clear that much less atmospheric carbon dioxide is needed to produce warm, wet conditions late in Mars history because of solar luminosity values close to those of today. Even at the greatly reduced solar luminosity of earliest Mars history, Pollack and others (24) calculate that on the order of 1 bar atmospheric pressure is required to bring the Martian surface temperature to the melting point of water ice. Potential sources of CO_2 are sufficient (Table 3), and feedback mechanisms involving the atmospheric effects of associated massive amounts of water vapor will add to the surface warming.

It is remarkable that theoretical possibilities and observed Martian surface phenomena are in such accordance. The various Amazonian oceanic, volcanic, and glacial phenomena exist in temporal and spatial associations that imply a common genetic cause. Alternative hypotheses can be offered for many of the individual glacial, oceanic, fluvial, periglacial, and permafrost landforms that are ascribed to a global hydrological system. If these apply, how fortuitous that the resulting landforms have been positioned to also be consistent with regional glaciation, ocean formation, and associated climatological change. Alternatives may be found to the hypothesis of massive volcanism triggering the water outflows (16), but these must also explain the numerous attendant phenomena that are manifested in the Martian landscape. Any alternative scheme must provide for global hydrological cycling, achieving, as in Leonardo's paradox, an overall consistency and economy of explanation.

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Table 1: Hypsometry of Oceanus Borealis

Contour km	Volume 10^7 km^3	Area 10^7 km^3	Average Depth km	Equivalent Water Layer m
0	6.6	4.0	1.6	450
-1.0	3.2	2.0	1.1	220
-2.0	1.0	1.4	0.7	70

Table 2: Filling Rates for Oceanus Borealis

	Contours (m)		
	0	-1.0	-2.0
Filling Rates			
10^9 m^{3}s^{-1}	2 yr	1 yr	15 wk
10^{10} m^{3}s^{-1}	11 wk	5 wk	10 days
Source Zone Thickness at			
25% Porosity	2.6 km	1.3 km	0.4 km
10% Porosity	6.6 km	3.2 km	1.0 km

Table 3: Sources of Carbon Dioxide

A. North Polar Cap	20 mb
B. Massive Volcanism	100 mb
C. Sequestered in Previous Cycle	
1. Adsorbed in Regolith	
a. Ocean Basin	~200 mb
b. Land	~600 mb
2. Ground Water (Confined)	~1000 mb
3. CO_2 Clathrate	~1000 mb