GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 17, 1827, doi:10.1029/2002GL015178, 2002

The martian hydrosphere/cryosphere system: Implications of the absence of hydrologic activity at Lyot crater

P. S. Russell and J. W. Head III

Department of Geological Sciences, Brown University, Providence, RI, USA

Received 20 March 2002; revised 21 June 2002; accepted 26 June 2002; published 6 September 2002.

[1] The Amazonian-aged 215 km-diameter Lyot crater represents a transient 'drill-hole' into the martian hydrosphere/cryosphere system. Cratering mechanics predict that the event should have penetrated the cryosphere and released groundwater held under artesian conditions. A plausible explanation for the lack of evidence for hydrologic activity within Lyot is an absence of abundant subsurface groundwater in the region at the time of impact. *INDEX TERMS:* 6225 Planetology: Solar System Objects: Mars; 5420 Planetology: Solid Surface Planets: Impact phenomena (includes cratering); 1829 Hydrology: Groundwater hydrology; 1823 Hydrology: Frozen ground. **Citation:** Russell, P. S., and J. W. Head III, The martian hydrosphere/cryosphere system: Implications of the absence of hydrologic activity at Lyot crater, *Geophys. Res. Lett.*, *29*(17), 1827, doi:10.1029/2002GL015178, 2002.

1. Introduction

[2] The hydrologic model of *Clifford* [1993] provides an interpretive framework for ground-ice and groundwater distribution and surface interactions on Mars. This model predicts a global, interconnected, sub-cryospheric groundwater system, throughout which hydraulic pressure may be transmitted (Figure 1). One of the model's major implications is that disruption of the cryospheric seal has the potential to produce large-scale water outflow driven by "artesian-like" conditions, a situation thought to have been responsible for major Hesperian outflow channels [e.g., *Carr*, 1979; *Clifford*, 1993]. The northern lowlands are the most likely location for groundwater held under such conditions (Figure 1). Impact craters provide transient "drill-holes" into the hydrosphere/cryosphere system by which the predicted nature of the subsurface can be tested. To perform such a test, we examine Lyot (Figure 2), the largest young crater in the northern lowlands.

2. Crustal Structure and Lyot Crater

[3] The stratigraphic, physical, and thermal structure of the northern lowlands provides geologic context for discussion of subsurface hydrologic processes. The Hesperian-aged Vastitas Borealis Formation (Hv) currently blanketing the northern lowlands [*Greeley and Guest*, 1987] is interpreted as a sedimentary deposit averaging $\geq$100 m thick [*Head et al.*, 2002]. The underlying plains unit is interpreted as Hesperian ridged plains (Hr)-like wrinkle-ridged volcanic flows and estimated to be $\sim$1 km thick [*Head et al.*, 2002]. The number and sizes of subdued craters and impact basins apparent in MOLA topography of the northern lowlands indicates that a Noachian-aged surface is present below Hr, probably similar to that visible in the southern highlands today [*Frey et al.*, 2001]. At the southern margins of the northern lowlands, Lyot crater material is superposed on Late Hesperian channel materials and extensive Amazonian-aged knobby and smooth plains of diverse origins [*Greeley and Guest*, 1987].

[4] The constituents and structure of the average martian megaregolith and upper crust are summarized by *Clifford* [1993]. Impact ejecta interbedded with lava flows, sediments, and weathered materials comprise the allochthonous breccia of the megaregolith, below which is an autochthonous breccia of fractured basement rock. Porosity within the entire upper crustal column is represented by exponential decay of surface porosity due to lithostatic pressure to near-zero (1%) at the depth of self-compaction. Surface porosities of 20-50% yield self-compaction depths of 8.5 to 11 km, above which large quantities of subsurface water may reside (Figure 1). Analogy to terrestrial permeability structure allows for global-scale communication of groundwater to depths of $\sim$26 km on Mars [*Clifford and Parker*, 2001]. The model of an impact-fractured martian crust probably best applies to the heavily cratered highlands. However, on the basis of the evidence for Noachian heavily cratered terrain [*Frey et al.*, 2001] underlying the northern lowlands, we consider this physical structure profile of *Clifford* [1993] to be reasonable for the crust beneath Lyot. While porosity and permeability structures are to be taken as global averages, it is important to test these global-average estimates as a step towards determining actual values and the degree of heterogeneity present.

[5] Under current martian climatic conditions, a cryosphere (zone of crust in which temperature is always below the freezing point of water) extends from the surface to a depth that depends on the factors listed in Table 1 [*Clifford*, 1993]. The theoretical position of the base of the cryosphere reflects relief in surface topography to the first order (Figure 1). Below the cryosphere, liquid water is stable. Any water entering the cryosphere from above or below will freeze, restricting water transport to diffusion processes and effectively inhibiting the passage of liquid water [*Clifford*, 1993].

[6] These structural and thermal considerations led *Clifford* [1993] to predict a globally interconnected groundwater system beneath a confining cryosphere (Figure 1). Given enough water in the global inventory and sufficient variation in surface relief, subsurface water will accumulate above the depth of self-compaction as depicted in Figure 1. The system will remain confined beneath the cryosphere under hydrostatic pressure as long as the local lithostatic

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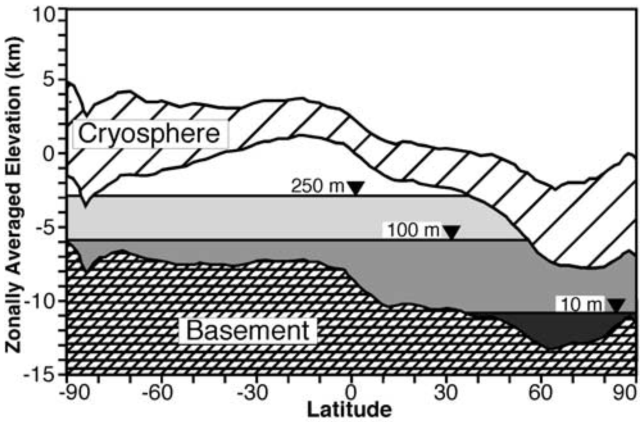

Figure 1. Nominal model of the hydrosphere/cryosphere system with three examples of global-layer equivalent volumes of water (from *Clifford* [1993]).

pressure of the cryosphere exceeds the hydrostatic pressure exerted by saturated ground at higher elevations [*Clifford and Parker*, 2001]. If hydraulic pressure becomes too great, or the cryosphere is disrupted by some external means, water is predicted to flow to the surface on its own, under "artesian-like" conditions. Variations on this model have been used to explain outflow channels near Tharsis and Elysium [e.g., *Carr*, 1979; *Clifford*, 1993; *Russell and Head*, 2001]. Impact cratering is among the geological processes potentially able to penetrate a cryosphere several kilometers thick. Impacts may excavate the cryosphere overlying candidate groundwater zones and provide transient heat input, each potentially effecting groundwater flow. We examine the crater Lyot as a candidate transient "drill-hole" probing the subsurface and testing the predictions of the hydrosphere/cryosphere model (Figure 1).

[7] The crater Lyot was chosen because a) it is at low planetary elevation (where global hydraulic pressure head should be greatest), b) it is Amazonian in age (a time when evolving cryosphere thickness is able to contain the greatest volume of water [*Clifford and Parker*, 2001]), c) it is furthest south among northern lowland craters (thus minimizing the local cryosphere thickness), and d) its large diameter maximizes the probability that it penetrated to sufficient depths to disrupt the cryosphere.

[8] In the current topographic configuration, ~3 km-deep Lyot crater does not extend below the base of the 4 km-thick nominal cryosphere (Table 1) into the zone where liquid water might exist (Figure 3a). We wish to examine, however, the disruptive effects of the crater during, and shortly after, its formation. Scaling laws, given the current diameter and depth of Lyot, allow such estimates to be made [e.g. *Melosh*, 1989; *O'Keefe and Ahrens*, 1993]. Most likely conditions of impact are taken to be an ordinary chondrite, a 10 km s^{-1} impact velocity, and a basalt-like target. The depth to which near-surface material (cryosphere included) is expected to be excavated and ejected is ~11 km (Figure 3b). The zone of crustal material that is physically disturbed may be represented by the dimensions of the transient crater. While the transient crater does not exist as a "hole in the ground" for a significant amount of time, its formation is accompanied by radial fracturing and fragmentation of the substrate and its collapse is associated with uplift of the crater floor and listric faulting of crater walls [*Melosh*, 1989]. At Lyot, this zone of physical disruption would reach to a depth of ~33 km (Figure 3b). The impact event also imparts heat to the target. The delivery of 35% [*O'Keefe and Ahrens*, 1977], or 7.9×10^{22} J, of projectile kinetic energy to target material results in impact melt-formation [*O'Keefe and Ahrens*, 1977] and heating of the ground [*Bratt et al.*, 1985], that easily elevates ground temperatures above the melting temperature at all depths below Lyot (Figure 3c). Physical removal and fracturing of ~11–33 km of upper crustal material as well as melt production and heating by ≥100 K in the upper ~15 km of remaining crustal material should be sufficient, even individually, to penetrate through or destroy a frozen, confining cryosphere of nominal thickness (Figure 3). Given the hydraulic pressures implied in the hydrosphere/cryosphere model presented above (Figure 1), artesian conditions should be produced by the Lyot impact event, leading to the potential for extensive effusion of groundwater to the surface (Figure 3).

[9] We examined Lyot crater (Figure 2) and its surroundings in Viking, MOLA, and MOC data, with particular attention to possible evidence of hydrologic activity, such as the presence of channels, valleys, crater wall gullies, crater floor sedimentation, or layered deposits [e.g., *Carr*, 1996; *Malin and Edgett*, 2001]. Lyot has a high broad inner ring and a ~400 m-high central peak structure. Most surfaces within the crater are rough and show no signs of features that might be associated with hydrologic activity. Small local depressions in the walls and floor are smoothed or softened, but are not flat as might be expected from aqueous sedimentation. Ejecta around the northern half of the crater is very extensive and crisp in appearance. Pristine secondary craters extend out >1 crater diameter. In the SE, ejecta is patchy, as if partially covered or destroyed. To the S/SW, amidst the mesas of Deuteronilus Mensae, there are no signs of an ejecta blanket beyond the crater rim. The rim of Lyot is rugged but shows no signs of incision, breaching, or erosion by fluvial activity. Fluvial features south and upslope of the crater are related to Hesperian-aged activity [*Greeley and Guest*, 1987] and do not emanate from Lyot. MOLA topography of the crater shows little evidence for smoothing of the interior and floor that might have accom-

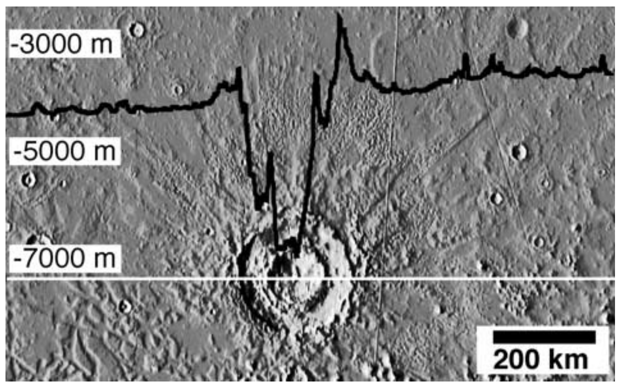

Figure 2. MOLA gradient topography of Lyot crater and altimetric profile showing present geometry and depth. Vertical exaggeration: ~122x. Lyot is centered at 50°N, 330°W.

Table 1. Sets of Variables Used in Calculating Three Estimates of Cryosphere Thickness and Examples for Three Latitudes in Each Case

	Variable			Thickness (km)		
Cryosphere Estimates	Q (mW/m^2)	Tm (K)	K (W/m/K)	0°N	50°N	90°N
Minimum	45	210	1.0	–	0.38	1.24
Nominal	30	252	2.0	2.27	3.93	6.53
Maximum	15	273	3.0	11.0	16.0	23.8

Thickness = K (Tm-Ts)/Q. Q = geothermal heat flux; Tm = melting temperature of water; K = thermal conductivity; Ts = average annual surface temperature at respective latitude (218K at equator, 193K at 50°N, 154K at pole). All values from *Clifford* [1993].

panied flooding and sedimentation. In summary, we find no evidence for water having effused or erupted within the interior of Lyot crater or poured over the rim. Smooth, sloping areas appear more likely to have resulted from eolian activity. To the south of the crater, the paucity of ejecta may have resulted from processes of erosion, sediment transport and deflation, or oblique impact.

3. Discussion and Conclusions

[10] The lack of evidence for hydrologic activity or aqueous sedimentary deposits in Lyot crater expected on the basis of predictions of the hydrosphere/cryosphere model of *Clifford* [1993] (Figure 1), suggests that some aspects of the model may need revision. We assess several candidate explanations for our observations and explore their implications for the nominal hydrosphere/cryosphere model.

[11] *Explanation 1: The global hydrologic system did not contain abundant groundwater at the time of the Lyot event*: The amount of water in the global groundwater system below the base of the cryosphere, and hence the hydraulic pressure head of the groundwater, may not have been sufficient to have forced water up to the elevation of the base of the crater at ∼−7 km. The Chryse channels, however, may be evidence for the level of saturated groundwater being at ∼0.5 to −3.7 km in the Mid-Late Hesperian [*Carr*, 1979; *Clifford and Parker*, 2001]. A level of ∼−3.5 km at NW Elysium in the Early Amazonian is suggested by *Russell and Head* [2001]. Thus, in order for the area underlying Lyot to be devoid of groundwater, an enormous amount of water would have to have been lost from the groundwater system to another sink (e.g., megaregolith/cryosphere, polar cap, space) in a relatively short time. Melting of ground ice in the cryosphere and ensuing hydrothermal activity might also be expected from impact heating. While the present investigation focuses on evidence for artesian flow, no clear indication of hydrothermal activity was found. Absence of evidence of melting of ground ice may indicate that the cryosphere itself was locally volatile poor [S. Clifford, LPI, personal communication, 2002], or may be due to impact dessication of the surrounding megaregolith.

[12] *Explanation 2: The cryosphere was much thicker than envisioned in the nominal case*: As seen from above calculations, in order to prevent the physical and thermal disruption associated with excavation, transient crater processes, and heating from reaching through the entire cryosphere, the cryosphere would have to be tens of kilometers thick (barring any additional disruptive effects of hydrostatic pressure of the groundwater) (Figure 3b). These thicknesses are within or well above the range of the maximum predicted thickness of the cryosphere: 16 km at 50°N, with a geothermal heat flux of 15 mW m^{-2}, a melting temperature of 273 K, and a thermal conductivity of 3.0 W m^{-1} K^{-1} [*Clifford*, 1993] (Table 1). This lower value of heat flux is more consistent with the latest estimates for the northern plains, 15–22 mW m^{-2} in Utopia [*Zuber et al.*, 2000]. Without addition of the geothermal gradient to impact heating, the difference between the surface temperature at 50°N (193 K) and melting temperature (273 K) is exceeded at depths down to ∼30 km, following calculations of *Bratt et al.* [1985]. Thus, impact heating is capable of raising the temperature above freezing to depths exceeding those of self-compaction (≤11 km) and negligible permeability (∼26 km) [*Clifford and Parker*, 2001]. If physical and thermal effects of impact are both capable of disrupting a cryosphere at least down to, depths of negligible porosity and permeability, yet no liquid water appears in the crater, a second possibility to the absence of water (Explanation 1) is that any water throughout this range of the subsurface adjacent to the impact is frozen and would not flow. This prospect would seriously inhibit the ability of groundwater to communicate with the surface on a large scale anywhere on the planet at this time. Any cryosphere thickness approaching or exceeding that of the maximum case (16 km) would require 1) heat flux below that currently postulated [*Zuber et al.*, 2000], 2) high melting temperatures, implying the absence of salts to contribute to freezing point depression, and 3) thermal conductivity at the high end of the range of values obtained for frozen soils and basalts [*Clifford*, 1993].

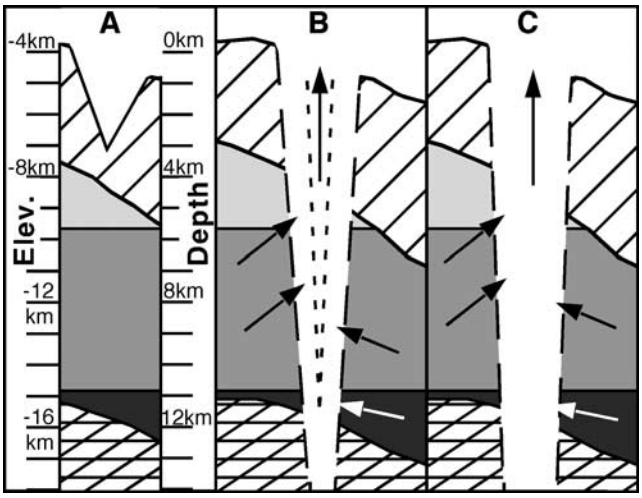

Figure 3. Predicted nominal configuration of the crust [*Clifford*, 1993] at the Lyot sub-impact point and implications. Each frame is an enlargement from Figure 1 centered on 50°N. (a) Present crater depth. (b) Predicted zone of physical disruption due to excavation (short dashes) and transient crater processes (long dashes), with expected groundwater flow (arrows). (c) Predicted zone of thermal disruption due to impact-heating and melt production, with resulting groundwater flow.

[13] *Explanation 3: The hydrologic system is not as interconnected as the globally-averaged model*: The megaregolith around Lyot may be less homogeneous, permeable, or porous than predicted for an average Mars. More prevalent volcanic, magmatic, and hydrologic activity on Mars may have emplaced more dikes, sills, lava flows, and fine-grained sediments than considered in a lunar megaregolith analogy [*Clifford*, 1993]. By acting as aquitards, these structures could cause a more locally controlled distribution of groundwater such as perched aquifers or relatively isolated pockets of high/low porosity material. *Clifford and Parker* [2001] note that heterogeneity of megaregolith characteristics over a similar range as present on Earth may be expected on Mars. In the case of Explanation 3, the lack of hydrologic activity at Lyot would be direct evidence of such heterogeneity. The area affected by the Lyot impact is $>3 \times 10^4$ km^2 of terrain argued above to be amongst the most likely of any on Mars to match the lunar models [e.g., *Frey et al.*, 2001]. Indications of a subsurface at Lyot that is less interconnected than the predicted global average may thus have important implications for the martian upper crust as a whole. Alternatively, Explanation 3 supports regional scale heterogeneity in the form of lower porosity/permeability in the northern lowlands resulting from crustal annealing by higher early heat flow [*Clifford and Parker*, 2001].

[14] *Explanation 4: The martian regolith may be saturated and physically interconnected as postulated, but average or typical effective permeabilities may be too low to allow significant flow within and from a saturated groundwater zone to the crater before refreezing occurred*: On Earth, permeability generally decreases with depth, but that of a given volume may deviate from the depth-average by several orders of magnitude [*Clifford and Parker*, 2001]. Preliminary calculations of the time it would take water to flow at depth from the distance of Lyot's rim to its center (representing a zone of impact-induced desiccation) suggest flow at low permeabilities (10^{-13}–10^{-16} m^2 [*Clifford and Parker*, 2001]) would be too sluggish to reach the surface before the cryosphere re-froze enough to contain it. High permeabilities used in discharge calculations at Chryse outflow sources (10^{-9} m^2 [*Carr*, 1979]) suggest effusion should have occurred. As permeability of $\sim 10^{-9}$ m^2 is an unlikely average over the area and depths considered at Lyot [*Clifford and Parker*, 2001], major outflow due to cryosphere disruption may require a heat source more focused or sustained than an impact, and/or especially high local to regional permeability.

[15] *Explanation 5: The groundwater configuration might be consistent with that predicted despite lack of surface hydrological activity, given uncertainties in the cratering process*: Our analysis is based on the current knowledge of the impact cratering process, which predicts that disruption of the crust by the Lyot event should have occurred to substantial depth. We use parameters we feel are most likely to describe the impact event, but these are imperfectly known, as are many aspects of the cratering process. Minor adjustment of values within most plausible ranges does not qualitatively alter our results that groundwater effusion should have been enabled by the Lyot impact. Extreme combinations of variables or the case of a highly oblique impact are not considered here.

[16] *Explanation 6: Subsurface volatiles are not dominantly water*: The *Clifford* [1993] model assumes water is the predominant component of the hydrosphere/cryosphere system. If CO_2 and clathrates have played a major role [e.g., *Hoffman*, 2000], then the predicted consequences of the Lyot event might not have been the simple outflow of groundwater.

[17] In summary, tests of the nominal cryosphere/hydrosphere model of *Clifford* [1993] based on predictions and observations at Lyot crater do not support expected groundwater liberation and outflow under artesian conditions, suggesting aspects of the nominal model need revision. While we consider the absence of sufficient water at depth and a more limited interconnectedness of the megaregolith as the most likely explanations, it may be that an additional, undescribed factor in the impact process inhibits those physical and thermal factors described above from providing groundwater a path to the surface. We are currently examining additional locations of disruptive processes or discharge to test these ideas and assess martian hydrological conditions further.

[18] **Acknowledgments.** We gratefully acknowledge the Mars Data Analysis Program which helped support this work, as well as insightful comments from Steve Clifford and Boris Ivanov.

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P. S. Russell and J. W. Head III, Department of Geological Sciences, Brown University, Providence, 02912 RI, USA.