Martian outflow channels: How did their source aquifers form, and why did they drain so rapidly?

J. Alexis P. Rodriguez, Jeffrey S. Kargel, Victor R. Baker, Virginia C. Gulick, Daniel C. Berman, Alberto G. Fairén, Rogelio Linares, Mario Zarroca, Jianguo Yan, Hideaki Miyamoto & Natalie Glines

Catastrophic floods generated ~3.2 Ga by rapid groundwater evacuation scoured the Solar System's most voluminous channels, the southern circum-Chryse outflow channels. Based on Viking Orbiter data analysis, it was hypothesized that these outflows emanated from a global Hesperian cryosphere-confined aquifer that was infused by south polar meltwater infiltration into the planet's upper crust. In this model, the outflow channels formed along zones of superlithostatic pressure generated by pronounced elevation differences around the Highland-Lowland Dichotomy Boundary. However, the restricted geographic location of the channels indicates that these conditions were not uniform. Furthermore, some outflow channel sources are too high to have been fed by south polar basal melting. Using more recent mission data, we argue that during the Late Noachian fluvial and glacial sediments were deposited into a clastic wedge within a paleo-basin located in the southern circum-Chryse region, which at the time was completely submerged under a primordial northern plains ocean. Subsequent Late Hesperian outflow channels were sourced from within these geologic materials and formed by gigantic groundwater outbursts driven by an elevated hydraulic head from the Valles Marineris region. Thus, our findings link the formation of the southern circum-Chryse outflow channels to ancient marine, glacial, and fluvial erosion and sedimentation.

At the end of the Noachian Period Mars experienced an abrupt transition into a climate dominated by extremely cold and dry conditions, which resulted in the subsequent confinement of the planet's hydroosphere in highly pressurized aquifers beneath thick upper crustal permafrost materials. A popular model proposes that the vast Noachian surface water systems were cold-trapped in the planet's south polar region to form an ice cap, which gradually infiltrated into a global mega-regolith as a consequence of pressure-induced basal melting. The catastrophic floods that excavated the Late Hesperian southern circum-Chryse outflow channels would have occurred in zones where the elevation difference between the Martian south polar region and lower terrains generated superlithostatic pressures.

In order to explain the relative localized occurrence of catastrophic-flood-formed Martian outflow channels, it was hypothesized that the causative flooding emanated from a compartmentalized global hydrosphere that was also contained within a planetwide megaregolith. In this model, the existence

1Planetary Science Institute, 1700 East Fort Lowell Road, Suite 106, Tucson, AZ 85719-2395, USA. 2NASA Ames Research Center, Mail Stop 239-20, Moffett Field, CA 94035, USA. 3Department of Hydrology & Water Resources, University of Arizona, Tucson, AZ 85721, USA. 4SETI Institute, 189 Bernardo Avenue, Mountain View, CA 94043. 5Centro de Astrobiología, M-108 km 4, 28850 Madrid, Spain. 6Department of Astronomy, Cornell University, Ithaca, NY, USA. 7External Geodynamics and Hydrogeology Group, Department of Geology, Autonomous University of Barcelona, 08193 Bellaterra, Barcelona, Spain. 8State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan, 430070, China. 9The University Museum, University of Tokyo, 113-0033, Japan. Correspondence and requests for materials should be addressed to J.A.P.R. (email: alexis@psi.edu)
of high elevation outflow channels in the circum-Chryse region\(^7,8\) can be explained by the presence of an aquifer system that extended from the Tharsis Montes to the outflow channel head source regions\(^9\). It was subsequently discovered that rather than possessing global megaregolith, much of the Martian upper crust appears to be dominated by Noachian sedimentary deposits of great stratigraphic thicknesses that both infill and bury numerous impact craters\(^10,11\). Hence, it was proposed that, instead of a megaregolith-trapped hydrosphere\(^1,2,6\), significant portions of these outflow-channel-source (OFCS) aquifers might have consisted of water-ice contained within buried impact craters and impact-fractured rocks\(^12,13\). However, because the sedimentary deposits are distributed globally on Mars, the unique conditions leading to the formation of the southern circum-Chryse outflow channel source regions are still poorly understood. Here, we propose a new geologic model linking the development of OFCS aquifers within the highlands of southern circum-Chryse (Fig. 1a) to a stage of Late Noachian large-scale regional marine sedimentation.

Results and interpretative synthesis

The long-held view is that regional groundwater outbursts led to the formation of extensive chaotic terrains (collapsed upper crustal materials) that are the sources of the southern circum-Chryse outflow channel\(^5,14–20\). More recently, zones of surface subsidence have been recognized as including much more extensive areas of adjacent highlands\(^12,13,21\). Consequently, the distribution of regional highland surfaces modified by collapse and subsidence were proposed to demark the approximate extent of the OFCS aquifers\(^12,13\). These chaotic terrains have been mapped in detail by previous investigator\(^4,16,22\), and here we present the first map showing the full extent of highland subsidence in this region of the planet (Fig. 1b,c). We show that these previously unmapped subsidence zones modify large areas of the highlands and connect eastern Valles Marineris to the initiation zones of numerous outflow channels (Fig. 1b). The subsided terrains include regionally extensive networks of broad valleys (e.g., Fig. 1b,c) that are characterized by faulted margins (Fig. 1c–e) and abrupt breaks-in-slope (Fig. 1c–e) that deform pre-existing landforms (e.g., Fig. 1d,e). These formational structures have been interpreted as synclinal and monoclinal folds and associated ruptures developed by subsidence over caverns that formed by the removal of ice, water, and fluidized sediment\(^12,13\).

The southern Margaritifer Terra highlands are extensively dissected by vast canyon systems (Fig. 1b and 2a), which exhibit flanks densely marked by channels (e.g., Fig. 2b)\(^4\). The formation of these canyons is thought to have been dominated by Middle and Late Noachian fluvial erosion\(^6\). Late Noachian equatorial glaciers may have also contributed to their development\(^23\). Within the study region, these canyons converge northwestward into the highlands containing the subsided terrains (Fig. 1a,b). Although the contact between these two terrain types is disrupted by the Margaritifer and Iani chaotic terrains, we have identified a relatively narrow stretch of plateau materials that includes a subset of canyons that exhibit transitional morphologies (Fig. 2a). These hybrid canyons include scarp margins marked by dense channel systems and extensional fractures generated by subsidence (Fig. 2c,d), thus offering a rare insight into the regional upper stratigraphy of the outflow channel source region, consistent with the existence of buried canyons underlying the subsided valleys. Similar hybrid morphologies are observable along the flanks of Ladon basin (Fig. 1a), which constitutes large impact basin that partly captured drainage from the upland fluvial canyons (Fig. 1b).
Figure 2. (a) Map showing the distribution of hybrid canyons in terrains located along the boundary between upland fluvial canyons and subsided valleys (context and location in Fig. 1b). (b) Topographic view of an upland fluvial canyon, which shows margins densely marked by small valleys/channels (black arrows). (c,d) Topographic views of a subsided valley (white arrow) that extends eastward to join a hybrid canyon that exhibits a margin dissected by small valleys/channels adjoined by subsidence related fractures (black arrow). We produced the map in this figure using Esri's ArcGIS geographic information system.
The terrain contact between the upland and hybrid canyons is defined by elevations ranging between −2050 m and −1900 m (Fig. 3a, label 1), which also mark a section of the dichotomy boundary west of the outflow channels (2), and the inter-crater plains of western Arabia Terra (3). Figure 3a, label 1 shows the elevations ranging from −2050 m to −1900 m, which mark the contact between the upland fluvial canyons and the subsided terrains (1), the dichotomy boundary west of the outflow channels (2), and the inter-crater plains of western Arabia Terra (3). Figure 3b shows the reconstruction of coastal line at approximately −1900 m during the proposed stage of regional Late Noachian sedimentation. Question marks show the locations of uncertain paleoshoreline stretches. We produced the maps in this figure using Esri’s ArcGIS geographic information system.

We propose the following regional geologic reconstruction leading to the development of the OFCS aquifers: The vast fluvial, or glacial-glaciofluvial, canyon systems of southern Margaritifer Terra4,23 discharged enormous volumes of sediments into southern circum-Chryse, where lower portions of these canyons were completely buried and integrated into the regional upper crustal stratigraphy (Fig. 4a). Coeval fluvial activity through the huge Uzboi-Ladon-Morava channel system, which connects the Argyre basin to the northern plains, is thought to have discharged vast volumes of water generated by the melting of a Late Noachian south polar ice sheet32. This enormous fluvial system could have also contributed to regional sedimentation in southern circum-Chryse2,33. In the proposed geologic scenario the upper extent of regional sedimentation would have been controlled by the elevation of Oceanus Borealis (Fig. 3b, sketches 1 and 2 in Fig. 4a).

We infer a relatively short-lasting duration for the conditions allowing deep upland erosion connected with the formation of the proposed massive clastic sedimentary wedge based on previous investigations that propose a major spike in erosional and sedimentation rates occurring near the Noachian-Hesperian boundary34–43. This geologic stage likely lasted just a few million years35. To establish a relative chronology for the proposed stage of large-scale sedimentation, we mapped the distribution of (1) collapsed craters, (2) buried craters, (3) flat-floored impact craters infilled up to their rims, and (4) impact craters that retain significant topography (Fig. 5a). Our mapping of buried craters is based on the identification of quasi-circular depressions distributed throughout the regional highlands. These features are thought to have formed by compaction of sediments overlying buried impact craters34. Impact crater statistics yield a Late Noachian age of 3.65 ± 0.01 Ga (Fig. 5b), and point to a major spike in impact cratering rates during this time period. This spike was likely the result of a late phase of the Late Heavy Bombardment thought to have affected Mars up to 3.6 Ga45. Increased global erosional and depositional rates associated with an active surface hydrosphere34–43 during the Late Heavy Bombardment are consistent with impact-induced climate change as proposed by Segura et al.46.

The rapid groundwater evacuation required to generate the Late Hesperian catastrophic floods would have required groundwater migration via extraordinarily permeable structures, most likely including...
extensive systems of large interconnected caverns filled with water and/or unconsolidated fluidizable sediment\textsuperscript{12,13}. We estimate that $\sim 2.8 \times 10^5$ km$^3$ of groundwater and eroded or fluidized sediments were rapidly evacuated from the hypothesized caverns. This value was calculated as the total area of subsided highlands ($\sim 4 \times 10^5$ km$^2$) times an average negative relief of $\sim 700$ to $\sim 1200$ m (Supplement). The distribution of the subsided valleys, here proposed to have been largely controlled by the distribution of the ancient buried troughs, indicates that the hypothesized caverns formed a direct connection between eastern Valles Marineris and a lower-lying equatorial belt of chaotic terrains located at the upstream portions of numerous outflow channels (dashed yellow line in Fig. 1a). These chaotic terrains occur within highland surfaces located within a narrow range of surface elevations (approx. from $\sim 500$ m to $\sim 1000$ m), which is consistent with groundwater outbursts produced by rapid release from an initially confined, underground body of water conforming to a potentiometric surface defined by the upper boundary of groundwater saturated crust in eastern Valles Marineris. Vast aquifers confined beneath a seal of ice-cemented permafrost are proposed to have existed within eastern Valles Marineris and nearby plateau regions during the Late Hesperian\textsuperscript{17–19}. These aquifers are thought to have reached superlithostatic pressures as a consequence of $\sim 3.5$ to $\sim 4.5$ kilometers of hydraulic head generated due to the warping of regional upper crustal rocks by the Tharis uplift\textsuperscript{19}.

Elaver Valles (Fig. 1a), located at an elevation of $\sim 2000$ m, is the highest outflow channel in eastern Valles Marineris. In contrast, the northern margin of the subsided terrain adjoining upper Ares Valles exhibits elevation ranges between approximately $\sim 1500$ and $\sim 2500$ m (Supplement). Moreover, elevation profiles from nearby undeformed highland surfaces show that the pre-subsidence topography was likely closer to approximately $\sim 1200$ m, ranging between approximately $\sim 500$ m and $\sim 1500$ m (Supplement). These relief estimates provide a basis to quantify relevant hydraulic pressures. Prior to the catastrophic outflows, hydrostatic pressures within the confined, water-filled caverns could have attained $h_w\rho_g$ between $\sim 13$ and $16.5$ MPa (or $11$ MPa, if corrected to pre-subsidence topography $h_w$ $\sim 3000$ m),
where $h_w$ is the relief in meters (~3500 m to ~4500 m), $g$ is Martian surface gravity (3.711 m/s²), $\rho$ is water density (1000 kg/m³). These estimates of regional groundwater pressurization approximate or exceed the upper estimate predicted to have caused outflow channel activity in circum-Chryse [10 MPa]⁵⁰. The pressure may have been even greater if the groundwater was highly saline, saturated in CO₂, or contained large volumes of fine-grained sediments. Following the groundwater outbursts, the hydraulic head within

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**Figure 5.** (a) Distribution of impact craters greater than 12 km in diameter. Measured impact craters include (1) collapsed craters, (2) buried craters, (3) flat-floored craters infilled up to their rims, and (4) degraded and pristine craters that retain significant topography. (b) Cumulative size-frequency distribution for all craters in study region. Calculated age includes craters with diameters larger than 12 km. Crater diameters were measured in ArcGIS software and cumulative size-frequency distributions were plotted using Craterstats2 software⁵⁹. The Hartmann⁶⁰ model production function and the Michael⁵⁹ chronology function were used to calculate an overall age of 3.65 ± 0.01 Ga for the sedimentary wedge (i.e., Late Noachian⁶⁰).
the previously confined cavernous water systems would have rapidly diminished due to drawdown of the regional water table, however, continued exsolution of CO₂ could have maintained the outflow channel discharges.

Our proposed scenario implies that the sedimentary deposits that buried the troughs were highly porous and likely included large volumes of hydrated clays and perhaps glacial ice. As Oceanus Borealis receded, these water-saturated deposits would have progressively frozen into extensive areas of ice-rich permafrost (Fig. 4a, sketch 2), which remained stable for a few hundred million years. Subsequent Late Hesperian groundwater eruptions and subsidence would have been controlled by the distribution of the buried troughs (Fig. 4a, sketches 3–5). Consequently, the water-filled caverns that produced the immense outflow channel discharges and related subsidence must have been excavated within the troughs’ permafrost or water-saturated infill. The generation and integration of these caverns have been attributed to localized permafrost melting by magmatic dikes in a way that large groundwater bodies were generated and confined by surrounding icy Late Noachian strata, which likely contained significant volumes of less permeable phyllosilicates. The integration of these caverns and their connection to kilometers-deep aquifer system in Valles Marineris would have allowed for the role of superlithostatic pressures in driving immense discharges to the southern Chryse basin. An alternative scenario might also involve the pressurization of meltwater beneath the Valles Marineris ice sheet.

We find that Southern circum-Chryse had a unique geologic history that combined large-scale fluvial sedimentation along the margin of an ancient Late Noachian ocean; conduit development within the sedimentary materials infilling vast systems of buried troughs; and the development of superlithostatic pressures within the lower reaches of these conduits, perhaps driven by elevated potentiometric surfaces transferred from eastern Valles Marineris. High hydraulic pressure gradients across large regions of water-filled caverns permitted the rapid drainage of the immense groundwater systems. This region of the planet contains the largest outflow channel system on Mars, so our hypothesis, including the precursory erosional and sedimentation processes, centers on one of the most dramatic hydrogeologic stories in the Solar System.

On Mars there is evidence for the long-term retention of large groundwater volumes within buried impact craters and within thick upper crustal hydrated mineral deposits. Clastic wedges containing large amounts of relic massive ice have been recognized within relatively young Earth deposits emplaced during recent glacial periods. These include glacial and glaciomarine sedimentary sequences produced during high sea-level stands that infilled and buried older valleys excavated by glacial and glaciofluvial erosion. However, frequent warm climatic excursions on Earth imply that these ice masses can only remain stable over relatively short geologic periods. On the other hand, the colder climate and lower geothermal heat flow on Mars could have allowed Martian clastic wedges to retain vast volumes of ice during billions of years. This model and our new observations provide support for the Martian primeval ocean and link the formation of the vast outflow channel source region aquifers to the emplacement of thick water-rich upper crustal sedimentary deposits during a spike in global hydrologic activity. The spike was perhaps triggered by impact-induced climate change during a late phase of the Late Heavy Bombardment. If these extensive Late Noachian aquifer systems formed globally, then their development could have significantly depleted the surface hydrosphere, thereby playing a potentially significant role in triggering the abrupt transition into the colder and drier conditions that characterized most of the post-Noachian climatic regimes. Thus, global Late Noachian sedimentary infill of buried canyons and craters might still retain much of the planet's hydrosphere.

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Author Contributions
J.A.P.R., J.S.K., V.R.B. and V.C.G. wrote the main text, J.A.P.R. prepared figures 1, 2 and 3 and the supplement. D.C.B. prepared figure 4, R.L. and M.Z. prepared figure 5. A.G.F., Y.J., H.M. and N.G. contributed to the development of specific aspects of the proposed hypotheses. All authors reviewed the manuscript.

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In the original version of this Article, the Abstract contained typographical errors.

“However, the restricted geographic location of the channels indicates that these conditions were not uniform Boundary.”

now reads:

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now reads:

“Using more recent mission data, we argue that during the Late Noachian fluvial and glacial sediments were deposited into a clastic wedge within a paleo-basin located in the southern circum-Chryse region, which at the time was completely submerged under a primordial northern plains ocean.”

In addition, there is a typographical error under 'Results and interpretative synthesis'.

“The mean elevation of the Late Noachian ocean shoreline, which is the one of relevance to this study, has been estimated to be approximately −1680 m24.”

now reads:

“The mean elevation of the Late Noachian ocean shoreline, which is the one of relevance to this study, has been estimated to be approximately −1680 m25.”

These errors have now been corrected in both the PDF and HTML versions of the Article.