Nature and hydrological relevance of the Shalbatana complex underground cavernous system

Jose Alexis Palmero Rodriguez and Sho Sasaki
Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan

Hideaki Miyamoto
Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona, USA

Received 30 October 2002; revised 28 January 2003; accepted 6 February 2003; published 22 March 2003.

[1] The geomorphology of the North East trending long fractured depression between the Ganges Chasma and the Shalbatana Vallis headwater source region is examined and interpreted to be the result of collapse of part of an extensive underground cavernous system. We propose that this cavernous system undermines at least a valley, which extends from the vicinities of the Ganges Chasma and terminates in the Shalbatana Vallis headwater source region and the Aromatum Chaos. We believe that the origin of this cavernous system was related to the formation and interconnection of discrete cavernous bodies and propose a hypothesis, which involves the interaction of permafrost and intrusive magmatism to explain their formation. The Shalbatana Vallis headwater source is interpreted as produced by a Noachian impact crater and surface collapse over part of the underground cavernous system. Finally, we propose that the water sources, which were involved in the excavation of the Shalbatana and Ravis outflow channels might have included water segregated from the permafrost through interaction of intrusive magmatism and permafrost, water drained from a paleolake in the Ganges Chasma and water released from the catastrophic evacuation of confined aquifers. *INDEX TERMS:* 1625 Global Change: Geomorphology and weathering (1824, 1886); 1655 Global Change: Water cycles (1836); 1749 History of Geophysics: Volcanology, geochemistry, and petrology; 1823 Hydrology: Frozen ground; 1832 Hydrology: Groundwater transport. **Citation:** Rodriguez, J. A. P., S. Sasaki, and H. Miyamoto, Nature and hydrological relevance of the Shalbatana complex underground cavernous system, *Geophys. Res. Lett.*, *30*(6), 1304, doi:10.1029/2002GL016547, 2003.

1. Introduction

[2] North of the Ganges Chasma on Mars there is an approximately 55 km wide and 300 km long fractured depression (Referred to here as Collapsed Conduit Complex, CCC, (Figure 1)). *Carr* [1995] interpreted the CCC as resultant from the roof collapse of a subsurface conduit produced by progressive gravitational drainage of an ice-covered lake in the Ganges Chasma [*Nedell et al.*, 1987; *Lucchita and Ferguson*, 1983] into a pre-existing terminal lower emergence located in the Shalbatana Vallis headwater source (SVHS, (Figure 1)) [*Cabrol et al.*, 1997].

2. The CCC General Geomorphology

[3] Our examination of Viking imagery of the CCC reveals an intricate network of round to oval interconnected pits, forming chains (Figure 1, Sub-frame F2). Pit chains have a general trend to the NE and occur at different elevations within the CCC.

[4] In order to discuss the formation of pit chains we examined two giant pits forming part of the largest pit chain. This NE trending chain, whose SW region has been highly degraded, represents most of the area forming the CCC. Pit A and Pit B (Figure 2) have an elliptical shape and their longest axis is oriented to the NE. Topography from the Mars Orbital Laser Altimeter (MOLA) reveals that Pit A is about 4 km deep and resembles a collapsed feature. Pit B shows a smooth and much shallower bottom and no chaotic terrain, which is generally associated with collapsed structures, is observed. The fact that the margin around Pit B is continuous in conjunction with the fact that the shapes, dimensions and orientations of Pit A and Pit B are very similar, suggest that collapse and sagging took place over discrete cavernous bodies for Pit A and Pit B respectively. Pit Z is also elliptical but its longest axis is oriented W-E. On its surface there is a sharp-rimmed depression (Figure 2, SRD), which we have interpreted as a sinkhole. Between Pit A and the Smaller Pit Chain there is a Linear Fractured Bounded Terrain (Figure 2, LFBT) and a Fracture Bounded Pit (Figure 2, FBP). The association of the discussed features points at collapse and subsidence, over a complex multilevel extensive system of chains of interconnected underground discrete cavernous bodies.

3. Extent of the Cavernous System

[5] A regional DEM (Figure 1, sub-frame F3; Figure 3) reveals that the CCC is part of a valley (The CCC valley), which extends to the NE from the vicinities of the Ganges Chasma and terminates in the SVHS and Aromatum Chaos (Figure 3, black dotted lines). The SE flank of the CCC valley widens up to the NE and gently dips towards the NW. We propose that this gentle dip was produced by regional subsidence as large amounts of materials were removed from the subsurface. There is a large system of interconnected linear depressions enclosed within the CCC valley SE flank. Many of these depressions are continuous and associated with some pit chains forming part of the CCC and along some of them there are sharp-rimmed depressions with irregular outlines and with a maximum depth of 1.5 km as revealed by MOLA data (Figure 1, SRD and Figure 3,

0094-8276/03/2002GL016547$05.00

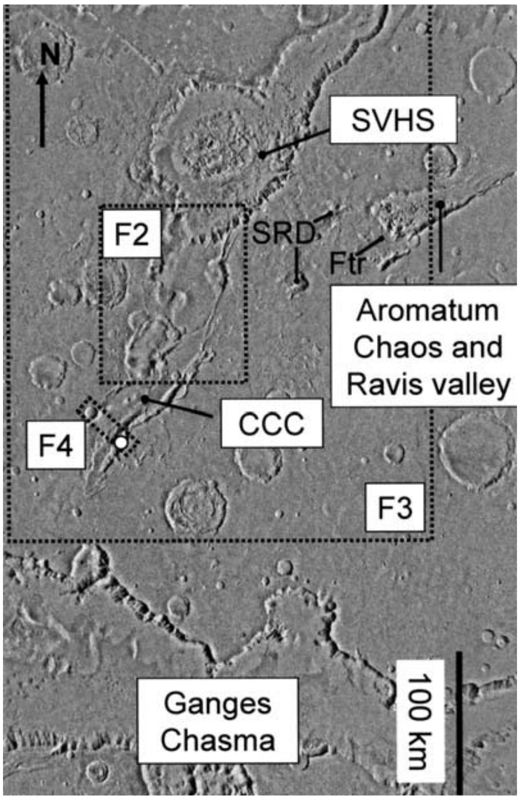

Figure 1. Viking mosaic of the area located between 2 N and 10 S, 49 W and 40.5 W. Sub-frames F2–F3 correspond to the positions of Figures 1–3 respectively. F4 corresponds to the MOC image M0906461 and the white circle within to the position of the region shown in Figure 4. SVHS stands for Shalbatana Valley Headwater Source, CCC for Collapsed Conduit Complex, SRD for sharp-rimmed depression and Ftr for fractured terrain.

SRD). We have interpreted them as sinkholes over an extensive cavernous system, which we have called the Shalbatana Complex Cavernous System (SCCS). We propose that the CCC valley is the result of surface collapse and subsidence over the SCCS, which we have inferred to undermine at least the region within the CCC valley.

4. Tecto-magmatic and Permafrost Interaction Mechanisms for the Formation of SCCS

[6] *Burr et al.* [2002] proposed that the Cerberus Fossae fissure system has been the source of both recent lava flows and recent aqueous flooding. They suggest that a causative relationship between the two flows.

[7] The depression labeled Dp in Figure 2 is the convergence region for three NE trending grabens (Figure 2, g1, g2 and g3). Graben g3 terminates in the deeply gullied margin of the SVHS SE region. There is a cliff-bounded ridge (Figure 2, CBR), which extends to the NE about 10 km away from graben g3 into the SE region of the SVHS. The fact that it is topologically higher than the surrounding terrain indicates that it is lithologically more resistant than the surrounding material. We interpret this ridge to be an exposed and partially eroded dike. Based on the association of the dike and graben g3 we propose the grabens to be surface tensional features produced by surface stresses related to the dilatation of non-emergent dikes. Based on the criteria proposed by *Mège* [1999] to identify dike exposures based on their narrow, symmetrical, linear low relief ridges and the fact that both dike's sides have steep slopes, we have interpreted ridges found at the valley bottom of a pit chain within the CCC, as dike outcrops (Figure 1, sub-frame F4; Figure 4, Rd). The observation that dike outcropping in the surveyed area is limited to topographically depressed regions, which we have interpreted as produced by surface collapse, is consistent with these dikes being non-emergent.

[8] We propose that the SCCS resulted from processes related to the intrusion of dikes in ground ice. A hypothesis consistent with the observations discussed in section 2 is that heat released from the dikes resulted in the development of hydrothermal systems. An overlying frozen permafrost and an underlying compacted basement confined the hydrothermal circulation of liquid and vapor water. Hydrothermal circulation led to the melting and removal of the ice-binding matrix, what resulted in the segregation of the solid phase and differentiation of the liquid/vapor water into a discrete cavernous body. The SCCS might have resulted from the interconnection of discrete cavernous bodies.

[9] Other processes that might have operated during the formation of the subsurface conduits or modified preexisting ones include water flowing along fractures created during magmatic intrusive events, gravitationally [*Cabrol et al.*, 1997], pressure [*Carr*, 1974] or temperature [*Gulick*, 1998] driven outflows of permafrost confined or semi-confined aquifers, and drainage of surface ponded water [*Carr*, 1995].

[10] Alternatively or complementarily, the depressions observed in the CCC valley can be explained by a process, which involved the interaction between magmatic intrusions and liquid water in the subsurface below the ice-rich permafrost. Groundwater that is heated by magma forms an upwardly moving buoyant plume. Colder, denser ground-

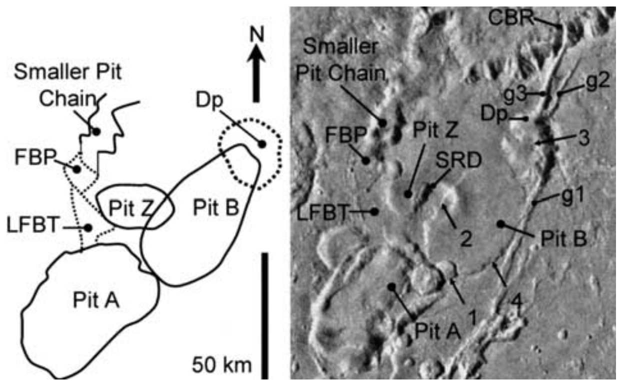

Figure 2. Viking mosaic [1.1 S and 3.6 S, and 45.4 W and 47.5 W] of a CCC section (right) and correspondent diagram (left). The white arrows 1 to 4, point at parts of the Pit B margin, which has been modified to different extents. Number 1 points at a section of the margin which has been obliterated by an impact crater, number 2 points at a section of the margin which seems to have been deformed by Pit Z, number 3 points at a section of the margin which forms a ridge and number 4 points at a section of the margin which forms a sharp cliff face. SRD stands for sharp-rimmed depression, LFBT for Linear Fractured Bounded Terrain, FBP for Fracture Bounded Pit, CBR for cliff-bounded ridge, Dp for depression, and g for graben.

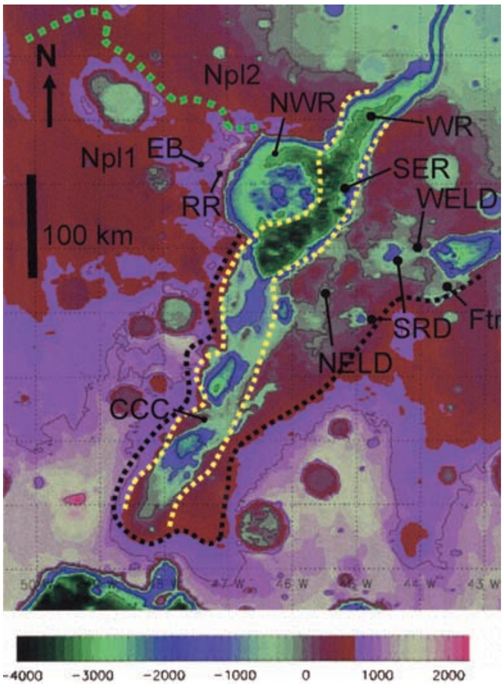

Figure 3. MOLA derived DEM. NWR stands for North Western Region, SER for South Eastern Region, NELD for NE trending linear depression, WELD, for W-E trending linear depression, SRD for sharp-rimmed depression, CCC for Collapsed Conduit Complex, WR for Shalbatana Channel upstream widest reach, Fr for fractured terrain, EB for ejecta blanket, RR for rim ridge. The dotted yellow lines demark the 55 km wide NE trending continuous region formed by the CCC, the SER and the WR. The black dotted lines demark the margins of the CCC valley. The thick dotted green line depicts the approximate position of a geological boundary between the Noachian plains 1 (Npl1) and the Noachian plains 2 (Npl2) in relation to the NWR.

water flows in toward the intrusion from surrounding regions, and continues to replace the upwards-moving groundwater as long as a thermal gradient exists [*Gulick*, 1998]. Ground ice above and near the intrusion would be melted, locally eliminating or thinning the permafrost zone [*Gulick and Baker*, 1992; *Gulick*, 1993], creating an instability over the region of the subsurface magmatic intrusion(s). If the intrusion was particularly deep (several km or more) or in regions adjacent to the intrusion, surface expression might be minimal. Another possible process would have involved the viscous flow departure of fluidized subsurface material [*Carr*, 1995] in response to extension associated with subsidence of the SE flank of the CCC valley, resulting in the collapse or sagging of an overlying rigid layer.

[11] The trend of the ridges, we have interpreted as dikes, is roughly SW-NE, what is consistent with the position of the third wave of the peripheral Tharsis radial fault system [*Cabrol et al.*, 1997]. This trend also dominates the orientation of the linear depressions (Figure 3, NELD) and pit chains within the CCC valley (Figure 3, black dotted lines).

5. The Origin of the SVHS

[12] The SVHS was mapped by *Scott and Tanaka* [1986] as chaotic terrain. *Cabrol et al.* [1997] attributed its formation to the catastrophic evacuation of a confined aquifer and subsequent surface collapse. They proposed that at an interception of the radial and concentric fault systems around the Tharsis rise, a tabular igneous body penetrated the upper crust into the cryosphere. A zone of pressured vapor resulted and was subsequently sealed by the base of an ice rich cryosphere [*Clifford*, 1991]. Finally water condensed, emerging at the points in the fractured megaregolith and eroded the surrounding friable material.

[13] MOLA derived DEM's reveal a dichotomy, which separates the SVHS into a North Western Region (NWR) and a South Eastern Region (SER) (Figure 3). Both these regions have distinctive geomorphic features and topographic characteristics.

[14] The NWR has a polygonal rim with the terrain around it forming a topographic high, which resembles a crater ejecta blanket (Figure 3, EB). A rim ridge is found to flank parts of the rim (Figure 3, RR). These observations are coherent with the NWR being the remnants of an approximately 110 km diameter impact crater. The SER on the other hand does not show any crater related features. This region is considerably deeper with an average depth of about 4 km when compared to the 2.5 km of the NWR. It has a surface roughness, as measured from MOLA elevation profiles, similar to that of collapsed regions such as chaotic terrains.

[15] The CCC, the SER and the Shalbatana Channel upstream widest reach, form a NE trending continuous region about 55 km wide (Figure 3, dotted yellow line). There is a maximum depth of about −4 km that forms a

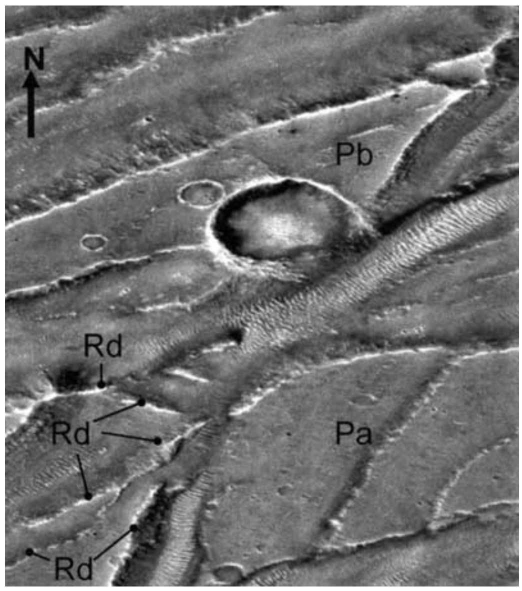

Figure 4. The region depicted in this MOC image M0905461 sub-frame corresponds to a section of the floor of a NE trending pit chain within the CCC (See Figure 1, sub-frame F4). Image width 2.93 km. Illumination from the NW. There are two plateaus (Pa and Pb) whose surface texture is like that found in the terrains adjacent to the pit chain. Both Pa and Pb are broken up into blocks. We have interpreted them as cavernous roof material. There is a complex system of NE trending valleys along which there are narrow, symmetrical, linear low relief ridges (Rd). We have interpreted these ridges as dike outcrops.

baseline for the whole region. We have interpreted this whole region to be the result of collapse to different degrees of an extensive cavernous body.

6. Stratigraphy of the SVHS

[16] During the middle Noachian heavily cratered terrains, made up of a mixture of lava flows, pyroclastic material and impact breccias, formed (Plateau unit Npl1 in Figure 3). During the late Noachian these terrains were subdued by volcanic, eolian and fluvial deposits (Plateau unit Npl2 in Figure 3) [*Scott and Tanaka*, 1986; *Dohm et al.*, 2001]. The margin of the NWR is in contact with the Npl1plateau unit to the W and NW and with the Npl2 plateau unit to the N (Figure 3). Although the topographic features interpreted as a rim ridge and ejecta blanket are well developed over the Npl1 unit terrains, they poorly developed over the terrains forming part of the Npl2 unit. This suggests that these topographic features were partly subdued by processes involved in the deposition of the Npl2 unit. We propose an age between the middle and late Noachian for the impact crater.

[17] Magmatic-tectonic activity related to the Tharsis rise resulted in the formation of radial and concentric fault systems, mainly during the late Noachian and then diminished substantially during the early Hesperian [*Dohm et al.*, 1998; *Dohm and Tanaka*, 1999; *Dohm et al.*, 2001]. This is consistent with the ridges interpreted as a dikes (Figure 1, sub-frame F4; Figure 4, Rd) eroding into the middle Noachian Npl1 material and therefore being of a younger age, possible late Noachian. This suggests that the SCCS mainly formed during the late Noachian. We estimate that water was first released to form the Shalbatana Channel some time between late Noachian – early Hesperian. The Shalbatana Channel remained active until late Hesperian – early Amazonian [*Scott and Tanaka*, 1986].

7. Discussion

[18] According to the classic views on the geological history of the region, the CCC was the result of surface collapse over a subsurface conduit, which formed by drainage of a paleolake in the Ganges Chasma into the Shalbatana outflow channel system [*Carr*, 1995]. Three seemingly chaotic regions along the Shalbatana Vallis (One of which, the SVHS) and the Aromatum Chaos were interpreted by *Cabrol et al.* [1997] and by *Coleman* [2002] respectively, to be consistent with permafrost disruption and flow from confined aquifers [*Carr*, 1979]. Water released from these confined aquifers, also participated in the excavation of their associated outflow channel systems.

[19] According to our views, the CCC was the result of partial surface collapse over an extensive cavernous system (SCCS), which once at least, interconnected the Ganges Chasma, the SVHS and the Aromantum Chaos. We propose that this cavernous system was mainly formed by the interaction of intrusive magmatism and permafrost, and that it served as a venue for migration of water segregated from the permafrost and drained from a paleolake in the Ganges Chasma, into both the Ravis and Shalbatana outflow channel systems. According to our observations the SVHS was produced by a middle to late Noachian impact crater and surface collapse over part of a cavernous system in the late Noachian to early Hesperian. Consequently, we suggest the Aromatum Chaos and only two of the three seemingly chaotic regions along the Shalbatana Vallis, resulted from permafrost disruption and flow from confined aquifers. Our conclusions support the prevalent hypotheses that there is a water rich cryosphere on Mars and that its interaction with tectonic-magmatic processes has played an important role in the planet's hydrological evolution.

[20] The SCCS extent and its internal structure, as well as the possible existence of water remain unresolved key issues in the investigation of the area. We hope that data from the Mars Express Mission MARSIS instrument (Mars Advanced Radar for Subsurface and Ionosphere Sounding) will help clarify these issues.

[21] **Acknowledgments.** We are grateful to Dr. Natalie Cabrol for her support and informal review of this paper and to Dr. Goro Komatsu, Dr. Virginia Gulick and Dr. Pascal Lee for their formal review of this paper.

References

Burr, D. M., A. S. McEwen, and S. E. H. Sakimoto, Recent aqueous floods from the Cerberus Fossae, Mars, *Geophys. Res. Lett.*, *29*(1), 1013, 10.1029/2001GL013345, 2002.

Cabrol, N. A., A. G. Ednmon, and G. Dawidowicz, A model of outflow generation by hydrothermal underpressure drainage in volcano-tectonic environment, Shalbatana Vallis (Mars), *Icarus*, *125*, 455–464, 1997.

Carr, M. H., Tectonism and volcanism of the Tharsis region of Mars, *J. Geophys. Res.*, *79*, 3943–3949, 1974.

Carr, M. H., Formation of Martian flood features by release of water from confined aquifers, *J. Geophys. Res.*, *84*, 2995–3007, 1979.

Carr, M. H., The Martian drainage system and the origin of valley networks and fretted channels, *J. Geophys. Res.*, *100*, 7479–7507, 1995.

Clifford, S. M., The role of thermal vapor diffusion in the subsurface hydrologic evolution of Mars, *Geophys. Res. Lett.*, *18*, 2055–2085, 1991.

Coleman, N. M., Aqueous flows formed the outflow channels on Mars (abstract), *Lunar Planet. Sci.*, *XXXIII*, 1059, 2002.

Dohm, J. M., and K. L. Tanaka, Geology of the Thaumasia region, Mars: Plateau development, valley origins, and magmatic evolution, *Planet. Space Sci.*, *47*, 411–431, 1999.

Dohm, J. M., R. C. Anderson, and K. L. Tanaka, Digital structural mapping of Mars, *Astron. Geophys.*, *39*, 3.203.22, 1998.

Dohm, J. M., et al., Latent outflow activity for western Tharsis, Mars: Significant flood record exposed, *J. Geophys. Res.*, *106*, 12,301–12,314, 2001.

Gulick, V. C., Magmatic intrusions and hydrothermal systems: Implications for the formation of Martian fluvial valleys, Ph.D. thesis, Univ. of Ariz., Tucson, 1993.

Gulick, V. C., Magmatic intrusions and a hydrothermal origin for fluvial valleys on Mars, *J. Geophys. Res.*, *103*, 19,365–19,387, 1998.

Gulick, V. C., and V. R. Baker, Martian hydrothermal systems: Some physical considerations (abstract), *Lunar Planet. Sci.*, 463–464, 1992.

Lucchita, B. K., and H. M. Ferguson, Low gradient and ponded flow, *J. Geophys. Res.*, *88*, 553–568, 1983.

Mège, D., Dikes on Mars: (1) What to look for? (2) A first survey of possible dikes during the Mars Global Surveyor aerobraking and science phasing orbits, paper presented at Fifth International Conference on Mars, 1999.

Nedell, S. S., et al., Origin and evolution of the layered deposits in the Valles Marineris, Mars, *Icarus*, *70*, 409–441, 1987.

Scott, D. H., and K. L. Tanaka, Geologic map of the western equatorial region of Mars, *U.S. Geol. Surv. Misc. Invest. Map, I-1802-A*, 1986.

J. A. P. Rodriguez and S. Sasaki, Department of Earth and Planetary Science, Bldg. S-5, University of Tokyo, Tokyo 113-0033, Japan. (alexis170971@ yahoo.com)

H. Miyamoto, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA.