Caves on Mars: Candidate Sites for Astrobiological Exploration

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Introduction: Among the most important questions in planetary science is whether life developed elsewhere in the solar system. Chemoautotrophic ecosystems are known to exist in isolated terrestrial caves and survive without solar-energy input [1], suggesting that similar organisms could conceivably exist in isolated Martian cave environments if appropriate mineral deposits are present. The vast majority of terrestrial cave systems contain microbial life in some form [*Boston*, personal communication, 2009].

The Martian surface experiences a range of significant hazards such as micrometeoroid bombardment, solar flares, UV radiation, high-energy particles from space, intense dust storms [2-6] and extreme temperature variations [7]. If microbial life has ever existed on Mars then it may have been limited (or forced to migrate) to the protection of cave environments [e.g., 8,9], which offer effective long-term protection from these hazards. Caves are therefore among the only human-accessible locations on Mars capable of preserving evidence of past or present microbial life [5].

Caves on Mars:

Source Data: The Mars Odyssey Thermal Emission Imaging System (THEMIS) visible-wavelength camera observes the Martian surface at scales down to ~18 m/pixel [10] and was first to observe the candidate cave skylights discussed here. These features are too small to be resolved at thermal-infrared wavelengths by the 100 m/pixel THEMIS thermal-infrared (IR) camera. The Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) observes the surface at ~6 m/pixel [11], and provides clearly more defined skylight examples. At this time, CTX coverage does not include much of the region north of Arsia Mons where most of the THEMIS-observed skylights have been identified. Thus far, the MRO High Resolution Imaging Science Experiment (HiRISE) has observed one of these skylights in fine detail (~0.25 m/pixel – about 1/5000 of a single THEMIS 18-m pixel) [12], where an overhanging rim and dust-mantled interior are clearly resolved.

Observations: The skylight-bearing rille structures discussed here were all identified in the extensive rift apron north of Arsia Mons (southernmost of the massive Tharsis-ridge shield volcanoes). The proposed skylight entrances into these features appear in the images as intermittently occurring dark holes within rille structures that can be linear, sinuous, branched or braided, and can extend for more than 100 km. All of the observed rilles run continuously down-slope at angles of ~0.5° or less. Specific morphologies of these structures vary between individual examples, though most can be associated with one of two distinct morphological groups. Some of these rilles are visibly consistent with many known tube-fed lava flows on Earth [e.g., 13,14], appearing as relatively narrow channels (<60 m across, Figure 1) that follow a single, sinuous path along the crest of an axially running topographic rise with occasional rim levees, tumuli and skylights. These features are tell-tale indicators of a tube-fed system emplaced by inflation, which can be a dominant pāhoehoe emplacement mechanism across shallow slopes [15]. The rilles that run along the flow axis are downward-propagating cracks that result from extension of the upper crust during inflation, and do not necessarily indicate the diameter of a subsurface evacuated tube or that any internal collapse has occurred.

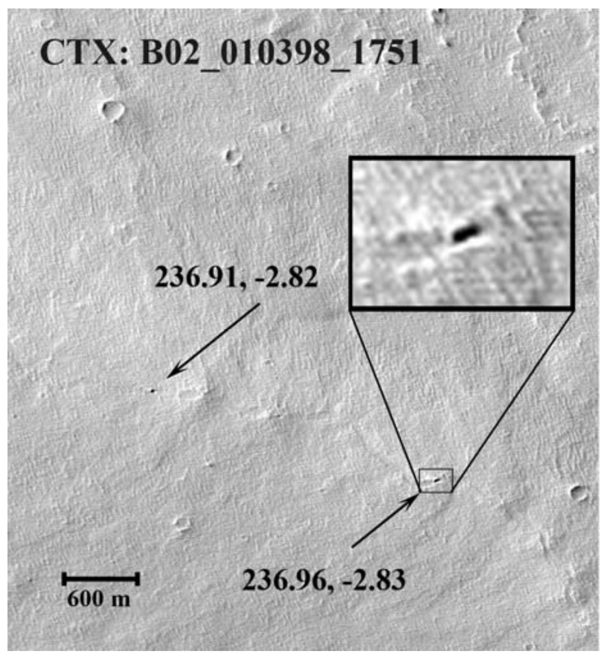

Figure 1: CTX image of a tube-fed lava flow containing skylight cave entrances.

Other rilles are considerably wider than the lava-tube rilles (~100-200 m, Figure 2). These are mostly linear with numerous sections that conjoin at sharp angles (usually slightly greater than 90º) and have the visible appearance of large tectonic fracture networks. Evidence that viscous volcanic materials took advantage of these subsurface fractures can be seen in the form of occasional rim levees, skylight entrances and lateral breeches with substantial outflow patterns. These volcano-tectonic rilles may be analogous to a feature in Kilauea Volcano's southwestern rift zone called 'The Great Crack,' which hosts caves that can exceed 180 m in depth.

Discussion: The rift apron north of Arsia Mons extends more than 500 km from the summit caldera, and consists of innumerable superimposed lava flows. Subsurface lava conduits likely facilitated the growth of such long flows by providing the insulation necessary for lava to maintain low viscosity as it traveled such great distances over shallow slopes [16-18]. Modeling the dependence of lava-tube length on effusion rate and tube diameter, *Keszthelyi* [16] determined that lava tubes (formed in Mars' thermal and atmospheric conditions) could easily exceed 800 km in length—even with effusion rates as low as 20 m^3/sec and tube diameters as narrow as 15 m. The skylight entrances discussed here, as well as their host structures, appear generally consistent with orbital views of candidate terrestrial analogs.

Habitat Potential: Cave interiors, by nature, are protected from all of the previously mentioned hazards that exist on Mars' surface. Dust storms and micrometeoroids cannot reach cave interiors, temperature variations are minimized in cave environments [e.g., 9, 20-22], and ceiling thicknesses of only 1-2 m are sufficient to effectively shield against all types of incoming radiation [23,24]. *Boston et al.* [5,9] discuss possibilities for past or present biological activity in Martian caves and new exploration technologies that must developed to explore them.

Exploration: Considerable advancements in exploration technology are necessary before visiting such structures can be considered. Precision landing techniques must be developed to target such small and specific sites (at relatively high elevations), and methods of entering and exploring cave environments (while maintaining contact with the surface) must also be developed (e.g., [9]). Furthermore, international planetary protection treaties forbid any visitation to candidate astrobiology sites until microbial contamination issues can be addressed [19]. Regardless of the challenges ahead, this identification of viable cave targets is a necessary step to promote development of a new category of planetary exploration technologies.

Conclusions: Volcanic regions are extensive across Mars and the discovery of cave entrances within them is not surprising. At least 2 different cave-forming mechanisms appear to have operated in the flow field north of Arsia Mons; lava tubes, and hybrid volcano/tectonic fracture networks. Now that specific examples have been identified, we can examine their characteristics in detail to ascertain their suitability for habitation and to determine what capabilities may be necessary for future explorers.

Future Work: Being a newly identified category of surface feature on Mars, considerable work is required before the global distribution and frequency of skylight occurrences can be determined. Because the structures discussed here were identified within a limited sample area, other examples are likely to exist in other volcanic regions across Mars. We will use both THEMIS and CTX data to conduct a planetwide survey. Future HiRISE observations are expected to show details of rim and floor morphologies that may help to constrain formation theories and identify exploration candidates.

The next generation of thermal-infrared camera to orbit Mars may observe the surface at resolutions of 10 m/pixel or finer, which is necessary to advance theories of how these structures extend beneath the surface. Determining the subsurface extent of these caves is crucially important to understanding their capability to protect or preserve biological activity. At this time, however, there are not yet plans to develop such an instrument.

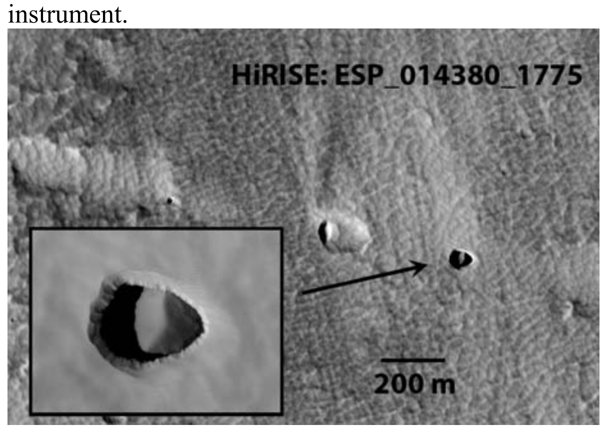

Figure 2: HiRISE observation of cave entrances in a proposed volcano-tectonic fracture network.

References: [1] Sarbu et al., 1996, *Sci.,* 272, pp. 1953-1955 [2] Mazur et al., 1978, *Sp. Sci. Rev*., 22, 3 –34 [3] Kuhn and Atreya, 1979, *J. Mol. Evol*., 14, 57–64 [4] Frederick et al., 2000, *Concepts and App. for Mars Expl.,* LPI [5] Boston et al., 2004, *AIP Conf. Proc*., v. 699, pp. 1007-1018 [6] Schulze-Makuch et al., 2005, JGR, 110, E12S23 [7] Cushing et al., 2005, *GRL*, 32, L23202 [8] Wentworth and MacDonald, 1953, *USGS Bulletin*, 994 [9] Boston et al., 2001, *Astrobio. J.*, 1(1):25-55 [10] Christensen et al., 2004, *Sp. Sci. Rev*., 110, 85-130 [11] Malin et al., 2007, *JGR*, 112(E5), E05S04 [12] McEwen et al., 2007, *JGR*, 112(E5), E05S02 [13] Greeley, 1971, *Mod. Geol*., 2, 207-223 [14] Cruikshank and Wood, 1972, *Moon*, v. 3, pp. 412-447 [15] Kauahikaua, et al., 2003, *USGS Prof. Paper* #1676 [16] Keszthelyi, 1995, *JGR*, 100(B10), 20411-20420 [17] Sakimoto et al., 1997, *JGR*, 102(E3), 6597-6614 [18] Keszthelyi and Self, 1998, *JGR*, 103(B11), 27447-27464 [19] COSPAR, 2008, http://cosparhq.cnes.fr/Scistr/PPPolicy(20-July-08).pdf [20] Wynne et al., 2008, *Earth and Planet. Sci. Lett*., 272, 1-2, 240-250 [21] Titus et al., 2010, *LPSC XLI* [22] Horz, 1985 . *Bases and Sp. Activities of the 21st Cent.* pp. 405-412 [23] NCRP, 2001, NCRP Publication N. 132 [24] De Angeles, 2002, *J. Radiat. Res*., 43: SUPPL., S41-S45.