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Searching for evidence of hydrothermal activity at Apollinaris Mons, Mars

M. Ramy El Maarry [a,b,*], James M. Dohm [c], Giuseppe A. Marzo [d], Robin Fergason [e], Walter Goetz [a], Essam Heggy [f], Andreas Pack [b], Wojciech J. Markiewicz [a]

[a] Max-Planck Institut für Sonnensystemforschung, Max-Planck Str., 2, 37191 Katlenburg-Lindau, Germany
[b] Universität Göttingen, Geowissenschaftliches Zentrum, Goldschmidtstrasse 1, 37077 Göttingen, Germany
[c] Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ 85721, USA
[d] ENEA, C.R. Casaccia, via Anguillarese 301, 00123 S. Maria di Galeria, Roma, Italy
[e] Astrogeology Science Center, United States Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ 86001-7034, USA
[f] NASA Jet Propulsion Laboratory, 4800 Oak Grove Drive, MS 300-243, Pasadena, CA 91109, USA

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ABSTRACT

A multidisciplinary approach involving various remote sensing instruments is used to investigate Apollinaris Mons, a prominent volcano on Mars, as well as the surrounding plains for signs of prolonged hydrologic and volcanic, and possibly hydrothermal activity. The main findings include (1) evidence from laser altimetry indicating the large thickness (1.5–2 km at some locations) of the fan deposits draping the southern flank contrary to previous estimates, coupled with possible layering which point to a significant emplacement phase at Apollinaris Mons, (2) corroboration of Robinson et al. (Robinson, M.S., Mouginis-Mark, P.J., Zimbelman, J.R., Wu, S.S.C., Ablin, K.K., Howington-Kraus, A.E. [1993]. Icarus 104, 301–323) hypothesis regarding the formation of incised valleys on the western flanks by density current erosion which would indicate magma–water interaction or, alternatively, volatile-rich magmas early in the volcano's history, (3) mounds of diverse geometric shapes, many of which display summit depressions and occur among faults and fractures, possibly marking venting, (4) strong indicators on the flanks of the volcano for lahar events, and possibly, a caldera lake, (5) ubiquitous presence of impact craters displaying fluidized ejecta in both shield-forming (flank and caldera) materials and materials that surround the volcano that are indicative of water-rich target materials at the time of impact, (6) long-term complex association in time among shield-forming materials and Medusae Fossae Formation.

The findings point to a site of extensive volcanic and hydrologic activity with possibly a period of magma–water interaction and hydrothermal activity. Finally, we propose that the mound structures around Apollinaris should be prime targets for further in situ exploration and search for possible exobiological signatures.

1. Introduction

Similar to Earth, the geologic record of Mars likely includes impact-generated (Newsom, 1980; Rathbun and Squyres, 2002; Abramov and Kring, 2005) and magmatic-driven (Dohm et al., 1998, 2008; Schulze-Makuch et al., 2007) hydrothermal activity. This is deduced from the widespread occurrence of impact, volcanic, and water-related features on the surface, which are often temporally and spatially associated. Martian surfaces of different ages, for example, exhibit hydrological features such as large outflow channels (Baker and Milton, 1974), valley networks (Scott et al., 1995), gullies and debris aprons (Malin and Edgett, 2001), polygonal-patterned ground (Kargel, 2004; Levy et al., 2009; El Maarry et al., 2010), glaciers (Kargel and Strom, 1992), rock glaciers (Mahaney et al., 2007), deltas (Ori et al., 2000a; Malin and Edgett, 2003; Di Achille and Hynek, 2010), and possible water bodies ranging from lakes to oceans (Scott et al., 1995; Fairén et al., 2003; Crown et al., 2005; Di Achille et al., 2006; Wilson et al., 2007; Dohm et al., 2009a), all of which indicate that Mars had liquid water on its surface at some time during its history, perhaps for considerably lengthy periods. Associated with this diverse and extensive evidence of martian aqueous activity, are the widespread and numerous impact craters (Barlow and Bradley, 1990) and massive magmatic complexes such as Tharsis and Elysium, along with their related tectonic features (Anderson et al., 2001, 2008) in addition to other diverse evidence of volcanism (Hodges and Moore, 1994). Both water and heat energy through exogenic (e.g., impact) or endogenic (e.g., magmatic) processes often interact in space and time (e.g., Carr, 1979; Newsom, 1980; Mouginis-Mark, 1990; Crown and Greeley, 1993; Tanaka et al., 1998; Dohm et al.,

* Corresponding author. Address: Institute of Physics, University of Bern, Sidler Str. 5, 3012 Bern, Switzerland.
E-mail address: mohamed.elmaarry@space.unibe.ch (M.R. El Maarry).

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2001a,b), which is expected to have produced widespread hydrothermal activity on Mars.

An example of potential martian impact-induced hydrothermal activity is Gusev Crater. Spirit, one of NASA's two Mars Exploration Rovers (MER), landed in Gusev Crater and many of its findings suggest the potential for hydrothermal alteration (e.g., Gellert et al., 2004; Schmidt et al., 2008; Yen et al., 2008; Ruff et al., 2011). Another example of recently proposed impact-induced hydrothermal activity on Mars is the impact crater Toro which is located in the northern margin of the Syrtis Major volcanic province. Toro is a 42-km-diameter and 2-km-deep complex crater, having a central peak and a central pit, both of which mark structural uplift, volatile release, and collapse. In addition, putative hydrothermal mounds are observed on and around the central uplift (Marzo et al., 2010). Analysis of spectral data in Toro impact crater shows multiple mineralogic signatures that include prehnite, chlorite, Fe-smectites, and opaline material. The observed suite of minerals is believed to be hydrothermal in origin (Fairén et al., 2010; Marzo et al., 2010), being linked to the impact crater event during the Hesperian Period. These observations are supported by geochemical simulations that indicate that such hydrothermal systems would form a suite of clay minerals in the central peaks and crater margins (Schwenzer and Kring, 2009). The large energies involved in creating impact craters can sustain hydrothermal systems for long geological periods provided that the target materials are water-enriched, as evident for Mars (e.g., Kieffer and Simonds, 1980). The estimated lifetime of impact-induced hydrothermal systems on early Mars ranges from ~70,000 years for a 30-km-diameter crater, ~400,000 years for a 180-km-diameter crater, to nearly 10 Myr for a Hellas-sized basin (Abramov and Kring, 2005).

Both impact- and magmatic-driven hydrothermal systems represent locations of exobiological interest due to the ability of such environments to sustain life on Earth (Valentino et al., 1999; Glamoclija et al., 2004; Parnell et al., 2010). As a result, many efforts have been devoted to locating optimum hydrothermal targets on Mars for exploration (e.g., Newsom, 1980; Newsom et al., 2001; Dohm et al., 2004; Schulze-Makuch et al., 2007). The work presented here is inspired by such efforts, particularly focusing on Apollinaris Patera (recently renamed to Apollinaris Mons, and as such, the newer terminology is used henceforth) which has already been identified as a site of potential magmatic-driven hydrothermal activity on Mars (Farmer, 1996; Schulze-Makuch et al., 2007). In this study, we test the hydrothermal hypothesis by investigating the entire Apollinaris Mons region and looking for key indicators of hydrothermal activity. We build upon the earlier mapping efforts found in scientific literature that focused on the volcano and its surroundings making use of the existing image databases (see online supplementary material) from the Thermal Emission Imaging System (THEMIS; Christensen et al., 2004), the narrow angle Mars Orbiter Camera (MOC; Malin et al., 1992), the Context Imager (CTX; Malin et al., 2007), and the High Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2007) cameras (approximately on average, 16–40 m/pixel, 1.5–20 m/pixel, 6 m/pixel, and 25 cm/pixel, respectively), topographic data from the Mars Orbiter Laser Altimeter (MOLA; Smith et al., 2001), and spectral data from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM; Murchie et al., 2007). Our primary objective is to assess the role of Apollinaris Mons in forming an extensive hydrothermal system that could be of significant interest for future in situ exploration, and simultaneously, review and build up on the current knowledge regarding the general morphology and geology of the various geological units comprising Apollinaris Mons and its surroundings as well as its stratigraphical and chronological relation with the Medusa Fossae Formation.

2. Morphology of Apollinaris Mons

2.1. Context and literature review

Apollinaris Mons (Fig. 1) is a prominent 200 km-wide and 5 km-high shield volcano with an average slope of ~5° (Plescia, 2004). It is located near the boundary between the northern plains and southern highlands (174.4°E, 9.3°S) and approximately 200 km north of Gusev Crater, the target of investigations by the Spirit rover (Squyres et al., 2004; Arvidson et al., 2006, 2008, 2010). It contains a multi-stage caldera complex approximately 80 km in diameter. The northern and eastern flanks of the edifice are surrounded by the Medusae Fossae Formation (MFF) (Scott et al., 1993) and terminate with clear scarps. The southern flank, however, is characterized by extensive fan deposits that drape parts of the volcano from summit to base. The western flank is surrounded by large (km-sized) blocks and knobs forming a terrain similar to the chaotic terrain found elsewhere on Mars such as those that source the channels of the circum-Chryse outflow chan-

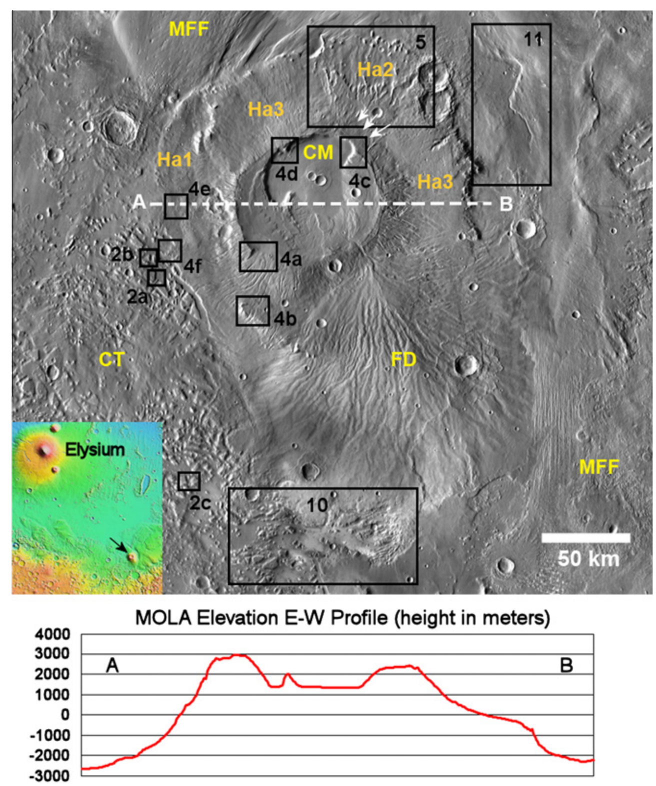

Fig. 1. (Top): Day-time IR THEMIS mosaic (100 m/pixel) of Apollinaris Mons and surrounding terrain. Apollinaris Mons occurs near the boundary that separates the northern plains from the southern highlands. Medusa Fossae Formation (MFF) partly surrounds the shield volcano to the north and east, and chaotic terrain (CT) is prevalent to the west of the volcano. The main construct is almost 200 km wide, displaying a caldera complex at its summit that is almost 80 km in diameter where the inner caldera material (CM) is affected by two impact events creating craters that are 4–5 km wide with rampart ejecta. The volcano is also notable for the extensive fan deposits (FD) that drape the southern flank and appear to originate from a small channel that dissects the southern rim. Black rectangles display the position of numerous images shown throughout the paper and the white arrows in the NE flank point to a spot suggested by Robinson and Smith (1995) to contain mineral deposits formed by fumarolic activity (see text). Other abbreviations in the figure include the geological classification of various units of the main edifice by Scott et al. (1993) from oldest to youngest which are Ha1, Ha2, and Ha3. Mosaic credit: JMARS. (Bottom): MOLA elevation profile passing through the area shown as a dashed white line in the top panel. Note the difference in steepness between the eastern flank where a notable scarp is present (right) and the western one (left) that shows various incised valleys.