Geomorphological Indication of Ancient, Recent, and Possibly Present-day Aqueous Activity on Mars

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Abstract

This paper overviews water sculpted Martian landscapes, ancient through to possibly present day, which have become more pronounced through each new orbiting, landing, and roving mission. Geomorphological evidence of ancient aqueous activity associated with lakes and putative oceans includes a diversity of features. Features include sedimentary sequences, debris flows, fluvial valleys, alluvial fans, giant polygons, and glacial and periglacial landscapes. Arguably one of the most significant geomorphological indicators of a paleoocean is deltaic landforms identified along a topographic zonal boundary which correlates with reported putative shorelines. Other evidence includes distinct geochemical/mineralogical/elemental signatures of aqueous weathering. In addition, relatively high-resolution imaging cameras onboard the Mars Global Surveyor, Mars Odyssey, and Mars Reconnaissance Orbiter have detailed features which indicate recent and possibly present-day aqueous activity such as slope streaks, slope linea, gullies which occur along faults and fractures and source from geologic contacts and tectonic structures, and possible open-system pingos, among other feature types. Ancient, recent, and possibly present-day features point to both surface and subsurface aqueous environments throughout time, and thus making Mars a prime target to address the ever-important question of whether life exists beyond the Earth.

Key words: Mars, geomorphology, hydrology, oceans, outflow channel, gullies, slope linea

I. Introduction

Mars’ missions continue to reveal aqueous-modified Martian landscapes. Geomorphological evidence includes a diversity of features, which include sedimentary sequences, debris flows, fluvial valleys, alluvial fans, deltas, and glacial and periglacial landscapes (Baker, 1978; Scott et al., 1995; Malin and Edgett, 2000a, b; Kargel 2004; Soare et al., 2007, 2014a, b; Di Achille and Hynek, 2010; El Maarry et al., 2013). In addition, there is significant geomorphological evidence of the interaction among magma, water, and basement structures such as in the case of Athabascas Valles and Cerberus Fossae (Burr et al., 2002; Mitchell and Wilson, 2003). Perhaps the most surprising finding from the post-Viking mission are a variety of features that indicate the Mars has been hydrologically active up until present day, including features that indicate hydrological activity in Valles Marineris (McEwen et al., 2011, 2013).

The purpose of this paper is to present evidence that points to aqueous activity during ancient (Early Amazonian–Noachian or older than ~ 1.03 Ga or 1.23 Ga based on Hartmann (2005) or Hartmann and Neukum (2001), respectively) and recent (~ younger than 1.03 Ga or 1.23 Ga) times, and even possibly present day, and thus making Mars a prime target to test the hypothesis...
of whether life exists beyond Earth. Below we discuss ancient aqueous activity on Mars followed by evidence of recent and possibly present-day activity.

II. Ancient aqueous activity on Mars

One of the most distinct ancient water-sculpted features on Mars is the circum-Chryse outflow channel system, which forms the northeast watershed of Tharsis (Dohm et al., 2001a, b). The circum-Chryse outflow channel system is hypothesized to have formed from linked Tharsis-driven magmatic activity and flooding, with associated ponding in the northern plains to form oceans and to drive transient climate change and hydrological cycling (Baker et al., 1991, 2007; Fairén et al., 2003; Komatsu et al., 2004) (Figs. 1 and 2).

In addition, geochemical/mineralogical/elemental signatures of ancient aqueous activity have been detected through orbital-, lander-, and rover-based spectroscopic imagers. Minerals from aqueous weathering and hydrothermal activity include hematite concretions referred to as blueberries (Fig. 3) (Moore, 2004; Ormö et al., 2004b; Havics et al., 2009), sulfates (Gendrin et al., 2005; Quantin et al., 2005; Mangold et al., 2007a, b; Murchie et al., 2009), clays (Fialips et al., 2005; Bibring et al., 2006), chloride-bearing materials (Osterloo et al., 2008; Davila et al., 2011), carbonates (Ehlmann et al., 2008; Morris et al., 2010), serpentine (Ehlmann et al., 2010), and pure silica (Squyres et al., 2008). In addition, elevated concentrations of potassium and thorium have been identified below the putative shorelines when compared to terrain above the shorelines, likely indicating ancient aqueous activity related to oceans (Dohm et al., 2009).

Such evidence indicates weathered zones and possible paleosols in stratigraphic sequences (e.g., Mahaney et al., 2001), transport of water and rock materials to sedimentary basins (e.g., Dohm et al., 2009), and the formation of extensive lakes (e.g., Scott et al., 1995; Cabrol et al., 2001) and possibly transient oceans (e.g., Fairén et al., 2003; Greenwood and Blake, 2006) on ancient Mars.

The growing geomorphological evidence of ancient hydrological modification of the Martian surface, which corroborates the existence of ancient oceans once occupying the northern plains of Mars, includes deltas at certain topographic zonal boundaries, consistent with the margin of the putative ocean, and thus referred to as circum-paleoocean deltas (e.g., Di Achille and Hynek, 2010) (Fig. 4). Arguably the most significant...
indicator of paleoceans on Mars, deltas are also identified in impact basins where river systems debouched sediment-laden water under lower-energy conditions (Cabrol and Grin, 1999; Irwin et al., 2005; Di Achille and Hynek, 2010).

In particular, carbonates occur east-southeast of Nili Fossae within deltaic deposits that were emplaced from a river system into the western part of the Jezero impact basin (Fig. 4d) during the Late Noachian–Early Hesperian (Ehlmann...
Regional to global geological and hydrological considerations, including spatial and temporal associations among the western margin of Isidis basin and a topographic interval consistent with other deltaic structures along the hemispheric dichotomy (Di Achille and Hynek, 2010) and the proposed Noachian–Early Hesperian ocean (Fairén et al., 2003; Ormö et al., 2004a), indicate that the Jezero paleolake was likely associated with hydrological activity (including elevated hydraulic head) of the more extensive ocean.

Additional evidence for ancient hydrological systems that included oceans are the giant polygons similar to those found on the ocean floors of Earth (McGowan, 2011) and impact craters and associated features reminiscent of impacts into Earth oceans such as tsunami-like return flow of the water displace by the impact event (Ormö et al., 2004a). In addition, the existence of ancient oceans is supported by Mars Odyssey Gamma Ray Spectrometer-based elemental information, which highlights distinctions between the regions below and above the putative shorelines (Dohm et al., 2009), long-wavelength topography consistent with deformation caused by true polar wandering (Perron et al., 2007), and Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) data which indicate that regionally occurring fine-grained sediments such as marine deposits and/or ice rather than lava flows best explain the radar signatures (Mouginit et al., 2012).

III. Recent and possibly present-day aqueous activity on Mars

Contrasting with an ancient warmer and wetter Mars, as indicated by the above geomorphological and geochemical evidence, present-day Mars is characterized by drier and colder conditions. With a mean surface pressure of about 8 kPa and a mean temperature of $-60^\circ$C below the triple point of water, liquid water at the surface of Mars is absent except possibly transiently (e.g., Haberle et al., 2001; Sears and Moore, 2004; Fairén et al., 2009a, b). Elemental information obtained through the Gamma Ray Spectrometer (GRS) instrument onboard the Mars Odyssey Spacecraft has led to the discovery of large quantities of near-surface water ice (Boynton et al., 2002; Feldman et al., 2002). Consistent with the GRS-based observation, the Phoenix Mission to Mars confirmed ice-cemented ground below a thin layer of dry permafrost through in situ exploration (Smith et al., 2009). The origin of the ice-cemented ground is still a matter of debate, but the presence of ice close to the surface, makes it possible that it occurs elsewhere and could contribute to present-day transient aqueous activity. In addition, brine may have also allowed water to remain liquid for sufficient time to produce geomorphological features indicative of aqueous activity near and on the surface; possible liquid water, likely brine, has been observed at the Phoenix landing site (Smith et al., 2009; Whiteway et al., 2009), and possible formation of night-time transient liquid brines which evaporate after sunrise has been observed through Mars Science Laboratory (MSL) data (Martín-Torres et al. 2015).
Fig. 4 The distribution and morphology of currently known candidate Martian deltaic deposits (modified from Dohm et al., 2011). (a) Context camera image (CTX) showing a multilobate depositional feature at the mouth of Sabrina Vallis. (b) CTX view of the multilobate deposit within the Eberswalde crater, showing evidence for vertical and lateral accretion and extensive channel avulsion over the putative delta plain. (c) Perspective view (CTX image draped over CTX-derived digital elevation model [DEM] with 2 × vertical exaggeration) of a possible Gilbert-type fan delta in Shalbatana Vallis (Di Achille et al., 2007, 2009). (d) Multilobate deposit within the Jezero crater showing typical characteristics of terrestrial river-dominated deltas, evidence for vertical and lateral accretion, and channel avulsion over the putative delta plain (CTX). (e) Possible Gilbert-type fan delta in Nephentes Mensae region (the same deposit is shown in the lower panel in a perspective view; CTX image draped over HRSC-derived DEM with 2 × vertical exaggeration). (f) CTX image of a previously unreported deposit in Tempe Terra. (g) Heavily eroded Gilbert-type fan delta at the mouth of Tyras Vallis; the two transversal scarps have been interpreted to be evidence for two main standings of the water level (Di Achille et al., 2006). (h) North polar stereographic projection from Mars Orbiter Laser Altimeter data with locations of candidate deltas of (a)–(g) shown. F indicates the approximate location of the delta fronts. Delta fronts mark the approximate elevation of the most stable highstand during which the deposits formed.
Fig. 5  Slope streaks with distinct anastomosing patterns observed in MOC images (a) M20-00897, (b) M16-00596, (c) M13-00834, and (d) M10-00967 (Miyamoto et al., 2004a, b). Also note that a relatively large flow sources from a small domical structure, indicating a continuous source. A competing hypothesis is dust avalanching for the feature (Sullivan et al., 2001). There is more and more evidence that points to water being involved with at least some of the dark slopes (Kreislavsky and Head, 2009). In addition, there are more recently identified feature types that occur on Martian hillslopes that point to seasonal and possibly present-day hydrologic activity such as within impact craters and Valles Marineris (McEwen et al., 2011, 2013).

Fig. 6  HiRISE stereo (ESP_0028500_1425_ESP_028922_1425) image showing evidence for multiple resurfacing events by different processes (including possible glacial, alluvial, periglacial, fluvial, among others) (Dohm et al., 2015). The impact crater is buried by flow materials; the margin of the flow has slumped into the impact crater basin (arrow).
As is often the case of geomorphological feature types on Earth, a single Martian type has multiple interpretations. For example, while dark slope streaks have been interpreted to be related to dust avalanching (Sullivan et al., 2001), at least a percentage of the total population of streaks could be indicative of present-day aqueous activity (Ferris et al., 2002), supported by viscoplastic flow numerical modeling techniques applied to anastomosing-patterned streaks (Miyamoto et al., 2004a). Thus, a single geomorphological feature such as a dark slope streak is a controversial marker of possible recent and possibly present-day aqueous activity using orbiting spacecraft data. On the other hand, it is hard to refute such possible activity when considering a collection of geomorphological feature types identified through relatively high-resolution imaging cameras onboard the Mars Global Surveyor, Mars Odyssey, and Mars Reconnaissance Orbiter. In addition to slope streaks (Ferris et al., 2002; Miyamoto et al., 2004a) (Fig. 5), gully and associated debris aprons (Malin et al., 2006), slope linea in and outside of Valles Marineris (McEwen et al., 2011, 2013), features indicative of recent glacial (Kargel, 2004; El Maarrrey et al., 2013) and periglacial activity (Soare et al., 2014a) (Fig. 6), gullies on dunes (Miyamoto et al., 2004b), and gullies and candidate open-system pingos (Soare et al., 2014b) (Fig. 7) point to recent and possibly present-day aqueous activity.
IV. Summary

There is wide-ranging geomorphological evidence of ancient and recent aqueous activity, even possibly present-day activity. Ancient features include sedimentary sequences, debris flows, fluvial valleys, outflow channels, alluvial fans, giant polygons, deltas, and glacial landscapes. In addition, there are distinct geochemical/mineralogical/elemental signatures of ancient aqueous weathering, which may include hydrothermal activity, such as hematite concretions, sulfates, clays, and serpentine. Features possibly marking recent and present-day aqueous activity include slope streaks, gully and associated debris aprons, slope lineae, and pingos. Many features appear to be tied to tectonic structures and possible heat, such as the candidate open-system pingos and outflow channels. On Earth, biology, hydrology, and geology are interlinked such that certain types of life are often associated with specific conditions, including rock type, pressure, temperature, and chemistry. There is evidence of both ancient and recent geologic and hydrologic activity on Mars, and thus making Mars a prime target in the search for life beyond Earth; Mars once had Habitable-Trinity conditions with an interacting landmass, ocean, and atmosphere through hydrological cycling driven by the Sun (Dohm and Maruyama, 2014). Through future reconnaissance of Mars, which includes in situ analyses, we hope to test hypotheses including whether Mars is geologically and hydrologically active, contains salty groundwater and magma at relatively shallow depths, has sustained elevated heat flow, and records seismic activity. Though, we among many hope to address the paramount question of whether fossilized and/or extant life exists on Mars. Either answer will have profound implications for diverse and far-reaching fields of study.

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地形学からみた火星における過去から現在までの水成活動

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本論では、最近の火星における各軌道衛星・着陸船・探査車による探査計画によって判明した、過去から現在までの水成侵食地形について概観する。過去に存在した湖や海洋に関連する地形的証拠には多様多様なものがある。例えば、堆積岩層、土石流跡、河谷、沖積扇状地、巨大多角形土、そして氷河・周氷河地形などである。おそらく古海洋の存在を示す最大の証拠は海岸線に対応する地形的境界に沿ってみられるデルタ地形であろう。化学・鉱物・元素上の諸特性も水の関与する風化作用が働いていたことを明示する。さらに、マーズ・オデッセイ、マーズ・リコネッサヤー、マーズ・オデッセイ、マーズ・リコネッサヤー、マーズ・リコネッサヤー、マーズ・リコネッサヤー、マーズ・リコネッサヤー、マーズ・リコネッサヤー、マーズ・リコネッサヤーに搭載された高解像度カメラも、現成の可能性もある新しい水成活動を示す詳しい地形を撮しだした。スロープ・ストリック、スロープ・リニア、断層・断裂に沿ってあるいは地質境界や地質構造に端を発するガリー、開放系ピンゴなどが該当する。これらの過去から現在までのさまざまな地形は、長期にわたる地表や地下の水文環境を示唆すると同時に、火星が「地球外生命はどこに存在するか?」という永遠の問いに答える最大の候補地であることを物語っている。

キーワード：火星、地形、水文、海洋、アウトフロー・チャネル、ガリー、スロープ・リニア

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