Planetary and Space Science 93-94 (2014) 101–118

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

A cold hydrological system in Gale crater, Mars

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ARTICLE INFO

Article history:
Received 7 November 2013
Received in revised form
14 February 2014
Accepted 5 March 2014
Available online 15 March 2014

Keywords:
Mars
Gale crater
Glacial/periglacial modification
Glacio-fluvial activity
Fluvial erosion
Ground ice

ABSTRACT

Gale crater is a ~154-km-diameter impact crater formed during the Late Noachian/Early Hesperian at the dichotomy boundary on Mars. Here we describe potential evidence for ancient glacial, periglacial and fluvial (including glacio-fluvial) activity within Gale crater, and the former presence of ground ice and lakes. Our interpretations are derived from morphological observations using high-resolution datasets, particularly HiRISE and HRSC. We highlight a potential ancient lobate rock–glacier complex in parts of the northern central mound, with further suggestions of glacial activity in the large valley systems towards the southeast central mound. Wide expanses of ancient ground ice may be indicated by evidence for very cohesive ancient river banks and for the polygonal patterned ground common on the crater floor west of the central mound. We extend the interpretation to fluvial and lacustrine activity to the west of the central mound, as recorded by a series of interconnected canyons, channels and a possible lake basin. The emerging picture from our regional landscape analyses is the hypothesis that rock glaciers may have formerly occupied the central mound. The glaciers would have provided the liquid water required for carving the canyons and channels. Associated glaciofluvial activity could have led to liquid water running over ground ice-rich areas on the basin floor, with resultant formation of partially and/or totally ice-covered lakes in parts of the western crater floor. All this hydrologic activity is Hesperian or younger. Following this, we envisage a time of drying, with the generation of polygonal patterned ground and dune development subsequent to the disappearance of the surface liquid and frozen water.

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1. Introduction

Glacial modification at the highlands–lowlands transition on Mars appears to have been pervasive at least since the Hesperian (Head et al., 2004, 2006; Dickson et al., 2008; Davila et al., 2013), and possibly earlier (Fairén, 2010; Fairén et al., 2011, 2012). Gale crater (5.4S, 137.7E), the study site for the ongoing Mars Science Laboratory (MSL), or Curiosity rover mission, is a ~154-km-diameter impact crater formed during the Late Noachian/Early Hesperian (~3.6 billion years ago; see Greeley and Guest, 1987, and possibly ~3.8 billion years ago; Thomson et al., 2011), and located on the dichotomy boundary and near the Medusae Fossae Formation, in the Aeolis quadrangle. The northern floor and rim of Gale are ~1–2 km lower in elevation than its southern floor and rim, and a lake has been suggested to have occupied at least parts of the impact basin in the past (i.e., Cabrol et al., 1999; Dietrich et al., 2013). Unlike other nearby craters and valleys, Gale is too young to have been substantially affected by more ancient processes forming fretted or knobby terrains (Wray, 2013). Gale also lacks very young (sometimes polygonised) "mantle" (cf. northern plains, see Head et al., 2003) and young fluviatile gullies, and therefore it seems likely that Gale's

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http://dx.doi.org/10.1016/j.pss.2014.03.002
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internal geomorphology has not been substantially modified by very recent climatic excursions affecting equatorial Mars, such as those noted by Balme and Gallagher (2009).

The mound located in the central part of the crater, 'Aeolis Mons', shows layered deposits. It is nearly 100 km wide and extends over an area of 6000 km^2, and is up to 5 km in height (Malin and Edgett, 2000). The origin of Aeolis Mons is still debated, with eolian activity (Greeley and Guest, 1987; Malin and Edgett, 2000; Thomson et al., 2011), volcanism (Greeley and Guest, 1987; Hynek et al., 2003; Kite et al., 2013), lacustrine deposition (Greeley and Guest, 1987; Cabrol et al., 1999; Malin and Edgett, 2000; Thomson et al., 2011) and spring-related activity (Rossi et al., 2008) all proposed to explain its formation. For comprehensive overviews of the formation of Gale, and of the geomorphology and mineralogy inside the crater, the reader is referred to Anderson and Bell (2010), Milliken et al. (2010), Thomson et al. (2011), Schwenzer et al. (2012), Wray (2013) and Kite et al. (2013), and references therein.

The aim of this paper is to offer a new interpretation of the geomorphology which considers the potential for glacial and fluvial modifications of Gale crater, including Aeolis Mons. This is based on morphological observations using high-resolution datasets, particularly those from the High Resolution Imaging Science Experiment (HiRISE) and Context Camera (CTX) on Mars Reconnaissance Orbiter, and the High Resolution Stereo Camera (HRSC) on Mars Express Orbiter. We describe a suite of features that are consistent with an interpretation that invokes ancient glacial, periglacial and fluvial (including glacio-fluvial) activity within Gale crater, and we verify the previously proposed former presence of rivers and lakes, which we suggest represent an interconnected hydrological system under cold environmental conditions. All the geomorphological evidence presented here for the occurrence of water–ice and liquid water inside Gale is interpreted to be associated with the last episode of aqueous modification of the crater, and thus not considered to provide information about earlier processes of formation and/or physical or chemical modification of the crater. We also predict that MSL may have the opportunity to test our hypotheses through identification of small-scale glacial, periglacial and glacio-fluvial features.

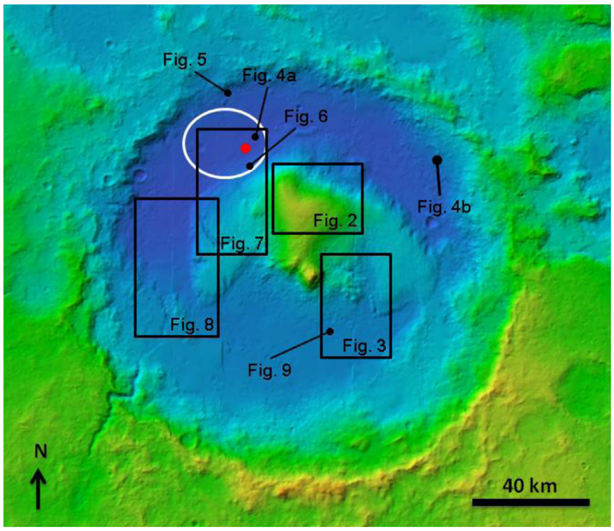

Fig. 1. HRSC shaded relief map of Gale crater, based on images H1916_0000, H1927_0000, and H1938_0000. The locations of the primary figures in the paper are indicated here. The white oval is the MSL landing ellipse and the red dot is the actual landing site of the rover. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

2. Observations

Our analysis is based on observations of a variety of remote sensing imagery, mostly high resolution HiRISE and medium resolution CTX and HRSC imagery, from the central mound in Gale crater and its immediate surroundings (see Fig. 1). We now describe various features according to their broad morphology and location, before interpretations are presented in Section 3.

2.1. Lobate features and valleys on Aeolis Mons

2.1.1. North/northeastern Aeolis Mons

Observation of the northern half of the main central mound in Gale crater reveals several lobate features that extend towards the crater floor (Fig. 2). These take the form of several lobes issuing from a larger source area labeled 'lobate features' in Fig. 2a. Three lobes are particularly obvious and orientated approximately south to north, but more degraded features also exist further to the west (Fig. 2b), again aligned roughly south to north.

The width of the more obvious lobes tends to remain fairly uniform at 1–2 km, but each 'trunk' clearly diverges and widens at their down-slope limit. Here, the terminus is clearly defined by an abrupt drop in elevation and the lateral limits of the lobe are also marked by a drop in elevation, which suggests that lobes themselves are of the order hundreds of meters thick (cf. Anderson and Bell, 2010). In contrast, the up-slope limit of the lobes is more diffuse and there are no obvious features that mark the onset or initiation of the lobes, which limits estimates of their precise length to a minimum of 6–8 km. In a broader context, the lobes can be seen to emanate from a shallow concave 'hollow' that characterizes the northern-most part of the central mound (Figs. 1 and 2a). However, the lobes do not extend down to the crater floor (elevation −4200 m), and instead terminate at an elevation of approximately −3600 m.

As noted by Anderson and Bell (2010), the lobes exhibit surface slopes typical of the large-scale slope of the mound (∼15°). It is difficult to ascertain the composition of the lobes but the surface texture is characterized by linear to sub-linear features orientated approximately perpendicular (transverse) to the surface of the lobe (Fig. 2c). Fig. 2b also shows the possibility that smaller, younger lobes have been superimposed on top of (presumably) older and larger lobes.

Located to the east of the distinct lobate features described above is a much larger fan-shaped deposit that is heavily fragmented and covers an area of ca. 100 km^2 (shown in Fig. 2d). It originates from the same broad hollow as the other lobate features, but the up-slope 'trunk' of this lobate deposit is less distinct than the lobes further west (Fig. 2b). Nevertheless, Anderson and Bell (2010) noted the narrow (1.8 km) and concave 'neck' that feeds into the lobate deposit, including a break in slope (from ∼15° to ∼5°) in this region. The deposit itself has a rugged and chaotic texture, but closer inspection reveals a more organized structure composed of arcuate ridges and depressions that are aligned perpendicular to the axis of the lobe (Fig. 2d). Horizontal layering and moraine-like features at the end of the eastern fan-shaped deposit are also visible (Fig. 2d, and see also HiRISE images ESP_025579_1755 and ESP_024379_1755). Anderson and Bell (2010) highlighted that the thermal inertia of the deposit increases towards its outer margins (up to $670\,J\,m^{-2}\,K^{-1}\,s^{-1/2}$), which suggests that these regions have more abundant rocks or cemented materials, as opposed to unconsolidated sediments (e.g. fine-grained materials such as sands and dusts) (Fergason et al., 2006). The whole fan abuts against a bedrock surface with distinct linear mounds, which in turn overlies a smoother, low albedo unit (see Fig. 2e).

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