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A cold hydrological system in Gale crater, Mars

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A R T I C L E I N F O

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A B S T R A C T

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.

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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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.

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.

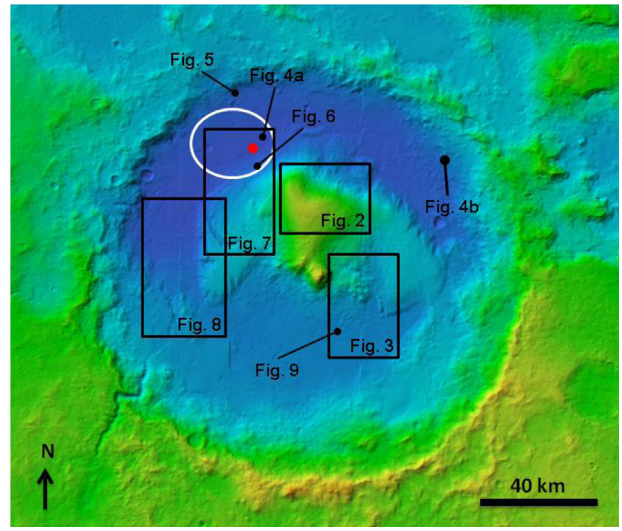

Fig. 1. HRSC shaded relief map of Gale crater, based on images H1916_0000, H1927_0000, and H1938_0000. The locations of the primary figures in the paper are indicated here. The white oval is the MSL landing ellipse and the red dot is the actual landing site of the rover. (For interpretation of the references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

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).

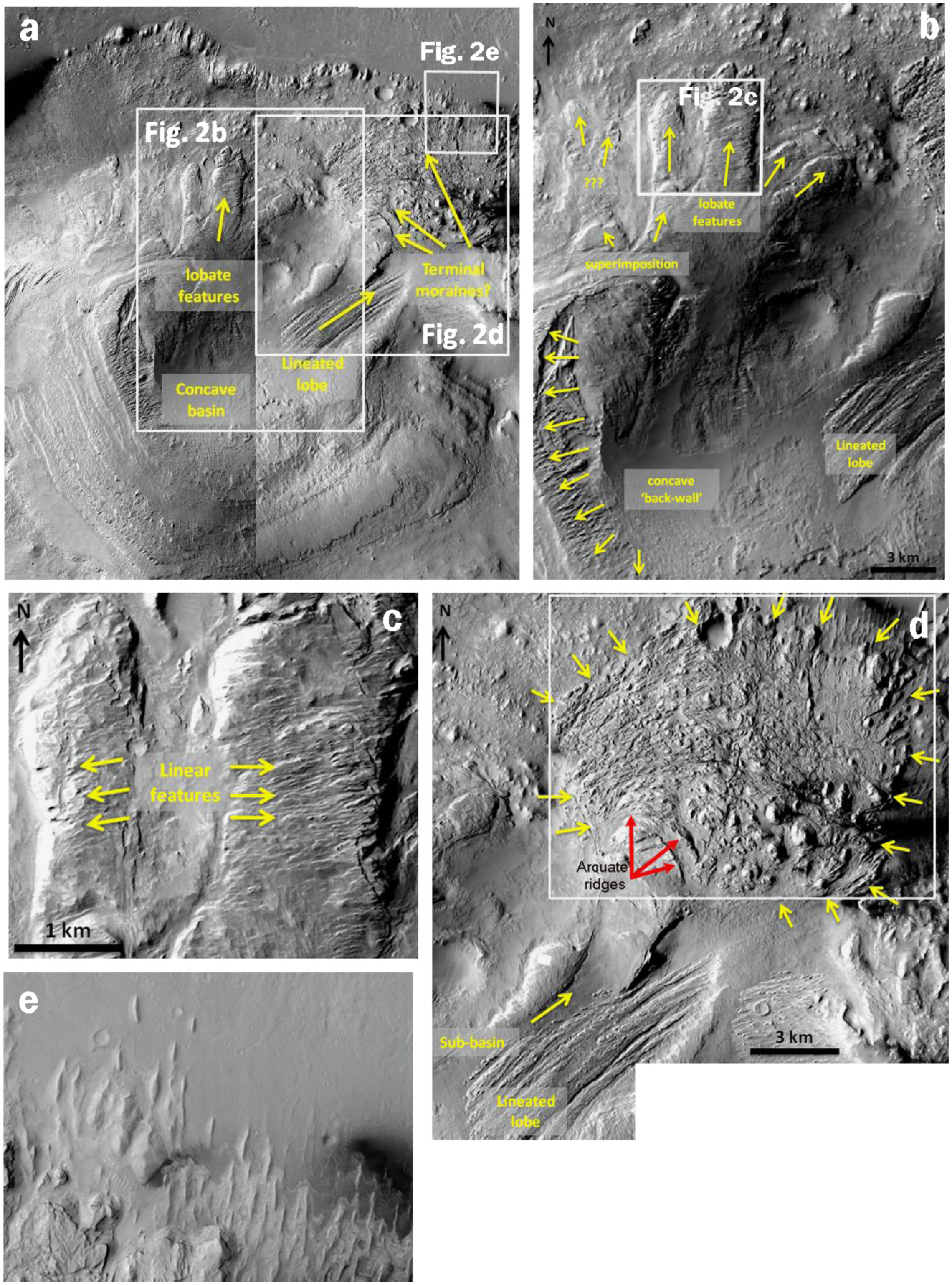

Fig. 2. (a) Composite image (CTX P04_01620_1749_XI_05S222W (left) and P04_002464_1746_XI_05S221W (right)) covering the northern half of the main central mound in Gale crater. (b) Details of the lobate features in the central mound. (c) Transverse linear features in the lobes at the northern half of the main central mound in Gale crater. (d) Divergent lobe (yellow arrows) with arcuate ridges (red arrows). (e) Portion of HiRISE image ESP_024379_1755, showing linear mounds northern of the fan. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

2.1.2. Southeastern Aeolis Mons

The southeastern part of the central mound stands out from other regions as being characterized by several large valley systems (Figs. 1 and 3a). In particular, a relatively long (ca. 20 km) valley with several short tributaries can be seen to extend from elevations of around −1700 m down to the valley floor at around −3000 m (Fig. 3a). The smooth appearance of the valley floor on HiRISE and CTX imagery suggests that this valley system has been partially infilled by sediments. Closer inspection reveals that the steep-headwall valleys have a smooth mantle even on the steeper slopes, as well as a smooth floor, although with some ripple-like forms. In addition, there are extensive transverse dune

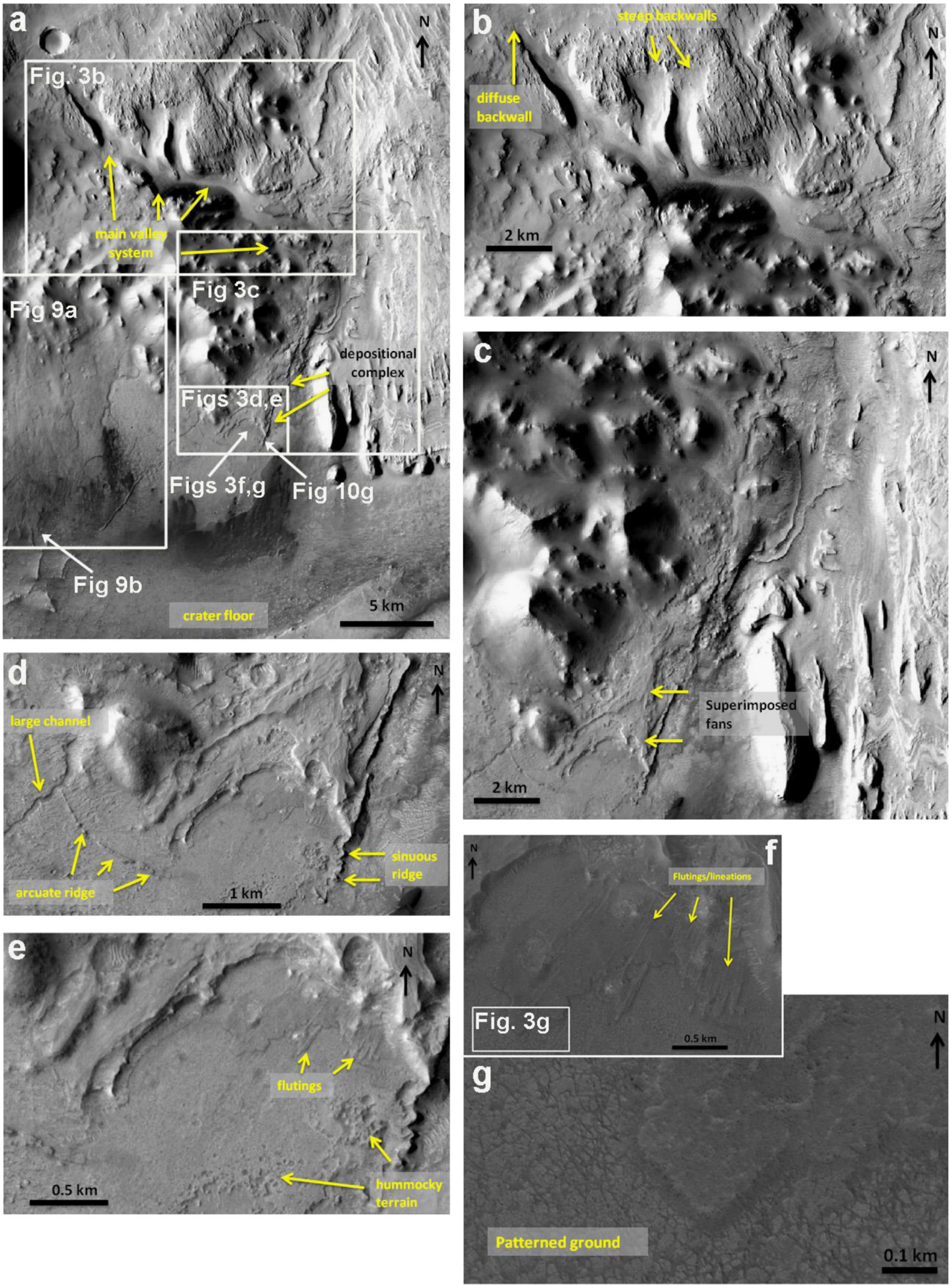

Fig. 3. (a) Image CTX P04_002464_1746_XI_05S221W, showing the region encompassing the south-eastern lower slopes of the main central mound in Gale crater. (b) Possible glacial valley incising the south-eastern lower slopes of Aeolis Mons. (c) Details of the depositional complex. (d) Details of the possible terminal moraine and the arcuate moraine ridge. (e) Closer view of a portion of (d), showing details of the terminal moraine, including a possible esker (see Fig. 10f), flutings and hummocky terrain. (f) HiRISE image PSP_003176_1745 showing possible glacial flutings in the terminal area of the depositional complex. The white box indicates the location of (g). Detail of (f).

systems similar to those commonly observed on Mars (Balme et al., 2008), which implies relatively fine-grained sediment (e.g. sands). This infilling precludes a detailed assessment of the valley cross-profile, but it is clear that the valleys are typically longer and uniformly broader than some of the more canyon-like valleys on the western flanks of Aeolis Mons (described below in Section 2.3), which tend to markedly widen down valley (e.g. compare Fig. 3b with the large canyon in Fig. 7b). Furthermore, the upslope limit of valley systems shown in Fig. 3b appears to initiate as broad systems and can often be seen to initiate in larger hollows, some of which (at least two of the three main tributaries) possess steep backwalls and sharp divides between them. In contrast, the canyon-like systems on western Aeolis Mons often start as narrow and shallow gullies that rapidly broaden and deepen down-valley. A further difference in this region is that the upland areas are clearly characterized by relatively sharp-crested ridges (Fig. 3b), often created by the juxtaposition of two valley sides or valley heads, whereas the canyon-like features on western Aeolis Mons are typically incised into a relatively flat or gently inclined plateau surface (Fig. 1).

The main valley feeds down-slope, and turning 90° from southeast to southwest, into a relatively large and complex fan-shaped deposit on the crater floor that covers around 20 km^2. This complex is characterized by a series of superimposed deposits that debouch onto the crater floor (see Fig. 3c). Closer inspection shows that the lower-most limit of these fan-shaped deposits in the southwest is marked by an isolated sharp-crested arcuate ridge that is approximately 40 m wide, very well defined, flat topped in places, and might even be layered (Fig. 3d). In places, the ridge is split into individual fragments and, towards the northwest, it is clearly cross-cut and incised by a channel, indicating that the ridge is older than the channel.

Another prominent feature associated with the depositional fan complex is a large sinuous ridge that emanates from its south-eastern edge (Fig. 3d). This ridge can be traced for about 3 km and exhibits higher sinuosity towards its lower limits on the crater floor. The ridge shows high thermal inertia in THEMIS data (see Fergason et al. (2006), and THEMIS image I49780001). Towards the lower limits of the ridge there also appears some hummocky terrain that is characterized by a series of pits and depressions (Fig. 3e). Elsewhere on the crater floor, a series of linear features can be seen emanating from 'underneath' the fan-shaped deposits that are clearly superimposed. These linear features are typically 150 m long but some extend for almost twice this distance. They display exceptional parallel conformity with each other and typical widths are <10 m, with spacing between individual ridges

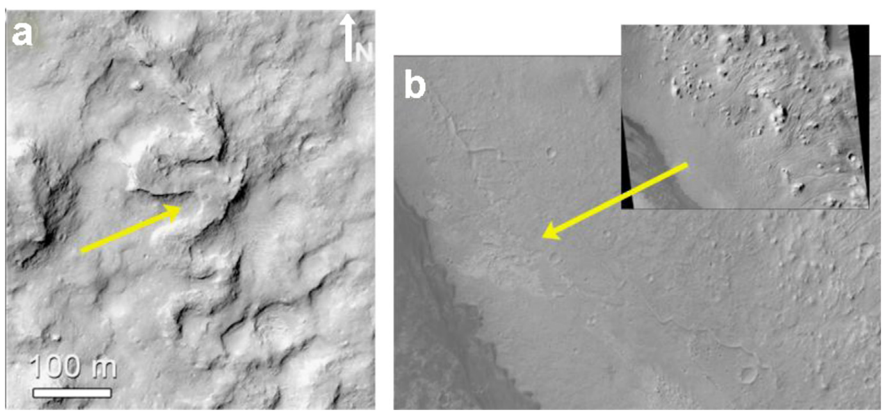

Fig. 4. (a) Portion of HiRISE image PSP_009751_1755 showing an inverted channel near the MSL landing site. The yellow arrow indicates where the channel has accreted, preserved as irregularly-spaced scroll bar surfaces. Location: 4.404°S, 137.535°E. (b) Sinuous ridges, probably inverted channels, extending over kilometric scales on the northeast crater floor, HiRISE images ESP_030748_1750 and ESP_030814_1750. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

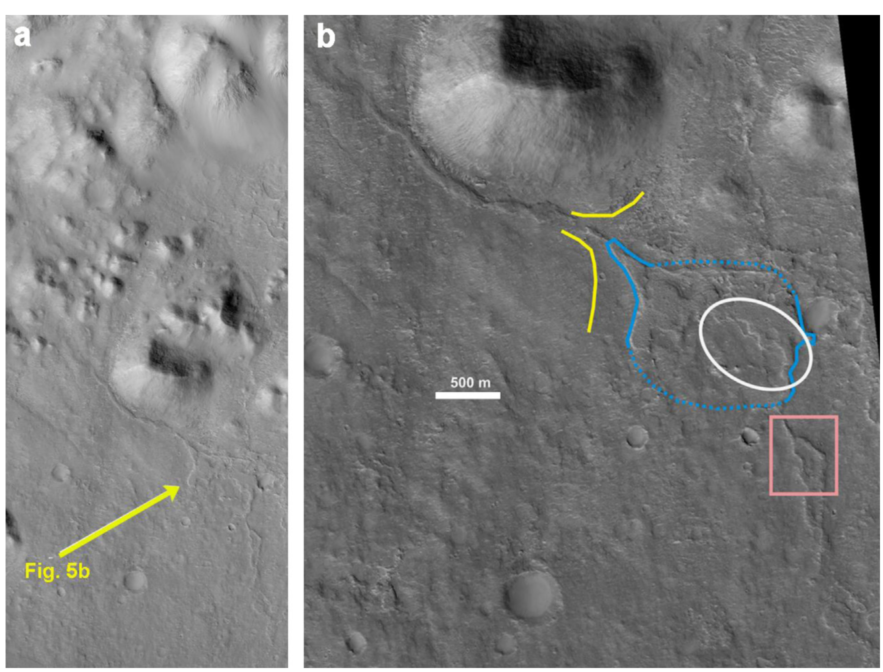

Fig. 5. (a) HIRISE image ESP_021900_1755 showing an inverted channel cutting across Gale's rim northwest the MSL landing site. (b) Close view of the area of the inverted channel where it both feeds into and emerges from a lobate fan/delta. Yellow line highlights an apparent break in slope, with steeper terrain to the left of the image. Blue line highlights the extent and inferred former extent (dashed line) of a reworked lobate (deltaic?) sediment accumulation. Meandering and channel bifurcation are highlighted within the white and pink areas respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

varying from 50 to 100 m. The linear features terminate at a shallow escarpment with a lower elevation surface beyond their limit which is characterized by polygonal patterned ground (Fig. 3f and g).

2.2. Meandering channels, lobate fans and patterned ground

Inverted channels are preserved in a number of locations in Gale crater (Fig. 4). The channels are often tightly meandering, with a sinuosity index of individual meander bends approaching 3 in some instances (Fig. 4a). Chute cut-offs are also apparent and, in addition, some of the channels demonstrate a repeated return to lateral accretion after multiple episodes of neck cut-off. Some of the sinuous channels inside Gale extend up to km scale (Fig. 4b). In places, the channels converge with one another.

We have also identified channels that both feed into and emerge from lobate fan-like forms (Fig. 5a). For example, the yellow lines in Fig. 5b mark a change in the character of the channel, corresponding to a break in slope. To the left of the lines, the channel is not distinctly sinuous and its morphology appears to have been governed by a steeper slope. To the right of the lines there is an apparent, though indistinct, meandering reach (white circled area), which appears to become bifurcated further down slope (pink box).

As noted above, several areas on the floor of Gale resemble polygonal patterned ground (see for example Figs. 3g and 6). The size of these polygonal features is of the order of meters, e.g. the 'width' of most polygons is around 10 m, and polygons are typically four-sided. Polygonal features occur in the distal part of the Peace Vallis (PV) fan inside the MSL landing ellipse, associated with a fan-shaped feature deposited by a channel that dissects the crater rim (see Figs. 1, 6c and 11). Interestingly, in some instances, polygonization is visible in one surface type (high standing), but not another (floor of depressions) (Fig. 6f). As mentioned earlier, the south-eastern crater floor also shows polygonally/rectilinearly fractured ground (Fig. 3).

2.3. Canyons, gullies and escarpments

Gullies and canyons occur in close proximity to the MSL landing site, along the western and northwestern lower slopes of the central main mound of Gale, see Fig. 7a. The most prominent features in this region are two large canyon systems which are incised into the lowermost northwestern section of the central mound (see Fig. 7b). The larger canyon seems to cut across the grain/structure of the underlying bedrock, and appears to feed directly into a narrow, but relatively deep channel or trough (labeled 'large channel' in Fig. 7b, and also shown in detail in Fig. 7c), which

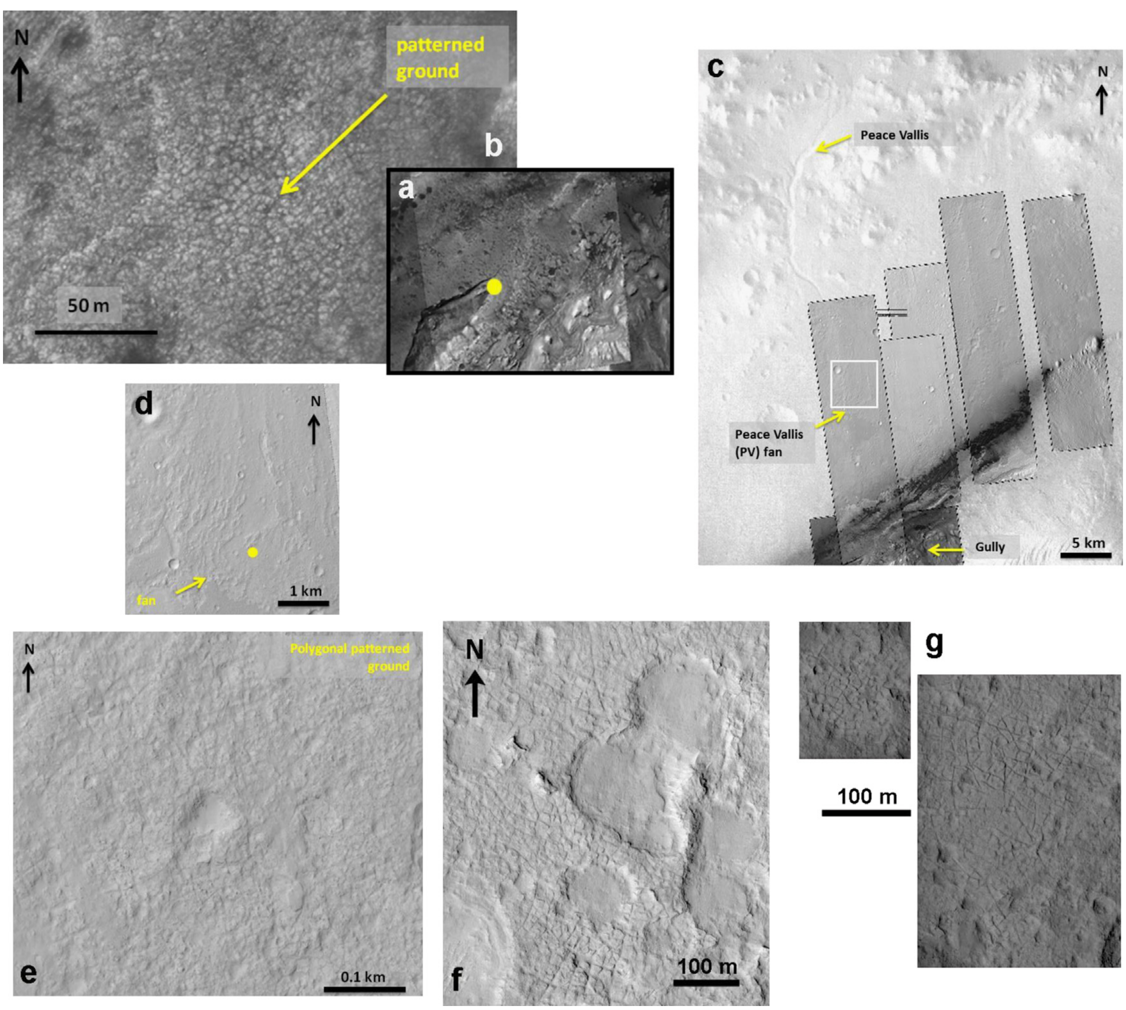

Fig. 6. (a) Portion of HiRISE image PSP_009650_1755, in the northern side of Aeolis Mons, near the MSL landing site. The yellow dot marks the location (b). (b) Closer view of patterned ground in (a). (c) Background HRSC image H1927_000 showing the location of polygonal features near (a), but closer to the landing site. The white square marks the location of (d). (d) Close up of (c) on HiRISE PSP_009650_1755. The yellow dot marks the location of (e). (e) Close up of (d). (f) Patterned ground in a portion of HiRISE ESP_029957_1755. (g) Circumferential polygons in different portions of HiRISE image ESP_029957_1755. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

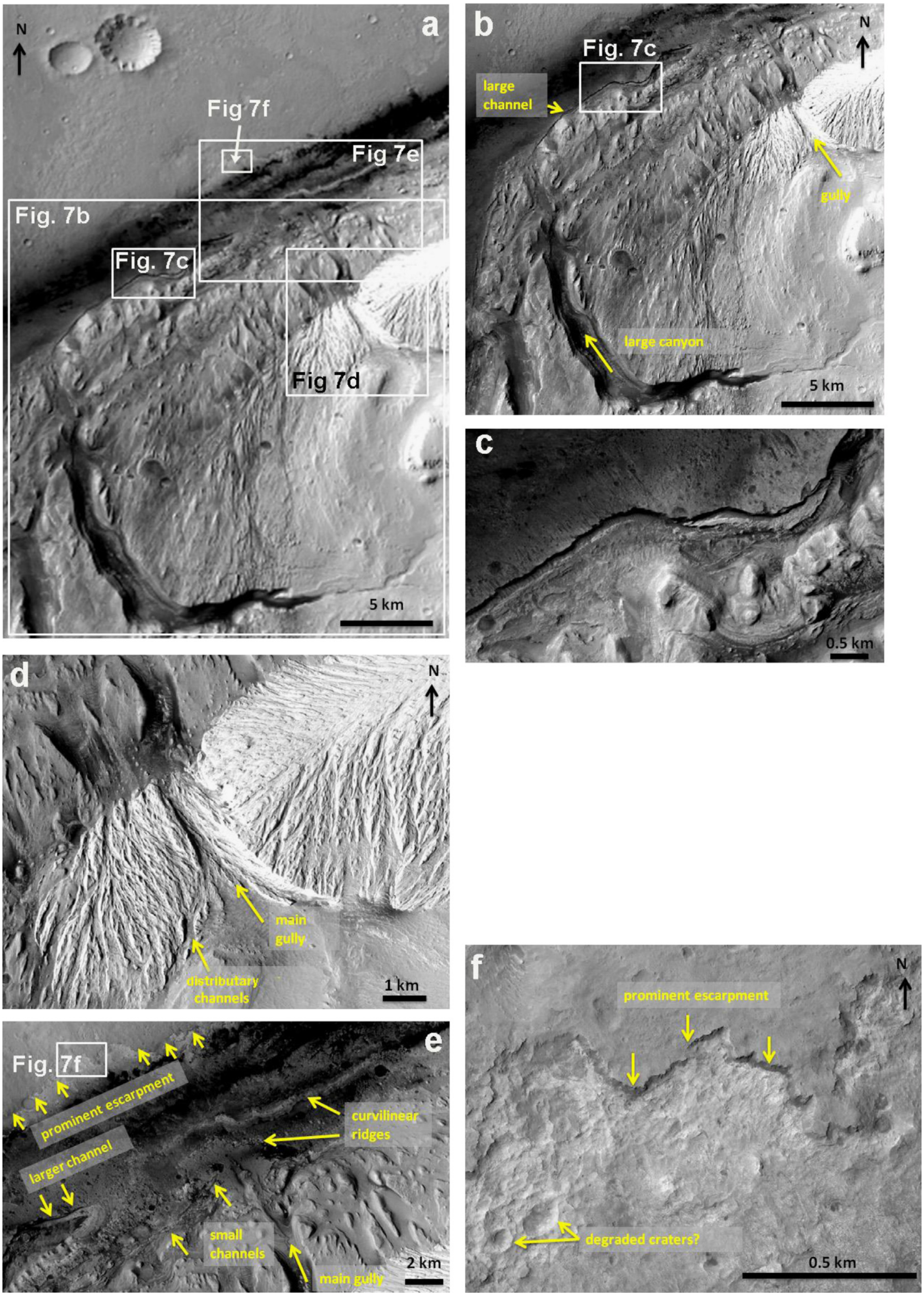

Fig. 7. (a) CTX image P01_001488_1751_XI_04S222W. This area includes the MSL landing ellipse (see Fig. 1). (b) Details of the canyon and gully. The white square marks the location of the large channel detailed in (c). (c) General aspect of the large channel running through the base of Aeolis Mons. (d) Details of the multiple channels and the main gully.(e) Main gully and curvilinear ridges near the base of Aeolis Mons. The white square marks the location of the escarpment shown in (f). (f) Close view of the prominent escarpments and 'ghost' craters on HiRISE PSP_009650_1755.

flows southwest towards lower ground. A smaller gully (labeled 'gully' in Fig. 7b) is also incised into the central mound in this region and opens out close to the onset of the large channel. Note the sharp, narrow onset of these valleys compared to the broader hollows that mark the onset of the valley system on the southeast section of the mound (Section 2.1.2, Fig. 3b).

To the southwest of the main gully there is an extensive multiple-channel system (see Fig. 7d), and several other channels, gullies and canyons are also observed. Drainage sources from the canyon, including the gully and the channel, debouch into a low-lying area marked by a complex sequence of curvilinear ridges (see Fig. 7e) that appear to be stratigraphically equivalent to other strata in the lower mound to the south, separated by (erosional) topographic depressions.

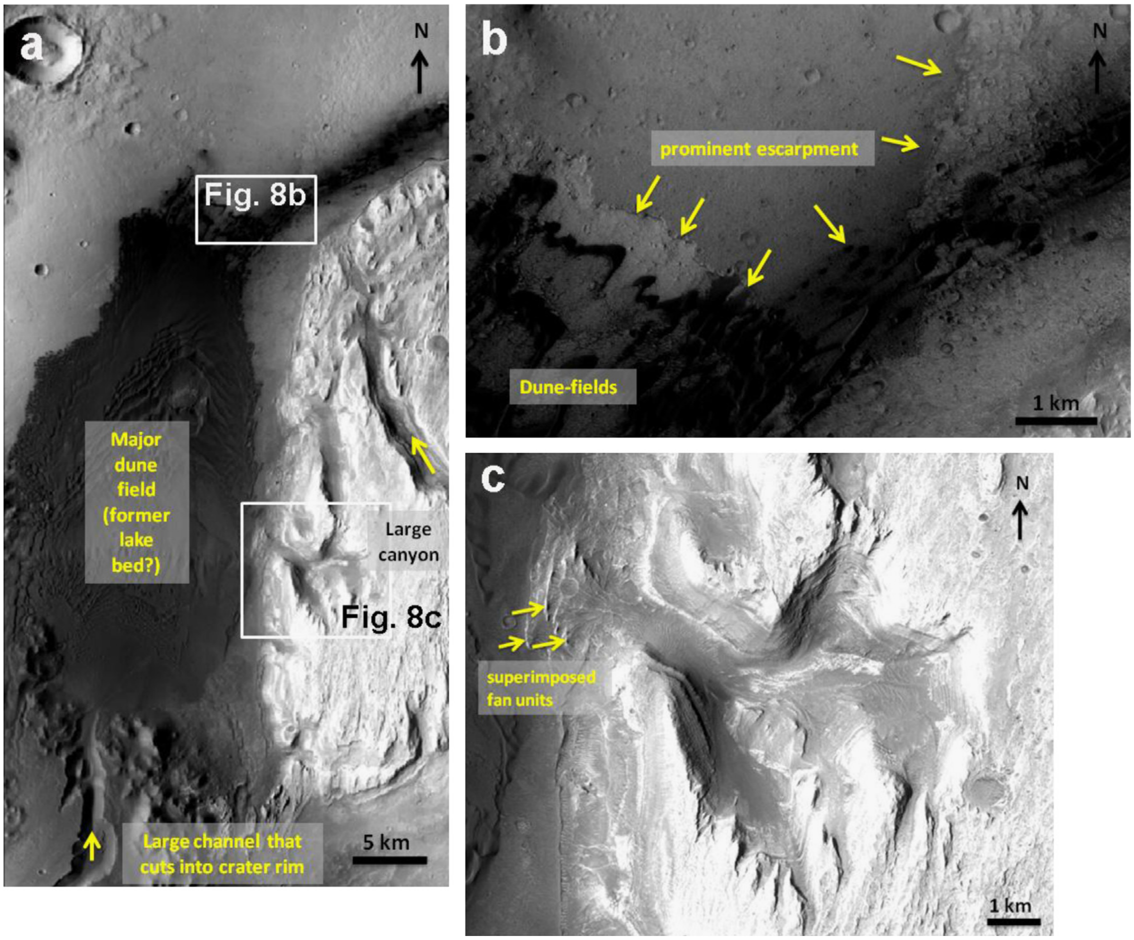

Fig. 8. (a) CTX image P04_002765_1746_XI_05S222W, showing a general view of the southwestern slopes of Aeolis Mons, including the wider dune field in Gale, the major channel cutting into the crater rim, and the larger canyon carved on Aeolis Mons. (b) Close view of the dune fields and the prominent escarpment near the base of Aeolis Mons, also shown in Fig. 7f. (c) Large canyon system draining towards the crater floor, possibly feeding into a former crater lake, on CTX P04_002675_1746_XI_05S222W.

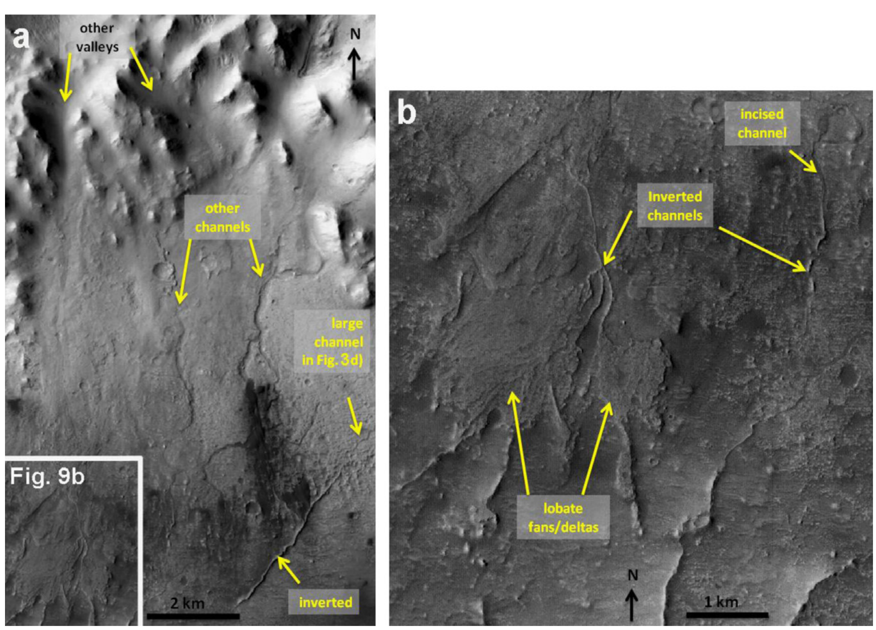

Fig. 9. (a) Inverted and incised channels in the terminal area of the depositional complex shown in Fig. 3. (b) CTX image P04_002464_1746_XI_05S221W showing channels emanating from broader valley basins in the lower central mound of Gale and terminating in broad fan-shaped deltas on the crater floor.

Another obvious feature is the prominent escarpment that separates the relatively flat, smooth and light-toned region to the northwest from a low-lying region with darker tones and which hosts the curvilinear ridges (see Fig. 7e and f), and numerous dark dunes. The slightly higher ground to the northwest of the escarpment (Fig. 8a and b) appears to be an intact surface that has been eroded into by processes occurring on the lower-lying valley floor to the southwest, where the terrain is incised and appears to be heavily eroded, with a more 'pitted' appearance that looks rougher and is manifest in a series of shallow and often interconnected depressions (Fig. 7f). Indeed, within the lower region, there is further evidence of channelized flow trending northeast–southwest, parallel to the escarpment and the main mound. These channels appear to be the dominant landform in the lower dark-toned region, recording flow from the northeast to southwest, skirting around the lower mound (consistent with the direction of the larger channel shown in Fig. 7b and c). It is also interesting that there are relict (degraded) craters on the floor of the low-lying areas (see Fig. 7f), whereas similar features are much less common on the smoother terrain on the upper side of the escarpment.

Further south, a similarly large, albeit more complex, canyon system drains towards the crater floor (as shown in Fig. 8c). Elsewhere, other large channels are observed to source from the hilly terrain of the central mound and debouch across the crater floor (see for example Fig. 9). Many of these channels terminate in broad fan-shaped deposits on the crater floor (as highlighted by Anderson and Bell (2010); see Fig. 9), but the appearance of the canyons is quite different compared to those on the south-east side of the central mound (Section 2.1.2), which are much larger, longer and display a more uniform depth to width ratio.

2.4. Dune fields

As noted above, observations south and west of the crater indicate that the dunes close to the escarpment continue and enlarge into a major dune field to the southwest. This major dune-field surrounds and superposes a large channel which incises into the crater rim and debouches into the crater (Fig. 8a). The total area of this dune field is over 300 km^2 (Hobbs et al., 2010) and we note that the margin of the dune-field almost always parallels the prominent escarpment (Fig. 8b). The identification of dune-fields in the lower-lying region would suggest the presence of mobile fine-grained sediment (predominantly sands).

3. Interpretations

We now discuss possible interpretations of the preceding observations, which are summarized in Table 1.

3.1. Lobate features and valleys: potential evidence of glacial activity

3.1.1. North/northeastern Aeolis Mons

There is compelling evidence that the lobate features represent some form of down-slope mass movement or flow. First, they are located on and aligned parallel to the dominant slope of the central mound. Secondly, their overall morphology is typical of many mass-movements or flow-like deposits in exhibiting a narrow 'trunk' of material that diverges towards a lobate terminus. Thirdly, the surficial texture of the lobes is characterized by flow-perpendicular features, namely linear to arcuate ridges and depressions, similar to the compositional banding that characterizes many flow features, e.g. debris flows/slides, debris avalanche and glaciers (e.g. Fig. 7.10 in Summerfield, 1991). Indeed, Anderson and Bell (2010) also drew attention to the texture of the features as being "similar to pressure ridges, and (…) consistent with a viscous, glacier-like flow" (p. 110), but they acknowledged that a glacial explanation is not the only possibility.

A key question, therefore, is whether the lobes represent some form of mass movement (e.g. debris flow, solifluction lobe) or whether they might be related to glacial and/or rock–glacier activity. Glacial activity, especially, would have important palaeoclimatic implications. In this regard, the lobate features are certainly very similar in morphology to terrestrial rock glaciers and their size would also be comparable, i.e. of the order of kilometers (Humlum, 1982; Martin and Whalley, 1987; Hamilton and Whalley, 1995; Serrano and López-Martínez, 2000; Whalley, 2004; see Fig. 10a–c). Indeed, Anderson and Bell (2010) pointed out the similarity between the lobate features in Gale and rock glaciers, suggesting that the well-defined and uniform width of the lobes (Fig. 2b) resemble the "tongue-shaped" rock glaciers illustrated in Whalley and Azizi (2003) (their Fig. 2). Also, the larger fan-shaped deposit further east (Fig. 2d) resembles a "spatulate" rock glacier, and the higher thermal inertia of the outer margins of this fan-shaped deposit resemble the arcuate form of terminal moraines and/or debris bands associated with divergent flow in glaciers (see Fig. 10d and e). However, Anderson and Bell (2010) also noted that the lobes in Gale do not originate from any obvious cirque. Whilst it is true that it is not possible to identify and delineate an obvious cirque form (e.g. a clear backwall and basin with reverse slope), it is clear that these features emanate from a hollow that characterizes the northern sector of the central mound and which Anderson and Bell (2010) (p. 110) describe as an "alcove" (easily distinguishable in HRSC DEMs).

A further morphological argument in favor of a rock–glacier origin would be the superimposition of lobes on its surface, which is typical of terrestrial rock glaciers (Fig. 10c). The transverse ridges and furrows are also entirely consistent with a rock glacier origin, which resemble fractures and debris bands that result from extensional flow (compare Fig. 2c with Fig. 2 in Whalley and Azizi, 2003). As noted by Whalley (2004), "flow related features (on rock glaciers) are commonly seen as ridges and furrows on the surface…". Similar transverse features can also be formed in debris slides and flows but a possible argument against a mass movement origin is that the termini of the deposits do not reach the bottom of the slope, unless the crater floor has been significantly eroded since their formation (Anderson and Bell, 2010). Perhaps more importantly, most types of mass movement (e.g. landslides, avalanches, rock-falls) are characterized by 'scarps' or 'scars' at the upslope limit (head) of the feature (see e.g. Fig. 7.6 in Summerfield (1991)). There is no evidence for any such scarps that might relate to the lobate features in Gale crater. One possible exception is that the lobes represent some form of solifluction lobe, which involves the down-slope movement of saturated soil, usually as a result of freeze–thaw cycles in the active layer of permafrost. However, solifluction lobes are typically found in consolidated fine-grained material (soil), and are of the order of meters high and tens of meters wide and long (Matsuoka, 2004); whereas the features in Gale crater are 100s of meters high and kilometers long, and appear to be composed of large unconsolidated rocks, based on their high thermal inertia (see above). An alternative could be gelifluction lobes/benches, which can be much larger than solifluction lobes, and can have a similar morphology to the features described here (see, for example, Fig. 11 in Marchant and Head (2007)), but probably this is only true if the gelifluction lobes are still ice-cored.

In view of the above, the erosional forms lying down-slope from the lobate complexes (Fig. 2e) may be interpreted as aeolian reworked drumlins, because the parallel beds align with the direction of the hypothesized glacial flow, they are roughly symmetrical around the long axis (Spagnolo et al., 2010), and are

Table 1
Summary chart including the various landforms identified in this work and a number of different possible origins (alternative formational hypotheses). Our preferred interpretations are highlighted in bold font.

Location	Observation	Possible interpretations
North/northeastern Aeolis Mons	Lobate features (Fig. 2b)	1. Mass movement (debris flow, solifluction lobe, landslides, avalanches, rock-falls) 2. **Former rock glaciers**
	Fan-shaped deposit (Fig. 2d)	1. Mass movement (debris flow, landslides, avalanches, rock-falls) 2. **Piedmont lobe of former rock glacier**
	Linear mounds (Fig. 2g)	1. Yardangs 2. **Drumlins**
Southeastern Aeolis Mons	Large valley systems (Fig. 3a)	1. Fluvial activity 2. Glacial activity
	Fan-shaped deposit (Fig. 3c)	1. Fluvial activity 2. Glacial activity
	Arcuate ridge (Fig. 3d)	1. Inverted channel 2. Remnant of a former fan/delta surface 3. **Terminal moraine**
	Sinuous ridge (Figs. 3e and 10f)	1. Inverted channel resulting from fluvial activity 2. **Esker**
Various locations	Meandering inverted channels (Fig. 4)	1. Presence of fines 2. **Evidence of ground ice**
Various locations	Patterned ground (Figs. 3g and 6)	1. Desiccation cracks 2. **Ground ice**
Western and northwestern Aeolis Mons	Canyons and gullies (Figs. 7 and 9)	1. Glacial activity 2. **Fluvial activity**
Southwestern Aeolis Mons	Dunes (Fig. 8)	1. Abrasion of the central mound 2. **Former lacustrine activity**
Western Aeolis Mons	Escarpment (Fig. 8)	1. Tectonics 2. **Former lacustrine activity (i.e. erosion at lake edge)**
Various locations	Large channels terminating in fan deposits (Figs. 5 and 9)	1. **Fluvial activity including river rejuvenation**

horizontally stratified (which is sometimes observed in drumlin fields, see e.g. Shaw and Kvill, 1984; and review in Stokes et al., 2011). Alternatively, they may be yardangs, although they typically show a similar pointed shape in the upwind and downwind ends, which is uncharacteristic of yardangs (Ward, 1979). If the parallel beds are drumlins, they would add important support to the glacial hypotheses; on the other hand, if they are yardangs, they would represent substantial aeolian reworking after the lower part of the northern central mound was formed (even possibly ongoing), and therefore would be irrelevant for the present study.

In summary, we suggest that the appearance of the lobate features fits the morphological definition of rock glaciers in being “a tongue-like body of angular boulders that resembles a small glacier, which generally occurs in high mountains and has ridges and furrows and sometimes lobes on its surface with a steep front or snout at the angle of repose” (Washburn, 1979). The origin of rock glaciers has undergone intense debate but the two most commonly-favored models (cf. Whalley, 2004; Berthling, 2011) are those relating to the creep of ice dispersed within weathered rock debris (the permafrost model) or a derivation from a glacier that has subsequently undergone complete burial by supra-glacial debris (the glacial model). The first would imply the presence of permafrost but the glacial model is not necessarily restricted to permafrost environments, although their existence would imply a cold climate that is insufficient to thaw the buried ice.

3.1.2. *Southeastern Aeolis Mons*

The valley and depositional system shown in Fig. 3 is perhaps more enigmatic, but is most likely related to glacial or fluvial activity, or a combination of both. In favor of glacial activity is that the main valley system is over-deepened to depths of a few hundred meters, and this is a minimum estimate given the infilling. The relatively straight plan form of the valley, which maintains a similar width and depth along its length and has few tributaries, is also characteristic of glacial valleys, as is the abrupt initiation of the valley heads in concave backwalls. Indeed, south of the main valley system, a series of hollows in shorter valley heads has created sharp-crested ridges that resemble an Alpine landscape of arêtes. A fluvial landscape might be expected to produce a more heavily incised landscape with higher stream-ordering and a greater number of tributaries. Nor is there any sign of an obvious channel either within the valleys or on the valley floor, although some channels emanate from the depositional complex. It is thus possible that a channel has been buried by subsequent infilling of the valley floor.

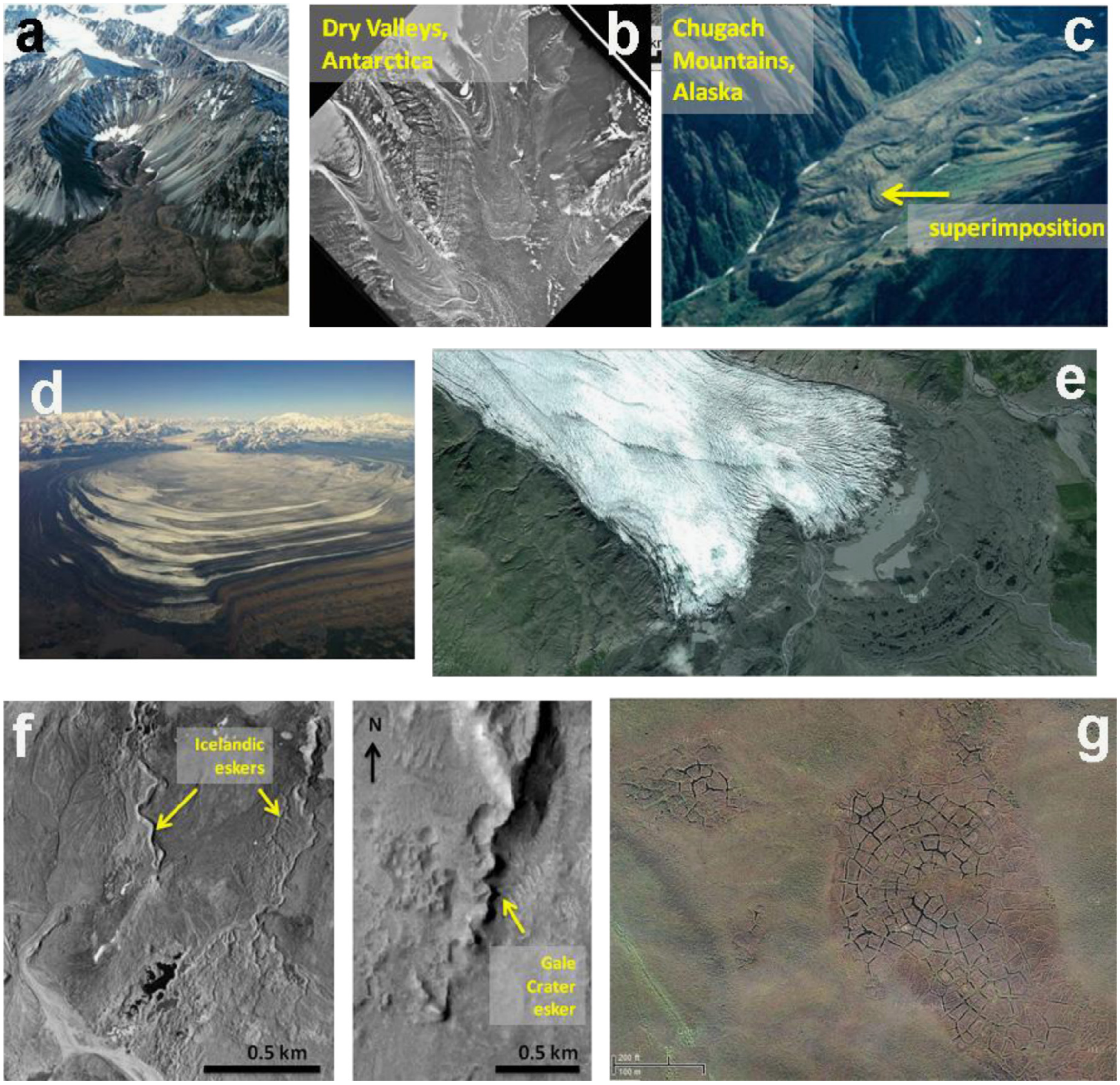

Fig. 10. Terrestrial analogs of some of the Gale features analyzed in this work. (a) Oblique aerial photograph of an unnamed rock glacier (approx. 1 km wide within the cirque) located on the southeast side of the Talkeetna Mountains, Alaska (from http://pubs.usgs.gov/of/2004/1216/glaciertypes/glaciertypes.html); note that once rock glaciers extend from the confines of their valley head, they will form a deposit that is higher than the surroundings, similar to the Gale lobes in Fig. 2b. (b) Vertical aerial photograph of rock glacier complexes, Beacon Valley, Dry Valleys, East Antarctica (from http://www-radar.jpl.nasa.gov/glacier/DryValleys/dryvalleys.html). (c) Oblique aerial photograph of an unnamed rock glacier (approx 1 km wide within the valley) with multiple flow lobes, located in the Metal Creek, northern Chugach Mountains, Alaska (from http://pubs.usgs.gov/of/2004/1216/glaciertypes/glaciertypes.html). (d) The 35-km wide Malaspina glacier, Alaska (photograph courtesy of Bob Mattson, http://www.panoramio.com/photo/60792911). (e) Detail of the Breiðamerkurjökull glacier system, in Iceland, showing a sandur plain in front of the glacier and several moraines (from Google maps). (f) Eskers emanating from the margin of Breiðamerkurjökull, in Iceland (from Evans and Twigg, 2002), and close view of the sinuous ridge in Fig. 3d, a possible esker in Gale. (g) Polygons forming circular patterns near Tuktoyaktut, Northwest Territories, Canada. (Google Maps image).

The down-valley depositional complex (Fig. 3c) could also be reconciled with fluvial or glacial activity. Under a fluvial regime, a river within the valley would diverge and lose energy as it reached the valley floor, producing a large delta complex. In this case, the sinuous channel shown in Fig. 3d and e may represent an inverted remnant of the channel, although its abrupt termination is, perhaps, difficult to explain. In contrast, a glacier interpretation would view the depositional complex as a large sandur-plain formed in front of the glacier margin. Indeed, we note that the sinuous ridge is very similar in scale and morphology to eskers, which fill sub- or en-glacial tunnels and which are preserved during ice retreat (Fig. 10f). In fact, the high thermal inertia of the ridge is consistent with a deposit of sand and gravel, as expected in materials forming an esker. Therefore, this esker interpretation seems more solid than other plausible mechanisms for inverting relief. Furthermore, the hummocky topography that is observed in association with the esker and the fan-complex is also characteristic of glacial foregrounds, where buried ice melts out to form a series of hummocks and depressions (see Evans and Twigg, 2002). This glacial interpretation might also view the linear features as glacial flutings, and we note that their morphology is almost identical to analogous features on Earth. These linear features are more difficult to reconcile with a fluvial origin but they may be related to a mass movement, such as a landslide deposit or debris flow. However, slope angles in this region are negligible, so it is difficult to see how they might be formed by some kind of mass movement down-slope. If the flutes are glacial scour, then they may be revealing a time when the ice extent was greater, and that the debris fan must have been emplaced later, and then eroded to reveal the flutes beneath.

The origin of the ridge at the lower-most limit of the fan complex (Fig. 3d) is also enigmatic. Its arcuate plan form and slope parallel location are difficult to reconcile with a fluvial origin (i.e. an inverted channel) and it does not appear to be related to the structural geology. One possibility, given its location down-slope from the main valley system, therefore, is that it may be some form of terminal moraine. Indeed, its morphometry is not dissimilar from some terminal moraines in contemporary glacier foregrounds on Earth. If the ridge is a moraine, its isolated nature is somewhat puzzling, as terminal moraines often align in a series of parallel to sub-parallel ridges. However, low amplitude isolated ridges (typically termed 'controlled moraines') are commonly formed in association with glaciers with limited debris transport capacity, as has been reported to occur in the Canadian High Arctic and the Antarctic Dry Valleys (cf. Fitzsimons, 2003; Benn and Evans, 2010). An alternative explanation would be that the ridge represents the remnant of a former fan/delta surface, and this possibility cannot be ruled out, although we view it as unlikely given its uniform width. In addition, a purely erosional remnant might be expected to be more highly fragmented, and it is difficult to envisage what process might lead to the preservation of one arcuate narrow ridge that formed part of a pre-existing fan/delta.

In summary, the southeast Aeolis Mons is characterized by a broad, uniform width valley system that can be linked to a large depositional fan complex on the crater floor. This system might be related to a large river valley and delta but some of the features associated with the possible delta are hard to explain as a result of a purely fluvial origin (e.g. lineations displaying exceptional parallel conformity and which are seen to terminate in a narrow arcuate ridge). In contrast, these features may be consistent with a glacial interpretation that views them as glacial lineations and moraines formed by a glacier occupying the main valley. Thus, whilst we are less confident of a glacial origin of these features compared to the features further north, we suggest that further study is needed to support or refute a glacial hypothesis for this upland region of valleys and crests.

3.2. *Meandering channels and patterned ground: indications for ground ice*

Inverted river channels in Gale crater exhibit multiple instances of a meandering plan form, thus requiring the ancient presence of conditions that would permit meander formation in fluvial channels. The formation of the meanders would have required stabilized channel margins in addition to sufficient fines to clog incipient chute cut-offs, preventing their reworking (Braudrick et al., 2009; Constantine et al., 2009). We suggest that ground ice significantly contributed to the cohesive bank sediments within Gale crater, as has been proposed for other regions of Mars (Fairén et al., 2013): the tight meanders in Fig. 4 suggest particularly resilient banks which could be attributed to ice. It is unlikely that the channels are solely due to fine sediment, as they are preserved as inverted channel ridges, suggesting that they were filled with coarser material than surrounding floodplains that were later winnowed away by eolian activity. This inverted preservation attests to a heterolithic partitioning of in-channel and overbank sediments for which there is no known comparable example in non-vegetated channels on Earth (Davies and Gibling, 2010a,b).

Polygonal patterned ground may be indicative of ground ice. It is well known that, on Earth, such patterned ground can form in areas where lakes have dried up or where ice has sublimated (e.g., Washburn, 1956; Drew and Tedrow, 1962; Black, 1976; Billings and Peterson, 1980); they can also form in areas of permafrost because of subsurface hydraulic pressure (Marchant et al., 2002; Levy et al., 2011). Some of the polygonal patterned ground in Gale form circular structures (Fig. 6g), similar to thermal-contraction polygons oriented radially around drained thermokarst-lakes (Soare et al., 2008) and polygons surrounding melted and collapsed pingos in the Arctic (Fig. 10g) (Oehler, 2013), suggesting a periglacial origin. This is further evidence for inundation of water in the low-lying region and, possibly, across the whole crater floor. Anderson and Bell (2010) also draw attention to these features, but they do not mention a possible ground ice origin. Ground ice is a likely origin for the polygonal patterned ground, given our interpretations of former glacial activity and other independent evidence of ground ice in the form of cohesive ancient riverbanks. Alternatives may include weathered jointing of exhumed sedimentary rocks, cooling cracks in lavas, and desiccation cracks. Desiccation cracks in a playa-like setting (Hallet et al., 2013) are an explanation that cannot be ruled out unequivocally, though the circular patterns of polygonal fractures (Fig. 6g), the generally irregular surface relief in the area, and the absence of evaporites, all are characteristics more typical of periglacial than playa settings. A playa interpretation would similarly support inundation of the low-lying regions of the crater, but given the other independent lines of evidence of cold-climate geomorphology in Gale crater, we think that a periglacial interpretation is more likely.

3.3. *Canyons and gullies: evidence for ancient rivers active in different times*

The presence of liquid water inside Gale in the past, including the formation of rivers and lakes, has been repeatedly proposed in the literature (see e.g., Cabrol et al. (1999) and Anderson and Bell (2010), and references therein), and it was a driving motivation for the selection of the crater as the landing site for the Curiosity rover. Here we confirm and extend previous interpretations of aqueous-derived paleomorphologies inside Gale, based mainly on the presence of canyons, gullies and associated channels and lacustrine features.

Our interpretation of the features in Fig. 7a is that there is little evidence of glacial activity, unlike the northeastern and southeastern slopes of the central mound. The shape of the large canyon in Fig. 7b, and the fact that it cuts across the underlying bedrock, suggests intense erosion, favoring fluvial incision. The several major channels, gullies and canyons suggest that fluvial activity was intense in this region, although probably episodic, as seen in the classic 'badland' or 'arroyo' geomorphology in arid/semi-arid environments on Earth (see e.g. Campbell, 1989). The gully system in Fig. 8c was also probably formed by fluvial erosion, similar to the canyons/gullies further north, possibly feeding into a former crater lake. Indeed, these large gully systems appear morphologically distinct from the much more streamlined and curvilinear valley system associated with possible glacial activity in southeast Aeolis Mons (Fig. 3b). Remnants of the erosional process that shaped the main gully and channels can be observed, and Anderson and Bell (2010) interpret these up-standing features to be yardangs (see their Fig. 18).

Regarding the prominent escarpment that separates the flat and the low-lying regions in Fig. 7e and f, we suggest that the low-lying area has been highly modified (eroded/washed), whereas the upper side of the escarpment is a more pristine surface apart from isolated channels, with sources outside the crater. Anderson and Bell (2010) also describe this escarpment as a 10-m-high cliff that marks the transition from the dark-toned basal unit to a hummocky plains unit. The narrow and relatively deep channel or trough shown in Fig. 7c could be a fluvial channel, as suggested by the shallow deposit that butts up against the base of the scarp along the largest bend. Alternatively, this feature could be a trough that formed at the margin of the floor material due to focused eolian modification at the margin of the mound. But we think this interpretation is weaker, because the morphology of the channel is much more consistent with the fluvial sedimentary deposition observed when water travels around a bend, and also the scarp that defines the northern boundary of the channel which looks too sharp to have been carved by eolian activity.

The crater floor is characterized by the presence of inverted channels and records a complex sequence/history of formation, with channels that both feed into and emerge from the lobate fans/deltas (Fig. 9). The formation of these features probably involved several episodes/pulses of channel formation and deposition, which we interpret as episodes of river rejuvenation. We have also found potential evidence for channel interactions with a fan-like body, shown in Fig. 5. We have highlighted an area of possible lateral fanning of sediment from a channelized point, which appears to have subsequently been partially removed (dashed blue line). Thus, it could be possible that this area records the first-generation/termination of a channel, either as a fan at the toe of the slope, or as a delta entering a lake or pond, that subsequently disappeared. If this is a former small delta, then the later removal (evaporation?) of the standing water (a lake on the crater floor?) that the sediment was being deposited in may have led to a rejuvenation of the channel, which subsequently extended its course downslope into the area marked with the pink rectangle. This could also explain the partial reworking and fragmentary nature of the delta area, prior to its inversion. In the area highlighted in pink (Fig. 5b), we cannot determine whether the two different courses were contemporaneous.

3.4. Dune fields, channels and escarpments: ancient ice-covered lakes?

The presence of dunes implies sand-sized material and saltation. This dune-forming material could have been sourced from eolian erosion and abrasion of the central mound. However, we note that the edge of the large dune field corresponds to the prominent escarpment (see Fig. 8), which suggests that there is a link between the formation of dunes (in mobile fine-grained sediment) and the escarpment. Our favored interpretation therefore, which is consistent with previous analyses (Greeley and Guest, 1987; Cabrol et al., 1999; Malin and Edgett, 2000; Thomson et al., 2011), is that the channel that incises the crater rim (Fig. 8a) was a major river, which debouched into the crater to form a large lake, probably partially or totally ice-covered. This lake was broadest in the western sector of the crater floor, coincident with the lowest elevations in Gale crater, and extended to the northeast, around the central mound, and close to the area of the MSL landing ellipse.

Based on our observations of the extent of the prominent escarpment and the dark-colored dune fields, this hypothesized lake basin had a minimum area of around 1000 km^2. In contrast, if the dune field was generated by eolian erosion and transport from the crater more generally, it is more difficult to explain why large dune fields only occur in the lower basin, bounded by the escarpment (they might be expected to be found elsewhere on the crater floor). As such, our preferred interpretation is that the channel carried water into the crater which formed a partially or totally ice-covered lake in the depression and cut the prominent escarpment. Once the lake dried up, fine-grained sediment was mobilized to form the dune field, which was initially restricted to the lake basin but is now migrating across edges of the lake basin.

4. Summary and discussion: ancient glaciers, ground ice, rivers and partially ice-covered lakes forming a connected hydrological system within Gale crater under a cold climate

It is important to state that we view these remote sensing observations and interpretations as preliminary and acknowledge that their origin, in some cases, cannot be unequivocally resolved. Therefore, our approach has been to generate a set of testable hypothesis for future work to support or refute. These are summarized in Table 1. Nevertheless, we favor an interpretation which suggests that the landscape in Gale crater was heavily influenced by glacial, periglacial and fluvial (glacio-fluvial?) activity, the nature of which we now summarize. Fig. 11 is a general graphical summary of our interpretations.

4.1. Rock glaciers

The most compelling part of the suite of data presented here is the glacier-like forms on the northeast of the Gale mound. The north–northeastern part of Aeolis Mons appears to exhibit a concave hollow. Closer inspection of this hollow reveals that it feeds several lobate features (Fig. 2a). Some of these features are relatively pristine in appearance (e.g. Fig. 2b), while others are more degraded. A particular striking feature is a large divergent lobe that comprises numerous arcuate/fractured ridges running perpendicular to the flow direction. We interpret the lobate features as former rock glaciers. An alternative interpretation is that these lobate features could be erosional remnants whose present appearance is dominated by erosional sculpting.

Although less persuasive than the features on the northern sector of the central mound, we propose that there is potential evidence for glacial activity along the south-eastern margin of Aeolis Mons. We suggest that the large linear to sub-linear broad and deep valley (Fig. 3b) is consistent with a glacial origin. Furthermore, this system feeds directly into a depositional fan system (Fig. 3c), which resembles a sandur-plain in the foreground of a modern glacier. This putative sandur is, furthermore, associated with a variety of other landforms typical of glacial activity, namely an arcuate moraine ridge (Fig. 3d), esker systems (Fig. 10f) and, potentially, flutings (Fig. 9). More generally, this region of the central mound (see Fig. 3a) resembles a glaciated Alpine system, with broad, flat-bottomed valleys incised into an upland area. The area should therefore be further targeted for testing of the glacial hypothesis. Interestingly, glaciers on the top of Aeolis Mons could have contributed to protect the central mound of Gale against erosion, as has been recently proposed to occur on terrestrial mountaintops covered with glaciers (Godon et al., 2013). This possibility could contribute to explain the differentiated preservation of the 5-km high Aeolis Mons.

4.2. Ground ice

A combination of bank stability and fine-sediment clogging of chute cut-offs is required to sustain a meandering planform within fluvial channels (Braudrick et al., 2009; Constantine et al., 2009). On Earth, these fundamental controlling elements are most commonly the indirect result of vegetation, through means of a series of complex and interconnected factors such as root-binding of substrates and the introduction of a bed roughness that promotes the retention and deposition of fine-grained sediments (see Tal and Paola (2007); Gibling and Davies (2012), for further details). The critical importance of vegetation in terrestrial meandering channels can be demonstrated in the geological record, where evidence for heterolithic lateral accretion sets is apparently completely absent in fluvial strata deposited prior to the evolution of land plants (Davies and Gibling 2010a,b; Eriksson et al., 2013). Thus, there is no known terrestrial analog from the ancient unvegetated Earth that can be directly compared with the Gale channels described here, and an alternative non-vegetation-derived mediator that prevented the reworking of the apparently heterolithic meander belts (Fig. 4), is required.

Ruling out vegetation, the bank stability in the Gale channels could only be provided by an extremely high clay content, hardpan

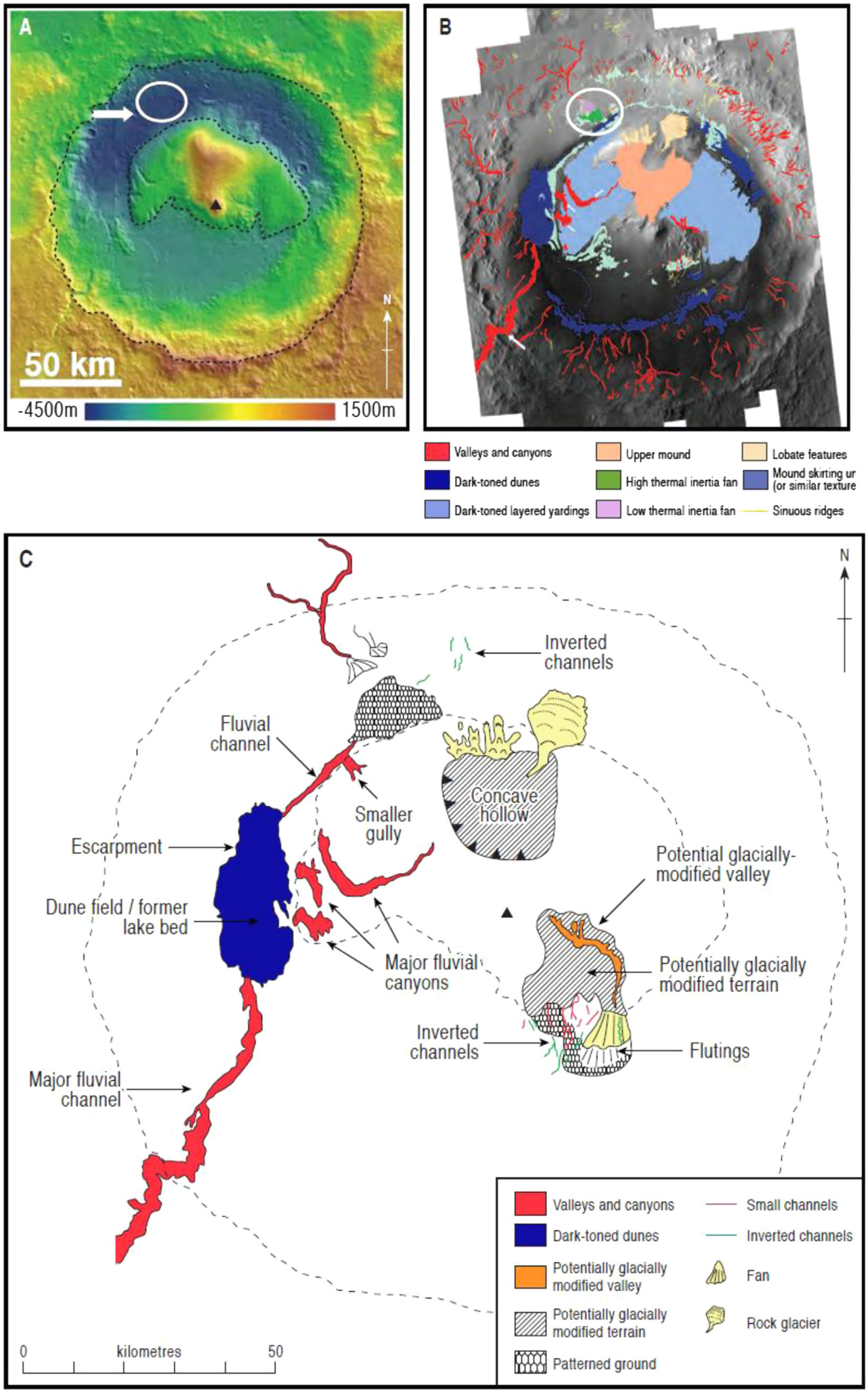

Fig. 11. Schematic map of the major landforms and terrains described in this paper and our interpretations. (A) DEM of Gale crater. (B) Anderson and Bell (2010) sketch map of the main features they identified. (C) Our interpretations of some of the features in Gale (see also Table 1), restricted to the localities which we focused on in this study (see Fig. 1 for coverage).

chemical precipitates, or ground ice. Clays are abundant in Gale (e.g. Milliken et al., 2010), but no evidence exists for particularly elevated clay contents near the inverted channels analyzed here. Chemical precipitates have already been proposed to have played an important role in the aqueous systems on Mars (Fairén et al., 2009; Fairén, 2010). Chemical cementation of the floodplain into hard pan sediments is a feasible medium for binding surrounding sediment (Howard, 2009), but the preservation of the channels in inverted relief suggests this may be less likely, as it is clear that, subsequent to their formation, the channel fills were more resistant than the surrounding floodplains. Chemical cementation may be expected to have provided more permanent protection to the surrounding floodplain sediments (including protection against later winnowing) than ground ice.

Here we suggest that, due to the unlikelihood of these alternative mediators for bank stability and the abundance of additional evidence for periglacial conditions in the Gale crater, there is reason to consider ground ice as being a primary contributing factor for the formation of the meandering channels (Fig. 4). Although it would have been unlikely to provide much surface roughness to aid the retention of fine grained sediment, ground ice is a prime candidate for increasing bank stability in Martian rivers (Fairén et al., 2013), potentially in conjunction with a prolonged supply of fine-grained sediment that could have been sufficient to clog incipient chute channels and prevent reworking of scroll bars. In instances where meander development was sustained enough to repeatedly proceed to a state of neck cutoff, bank stability would have had to be particularly high. Ground ice could feasibly have provided the means necessary to bind unconsolidated substrates at channel margins and promote self-sustained meandering. In light of the additional evidence for cold-climate geomorphology on Gale presented here, the existence of tight high-sinuosity meanders may be seen as strong circumstantial conditions for formerly frozen substrates, perhaps partially in conjunction with fine-grained sediments.

With regard to possible patterned ground, Anderson and Bell (2010) also note the presence of light-toned polygonal features on some areas of the crater floor, near the landing ellipse (see their Fig. 40). They suggest formation through differential erosion, or filled or cemented fractures of fluid flow through facture rocks, favoring an "aqueous alteration interpretation" (p. 93). Our favored interpretation is that they could be frost wedge polygons, as has been observed elsewhere on Mars (Lucchita, 1983; Mellon et al., 2008). For example, Levy et al. (2010) suggested that many Martian thermal contraction crack polygons resulted from an excess of ice in the substrate, pointing again to the presence of ground ice areas on Mars. And there is also evidence elsewhere on Mars for equatorial periglacial processes (Balme et al., 2009; Balme and Gallagher, 2009). Patterned ground similar to that observed in Gale is relatively common in Martian sedimentary terrains, and is especially frequent where hydrated minerals have been observed (e.g., El Maarry et al., 2010; McKeown et al., 2013), suggesting that periglacial processes were not exceptional in the past on Mars.

4.3. Rivers and ice-covered lakes

There is little evidence of glacier activity on the western slopes of the central mound (Figs. 7 and 8). Rather, the landscape appears to be one that has been heavily eroded, resembling an incised semi-arid fluvial landscape on Earth, characterized by intense gullying and with numerous small and large channels that run off the main Gale mound, and then skirt around (run parallel to) its lower break of slope towards the northeast. As such, the curvilinear ridges, like many other upstanding features (e.g., yardangs in Anderson and Bell, 2010), are likely to be erosional remnants, rather than depositional features. Anderson and Bell (2010) also favor fluvial erosion to explain the channels, gullies and canyons described here. In this sense, Cabrol et al. (1999) and Pelkey et al. (2004) previously noted the numerous valleys existing in Gale, both in the rim and in Aeolis Mons, emphasizing the importance of aqueous processes inside the crater in the past.

Pelkey and Jakosky (2002) suggest that the dark-toned material may be transported from the southeast part of the crater, and then northward around the mound. Likewise, we suggest that the dark-toned area comprising numerous channels is similar to areas on Earth which have been subjected to catastrophic flooding/inundation (i.e. skirting the lower-most areas of the crater mound). Such a water body/fluvial erosion would aptly explain the prominent escarpment, which resembles a small 'cliff' that demarcates the edge of the flood tract/water body. Indeed, the most obvious candidate for forming such a lake is the major channel incised into the southwest crater rim (Fig. 8a), feeding directly into the large dune fields, which we interpret to be formed in a former lake bed. The presence of a former lake bed is also suspected based on observations of sporadic polygonal patterned ground in the lowest-lying regions. It is not observed on higher terrain (e.g. the northern side of the escarpment or on the central mound). Although it occupies an entirely different tectonic setting, a potential Earth analog for this region would be Death Valley, California, which is known to have had intermittent lakes during colder stadials of the Late Quaternary, but where eolian activity dominates during intervening dry periods (i.e. now).

The particle size of dune materials in Gale basin has been estimated using high-resolution thermal inertia data. Grain sizes mostly range from medium to very coarse sand, and significant deposits of smaller particles have also been identified (Hobbs et al., 2010). The range in particle size is consistent with the presence of a paleolake within Gale Crater, as suggested by several authors. Cabrol et al. (1999) suggest that Gale crater may have hosted a lake intermittently from as far back as the Noachian Period until the Early Amazonian, speculating that it could have provided diverse environments for Martian life, ranging from warm hydrothermal waters shortly after the crater-forming impact, to more recent cold and ice-covered water. This hypothesis would tie in with our observations and interpretations, i.e. lake first at least on parts of the crater floor, maybe partially or totally ice-covered, and coincident with glacial activity in the central mound, then drying out as the environment turned colder, forming ground ice, and eventually producing the patterned ground and the dunes. Pelkey et al. (2004) noted that the valleys inside Gale extend to the crater floor, and therefore post-date the lake formation; and Thomson et al. (2008) suggest that there is no obvious change in slope that might account for the numerous fans, invoking that they entered a body of water (resulting in deltas): our observations are consistent with both hypotheses.

4.4. The last hydrological cycle in Gale crater

Taken together, our observations point to the presence of a connected hydrological system operating in a cold environment that formerly characterized the Gale crater. Though the exact time of the glacial and glacio-fluvial modifications is yet to be determined, we suggest that all the morphologies described here correspond to late-stage liquid water and water–ice activity (together, i.e. not only ice) on the surface of the equatorial regions of Mars. The last occurrence of ice near the equator could have been as recent as the Late Amazonian epoch (Dickson et al., 2008), but these obliquity-driven migrations of ice towards low latitudes would have not included the presence of liquid water (Head et al., 2003), and therefore could not have been responsible for the formation of all the morphologies inside Gale described here. On the other hand, our analyses provide no information about previous processes of formation, early development and/or physical or chemical modification of the crater, as all these processes occurred before the last time when liquid water and water–ice were present in large amounts inside Gale, as reported in our investigations above.

The observable surface of Gale, as described here, records the cumulative result of a prolonged evolution of the crater that included times where glacial processes dominated and others where fluvial processes were common. Our analyses of these morphologies provide information about the last time when liquid water and water–ice modifications were pervasive in this region of the Aeolis quadrangle of Mars. The termination of liquid water and water–ice activity on and near the Mars' equator is well constrained: evidence is provided both for glacier development (Head et al., 2004) together with dendritic valley formation (Mangold et al., 2004; Quantin et al., 2005; Pondrelli et al., 2005) and alluvial fan formation (Grant and Wilson, 2011), and repeated deposition of layered sediments in lacustrine environments (Glotch and Christensen, 2005; Quantin et al., 2005), in different near-equatorial locations as late as the Late Hesperian and into the Early Amazonian. Taken together, this evidence for liquid water and water–ice could provide approximate time constraints for the last glacial and glacio-fluvial processes inside Gale described here.

We can advance some potential relations among the morphological features described here. First, the long and deep canyons and channels that cut the central mound of Gale would have required a source of liquid water to maintain its activity and to remove the sediments necessary to carve the canyons. Rainfall on Mars is questioned even during the Noachian (e.g., Clow, 1987; Carr and Head, 2003; Scanlon et al., 2013; see a contrasting view in Craddock and Howard (2002) and Mangold et al. (2004)), at least hundreds of millions of years before the time of formation of the Gale morphologies described here. Therefore, it would be difficult to argue for rainfall along the equator of Mars during the Late Hesperian or later, in quantity and continuity enough to provide the water required to carve the canyons in Gale. Snowfall could have contributed to the accumulation of large bodies of ice, as snowfall has been proposed to have occurred elsewhere on Mars in the past (Clow, 1987; Carr and Head, 2003; Kite et al., 2011). The ice accumulated on Aeolis Mons would have shaped the rock glaciers and also would have been a convenient source of the liquid water required for carving the canyons and channels. Water collected on the floor of the crater forming lakes and eventual partially or totally ice-covered lakes would have had it most obvious source in the snowmelt water carried by canyons and rivers. This is best exemplified in Fig. 3, where a main valley system ends in an evolved depositional complex on the floor of the crater, including the formation of incised and inverted channels, possible eskers, lobate fans/deltas, superimposed fans, and patterned ground. Indeed, some of the water accumulated on the floor of Gale could also have been supplied from external sources, such as the large channel that cuts the southern crater rim, highlighted in Fig. 8a.

4.5. Terrestrial analogs and paleo-climatic implications

A potential analog for ancient glaciers/rock glaciers, ground ice, rivers and lakes on a cold Gale crater is the Antarctic Dry Valleys (Fig. 10b), believed to have been once filled with large lakes, and where the lakes seen now are relicts (Hall et al., 2002). These ice-covered lakes are all fed by seasonal glacial melt that flows subaerially. The flow of liquid water sets limits on the climate, as the pressure must be above the triple point and the air temperatures must get above freezing for a few days every year for the liquid water to flow and recharge the lakes. A similar climate regime in the area of Gale could have contributed to the formation of the rivers and lakes identified inside the crater. But even colder conditions could have been enough to form rivers and lakes inside Gale at later times. At the ice-covered Lake Untersee, which abuts an Antarctic glacier, the surface climate conditions are such that there is no surface melting of the glacier and no subaerial flow of water anytime during the year (Wand et al., 1997). But there is subaqueous melting of the glacial wall feeding the lake due to sunlight being absorbed in the water column, and a thermo-circulation setup in the lake. Therefore, there is no strong pressure and temperature constraint on the ambient climate: atmospheric pressures can be below the triple point and surface temperatures can remain continuously below 273 K, without precluding the existence of a large ice-covered lake.

Similar environmental conditions could arguably have characterized Gale at the time of formation of the geomorphologies described and analyzed here, especially if a "cold and wet" environment characterized Mars in the past (Fairén et al., 2009, 2011, 2012, 2013; Fairén, 2010). Obviously, all the geomorphologies described in this work postdate the impact excavation of Gale, and are therefore Hesperian or younger, implying the presence of substantial amounts of both flowing liquid water and water–ice together on post-Noachian Mars. In the same sense, if there were large glaciers on the dichotomy boundary at the Aeolis Mensae region (as recently proposed for the Late Hesperian/Early Amazonian, see Fairén et al. (2011) and Davila et al. (2013)), the generally degraded state of the northern rim of Gale (vs. the southern) is consistent with the possibility of glaciers eroding the northern walls of the crater.

5. Expectations for in situ MSL investigations

A major implication of our work is that the terrains that MSL will traverse are likely to have been modified by liquid water and water–ice, potentially revealing the final stages of aqueous activity in the Gale basin. Late-stage glacial, periglacial and fluvial (including glacio-fluvial) activity in Gale can be recognized both at large and small scales. We expect that MSL will find morphological traits of glacial, periglacial and glacio-fluvial deposition/erosion at scales typical of those associated with glacio-fluvial environments on Earth, assuming those features would have survived potentially billions of years of Martian physical weathering. Features that might be encountered include angular to sub-angular boulders and grain-size distributions, striated bedrock and/or striated boulder pavements, mechanical abrasion marks on boulders, boulder trains, and evidences for the formation and sedimentary properties of subglacial till. On Earth, sediments produced by glacial erosion of rocks generate particulate matter that exhibit little to no evidence of chemical weathering, and this should be expected to be found also on glacially-altered locations at Gale. In addition, glaciers emanating from higher elevations on Aeolis Mons could deliver lithologies from their source areas to the glacial termini, by calving into the glacio-lacustrine environment on the crater floor. Thus, there may be ice-rafted erratics (and, potentially, dropstones) to be identified with the MSL instruments. We also envisage direct accessibility to phyllosilicates, sulfates, salts and other aqueous minerals that could have been transported to the crater floor from higher reaches of the mound, which is equally appealing. Ultimately, our hypothesis will be testable with MSL investigations as the rover traverses Gale crater.

6. Conclusions

We have presented a hypothesis of an ancient cold hydrology of Gale crater, based on high resolution image data from orbit.

Evidence for the inferred presence of ancient rock glaciers, ground ice, rivers and partially or totally ice-covered lakes in the Gale crater basin collectively points to past glacial and glacio-fluvial environments that represent the components of an ancient cold hydrological system, probably a local expression of the "cold and wet" global environment that characterized Mars in the past (Fairén et al., 2009, 2011, 2012, 2013; Fairén, 2010). The evidence mostly corresponds with the more recent coeval liquid water and water–ice activity in the Gale basin, rather than more ancient episodes of sedimentation and/or weathering in the crater, or processes responsible for the formation of the crater or its central mound. We conclude that the last glacio-fluvial episode inside Gale crater occurred during the Late Hesperian or later, a finding which bears important implications for the coeval presence of substantial amounts of flowing liquid water and water–ice on Mars during post-Noachian times. We expect that MSL will find additional indications of local, small-scale glacial, periglacial and glacio-fluvial processes at Gale crater, which would contribute to understanding the climatological and hydrogeological histories of this region of Mars.

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References

Anderson, R.B., Bell III, J.F., 2010. Geologic mapping and characterization of Gale Crater and implications for its potential as a Mars science laboratory landing site. Mars 5, 76–128.

Balme, M.R., Berman, D.C., Bourke, M.C., Zimbelman, J., 2008. Transverse Eolian Ridges (TARs) on Mars. Geomorphology 101, 703–720.

Balme, M.R., Gallagher, C., 2009. An equatorial periglacial landscape on Mars. Earth Planet. Sci. Lett. 285, 1–15.

Balme, M.R., Gallagher, C., Page, D.P., Murray, J.B., Muller, J.-P., 2009. Sorted stone circles in Elysium Planitia, Mars: implications for recent martian climate. Icarus 200, 30–38.

Benn, D.I., Evans, D.J.A., 2010. Glaciers and Glaciation, second ed. Arnold, London

Berthling, I., 2011. Beyond confusion: rock glaciers as cryo-conditioned landforms. Geomorphology 131, 98–106.

Billings, W.D., Peterson, K.M., 1980. Vegetational change and ice-wedge polygons through the thaw-lake cycle in Arctic Alaska. Arctic Alpine Res. 12, 413–432.

Black, R.F., 1976. Periglacial features indicative of permafrost: Ice and soil wedges. Quat. Res. 6, 3–26.

Braudrick, C.A., Dietrich, W.E., Leverich, G.T., Sklar, L.S., 2009. Experimental evidence for the conditions necessary to sustain meandering in coarse-bedded rivers. Proc. Natl. Acad. Sc. USA 106, 16936–16941.

Cabrol, N.A., Grin, E.A., Newsom, H., Landheim, R., McKay, C.P., 1999. Hydrogeologic evolution of Gale Crater and its relevance to the exobiological evolution of Mars. Icarus 139 (2), 235–245.

Campbell, I.A., 1989. Badlands and badland gullies. In: Thomas, D.S.G. (Ed.), Arid Zone Geomorphology. John Wiley and Sons, London, pp. 159–183

Carr, M.H., Head III, J.W., 2003. Basal melting of snow on early Mars: a possible origin of some valley networks. Geophys. Res. Lett. 30, http://dx.doi.org/10.1029/2003GL018575 (24. 2245).

Clow, G.D., 1987. Generation of liquid water on Mars through the melting of a dusty snowpack. Icarus 72, 95–127, http://dx.doi.org/10.1016/0019-1035(87)90123-0.

Constantine, J.C., McLean, S.R., Dunne, T., 2009. A mechanism of chute cutoff along large meandering rivers with uniform floodplain topography. GSA Bull. 122, 855–869.

Craddock, R.A., Howard, A.D., 2002. The case for rainfall on a warm, wet early Mars. J. Geophys. Res. 107 (E11), 5111.

Davies, N.S., Gibling, M.R., 2010a. Cambrian to Devonian evolution of alluvial systems: the sedimentological impact of the earliest land plants. Earth Sci. Rev. 98, 171–200.

Davies, N.S., Gibling, M.R., 2010b. Paleozoic vegetation and the Siluro–Devonian origin of fluvial lateral accretion sets. Geology 38, 51–54.

Davila, A.F., Fairén, A.G., Stokes, C.R., Platz, T., Rodriguez, J.A.P., Lacelle, D., Dohm, J. M., Pollard, W., 2013. Evidence for Hesperian glaciation along the Martian dichotomy boundary. Geology 41, 755–758.

Dickson, J.L., Head, J.W., Marchant, D.R., 2008. Late Amazonian glaciation at the dichotomy boundary on Mars: evidence for glacial thickness maxima and multiple glacial phases. Geology 36, 411–414.

Dietrich, W.E., T. Parker, D.Y. Sumner, A. Hayes, M.C. Palucis, R.M.E. Williams, F. Calef, the MSL team, 2013. Topographic evidence for lakes in Gale Crater. 44th LPSC, Abs. # 1844.

Drew, J.V., Tedrow, J.C.F., 1962. Arctic soil classification and patterned ground. Arctic 15, 109–116.

El Maarry, M.R., Markiewicz, W.J., Mellon, M.T., Goetz, W., Dohm, J.M., Pack, A., 2010. Crater floor polygons: Desiccation patterns of ancient lakes on Mars? J. Geophys. Res. 115 (E10), E10006.

Eriksson, P.G., Banarjee, S., Catuneanu, O., Corcoran, P.L., Eriksson, K.A., Hiatt, E.E., Laflamme, M., Lenhardt, N., Long, D.G.F., Miall, A.D., Mints, M.V., Pufahl, P.K., Sarkar, S., Simpson, E.L., Williams, G.E., 2013. Secular changes in sedimentation systems and sequence stratigraphy. Gondwana Res. 24, 468–489.

Evans, D.J.A., Twigg, D.R., 2002. The active temperate glacial landystem: a model based on Breðamerkurjökull and Fjallsjökull, Iceland. Quat. Sci. Rev. 21, 2143–2177.

Fairén, A.G., 2010. A cold and wet Mars. Icarus 208, 165–175.

Fairén, A.G., Davila, A.F., Gago-Duport, L., Amils, R., McKay, C.P., 2009. Stability against freezing of aqueous solutions on early Mars. Nature 459, 401–404.

Fairén, A.G., Davila, A.F., Gago-Duport, L., Gil, C., McKay, C.P., 2011. Cold glacial oceans would have inhibited phyllosilicate sedimentation on early Mars. Nat. Geosci. 4, 667–670.

Fairén, A.G., Davila, A.F., Schulze-Makuch, D., Rodríguez, A.P., McKay, C.P., 2012. Glacial paleoenvironments on Mars revealed by the paucity of hydrated silicates in the Noachian crust of the northern lowlands. Planet. Space Sci. 70, 126–133.

Fairén, A.G., Davies. N.S., Squyres, S.W., 2013. Equatorial ground ice and meandering rivers on Mars, Lunar Planetary Science Conference, Abstract #2948, Lunar and Planetary Institute.

Fergason, R.L., Christensen, P.R., Kieffer, H.H., 2006. High-resolution thermal inertia derived from the Thermal Emission Imaging System (THEMIS): Thermal model and applications. J. Geophys. Res. 111, E12004, http://dx.doi.org/10.1029/2006JE002735.

Fitzsimons, S.J., 2003. Ice-marginal terrestrial landsystems: polar continental glacier margins. In: Evans, D.J.A. (Ed.), Glacial Landsystems. Arnold, London, pp. 89–110

Gibling, M.R., Davies, N.S., 2012. Palaeozoic landscapes shaped by plant evolution. Nat. Geosci. 5, 99–105.

Glotch, T.D., Christensen, P.R., 2005. Geologic and mineralogic mapping of Aram Chaos: evidence for a water-rich history. J. Geophys. Res. 110, E09006, http://dx.doi.org/10.1029/2004JE002389.

Godon, C.J.L. Mugnier, Fallourd, R., Paquette, J.L., Pohl, A., Buoncristiani, J.F., 2013. The Bossons glacier protects Europe's summit from erosion. Earth Planet. Sci. Lett. 375, 135–147.

Grant, J.A., Wilson, S.A., 2011. Late alluvial fan formation in southern Margaritifer Terra, Mars. Geophys. Res. Lett. 38 (8), http://dx.doi.org/10.1029/2011GL046844.

Greeley, R., Guest, J.E., 1987. Geologic map of the eastern equatorial region of Mars. USGS Misc. Map I-1802-B, Department of the Interior, U S. Geological Survey, prepared for NASA.

Hall, B.L., Denton, G.H., Overturf, B., Hendy, C.H., 2002. Glacial Lake Victoria, a high-level Antarctic lake inferred from lacustrine deposits in Victoria Valley. J. Quat. Sci. 17, 697–706.

Hallet, B., Sletten, W. Stewart, R. Williams, N. Mangold, J. Schieber, D. Sumner, G. Kocurek, the MSL Science Team, 2013. Fracture networks, Gale Crater, Mars. 44th LPSC, Abs. # 3108.

Hamilton, S.J., Whalley, W.B., 1995. Rock glacier nomenclature: a re-assessment. Geomorphology 14, 73–80.

Head, J.W., Mustard, J.F., Kreslavsky, M.A., Milliken, R.E., Marchant, D.R., 2003. Recent ice ages on Mars. Nature 426, 797–802.

Head, J.W., Marchant, D.R., Ghatan, G.J., 2004. Glacial deposits on the rim of a Hesperian–Amazonian outflow channel source trough: Mangala Valles, Mars. Geophys. Res. Lett., 31, http://dx.doi.org/10.1029/2004GL020294

Head, J.W., Nahm, A.L., Marchant, D.R., Neukum, G., 2006. Modification of the dichotomy boundary on Mars by Amazonian mid-latitude regional glaciations. Geophys. Res. Lett. 33, http://dx.doi.org/10.1029/2005GL024360 (L08S03).

Hobbs, S.W., Paull, D.J., Bourke, M.C., 2010. Eolian processes and dune morphology in Gale crater. Icarus 210, 102–115.

Howard, A.D., 2009. How to make a meandering river. Proc. Natl. acad. Sci. USA 106, 17245–17246.

Humlum, O., 1982. Rock glaciers in northern Spitsbergen: a discussion. J. Geol. 90, 214–217.

Hynek, B.M., Phillips, R.J., Arvidson, R.E., 2003. Explosive volcanism in the Tharsis region: global evidence in the Martian geologic record. J. Geophys. Res. 108, http://dx.doi.org/10.1029/2003JE002062 (E9. 5111).

Kite, E.S., Michaels, T.I., Rafkin, S., Manga, M., Dietrich, W.E., 2011. Localized precipitation and runoff on Mars. J. Geophys. Res. 116, E07002, http://dx.doi.org/10.1029/2010JE003783.

Kite, E.S., Lewis, K.W., Lamb, M.P., Newman, C.E., Richardson, M.I., 2013. Growth and form of the mound in Gale crater, Mars: slope wind enhanced erosion and transport. Geology 41, 543–546.

Levy, J.S., Marchant, D.R., Head, J.W., 2010. Thermal contraction crack polygons on Mars: a synthesis from HiRISE, Phoenix, and terrestrial analog studies. Icarus 206, 229–252.

Levy, J.S., Head, J.W., Marchant, D.R., 2011. Gullies, polygons and mantles in Martian permafrost environments: cold desert landforms and sedimentary processes during recent Martian geological history. Geol. Soc. 354, 167–182.

Lucchita, B.K. 1983. Permafrost on Mars: Polygonally fractures ground. In Permafrost: Fourth International Conference Proceedings, National Academy Press, Washington, D. C.

Malin, M.C., Edgett, K.S., 2000. Sedimentary rocks of early Mars. Science 290, 1927–1937.

Mangold, N., Quantin, C., Ansan, V., Delacourt, C., Allemand, P., 2004. Evidence for precipitation on Mars from dendritic valleys in the Valles Marineris area. Science 305, 78–81.

Marchant, D.R., Lewis, A.R., Phillips, W.M., Moore, E.J., Souchez, R.A., Denton, G.H., Sugden, D.E., Potter Jr, N., Landis, G.P., 2002. Formation of patterned ground and sublimation till over Miocene glacier ice in Beacon valley, southern Victoria Land, Antarctica. Bull. Geol. Soc. Am. 114, 718–730.

Marchant, D.R., Head, J.W., 2007. Antarctic dry valleys: Microclimate zonation, variable geomorphic processes, and implication for assessing climate change on Mars. Icarus 192, 187–222.

Martin, E., Whalley, W.B., 1987. Rock glacier morphology: classification and distribution. Prog. Phys. Geogr. 11, 260–282.

Matsuoka, N., 2004. Solifluction. In: Goudie, A. (Ed.), Encyclopedia of Geomorphology. Routledge, London

McKeown, N.K., Bishop, J.L., Silver, E.A., 2013. Variability of rock texture and morphology correlated with the clay-bearing units at Mawrth Vallis, Mars. J. Geophys. Res.: Planets 118, 1245–1256.

Mellon, M.T., Arvidson, R.E., Marlow, J.J., Phillips, R.J., Asphaug, E., 2008. Periglacial landforms at the Phoenix landing site and the northern plains of Mars. J. Geophys. Res. 113, http://dx.doi.org/10.1029/2007JE003039 (E00A23).

Milliken, R.E., Grotzinger, J.P., Thomson, B.J., 2010. Paleoclimate of Mars as captured by the stratigraphic record in Gale Crater. Geophys. Res. Lett. 37, L04201, http://dx.doi.org/10.1029/2009GL041870.

Oehler, D.Z., 2013. A periglacial analog for landforms in Gale crater, Mars, in: Proceedings of 44th Lunar and Planetary Science Conference, abstract #1322.

Pelkey, S.M., Jakosky, B.M., 2002. Surficial geologic surveys of Gale crater and Melas Chasma, Mars: integration of remote-sensing data. Icarus 160, 228–257.

Pelkey, S.M., Jakosky, B.M., Christensen, P.R., 2004. Surficial properties in Gale crater, Mars, from Mars Odyssey THEMIS data. Icarus 167, 244–270.

Pondrelli, M., Baliva, A., Di Lorenzo, S., Marinangeli, L., Rossi, A.P., 2005. Complex evolution of paleolacustrine systems on Mars: an example from the Holden crater. J. Geophys. Res., 110, http://dx.doi.org/10.1029/2004JE002335

Quantin, C., Allemand, P., Mangold, N., Dromart, G., Delacourt, C., 2005. Fluvial and lacustrine activity on layered deposits in Melas Chasma, Valles Marineris. Mars. J. Geophys. Res. 110, http://dx.doi.org/10.1029/2005JE002440 (E12S19).

Rossi, A.P., Neukum, G., Pondrelli, M., van Gasselt, S., Zegers, T., Hauber, E., Chicarro, A., Foing, B., 2008. Large-scale spring deposits on Mars? J. Geophys. Res. 113, E08016, http://dx.doi.org/10.1029/2007JE003062.

Scanlon, K.E., Head, J.W., Madeleine, J.B., Wordsworth, R.D., Forget, F., 2013. Orographic precipitation in valley network headwaters: constraints on the ancient Martian atmosphere. Geophys. Res. Lett. 40 (16), 4182–4187.

Schwenzer, S.P., Abramov, O., Allen, C.C., Clifford, S., Filiberto, J., Kring, D.A., Lasue, J., McGovern, P.J., Newsom, H.E., Treiman, A.H., Vaniman, D.T., Wiens, R.C., Wittmann, A., 2012. Gale Crater: formation and post-impact hydrous environments. Planet. Space Sci. 70, 84–95.

Serrano, E., López-Martínez, J., 2000. Rock glaciers in the South Shetland Islands, Western Antarctica. Geomorphology 35, 145–162.

Shaw, J., Kvill, D., 1984. A glaciofluvial origin for drumlins of the Livingstone Lake area, Saskatchewan. Can. J. Earth Sci. 21, 1442–1459.

Soare, R.J., Osinski, G.R., Roehm, C.L., 2008. Thermokarst lakes and ponds on Mars in the very recent (late Amazonian) past. Earth Planet. Sci. Lett. 272, 382–393.

Spagnolo, M., Clark, C.D., Hughes, A.L.C., Dunlop, P., Stokes, C.R., 2010. The planar shape of drumlins. Sediment. Geol. 232, 119–129.

Stokes, C.R., Spagnolo, M., Clark, C.D., 2011. The composition and internal structure of drumlins: Complexity, commonality, and implications for a unifying theory of their formation. Earth-Sci. Rev. 107, 398–422.

Summerfield, M.A., 1991. Global Geomorphology. Prentice Hall, London, UK

Tal, M., Paola, C., 2007. Dynamic single-thread channels maintained by the interaction of flow and vegetation. Geology 35, 347–350.

Thomson, B.J., Bridges, N.T., Milliken, R., Bell, J.F. III, Calvin, W.C., Weitz, C.M., 2008. New constraints on the origin and evolution of the layered deposits in Gale crater, Mars. In: Proceedings of the 39th Lunar and Planetary Science Conference. Abstract no. 1456.

Thomson, B.J., Bridges, N.T., Milliken, R.E., Baldridge, A., Hook, S.J., Crowley, J.K., Marion, G.M., de Souza Filho, C.R., Kargel, J.S., Brown, A.J., Weitz, C.M., 2011. Constraints on the origin and evolution of the layered mound in Gale Crater, Mars using Mars Reconnaissance Orbiter data. Icarus 214, 413–432.

Wand, U., Schwarz, G., Bruggemann, E., Brauer, K., 1997. Evidence for physical and chemical stratification in Lake Untersee, central Dronning Maud Land, East Antarctica. Antarctic Sci. 9, 43–45.

Ward, A., 1979. Yardangs on Mars: evidence of recent wind erosion. J. Geophys. Res.: Solid Earth 84, 8147–8166.

Washburn, A.L., 1956. Classification of patterned ground and review of suggested origins. Bull. Geol. Soc. Am. 67, 823–866.

Washburn, A.L., 1979. Geocryology: A Survey of Periglacial Processes and Environments. Arnold, London p. 1979

Whalley, W.B., 2004. Rock Glacier. In: Goudie, A. (Ed.), Encyclopedia of Geomorphology. Routledge, London

Whalley, Azizi, W.B.F., 2003. Rock glaciers and protalus landforms: analogous forms and ice sources on Earth and Mars. J. Geophys. Res. 108, 8032–8048.

Wray, J.L., 2013. Gale crater: the Mars science laboratory/curiosity rover landing site. Int. J. Astrobiol. 12, 25–38.