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Morphometric evidence of 3.6 Ga glacial valleys and glacial cirques in martian highlands: south of Terra Sabaea

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Abstract

The climate of early Mars remains unclear and the debate is topical. Recently, climatic models have suggested a cold climate during the Noachian/ Early Hesperian on Mars, which goes against the wet and warm climate often put forward. The purpose of this study is to seek geomorphologic evidence of this early cold climate. To achieve this, a step-by-step study of the geometry and morphology of several martian valleys has been done in the southern highlands. The analysis highlights the morphometric properties which enable the identification of martian glacial landscapes. We identified 100 cirques and 83 glacial valleys in two craters and on one mountain in the southern part of Terra Sabaea. The studied morphologies have the same morphometric characteristics and trends as terrestrial and martian glacial valleys and glacial cirques. In contrary, these trends are very different from those observed in fluvial valleys on Earth and on Mars. (1) The martian glacial valleys are U-shaped with a large flat floor and a V-index > 0.20 . While martian and terrestrial fluvial valleys are V-shaped with a V-index < 0.1 . (2) The length to width ratio is > 1 while for fluvial valleys this ratio is $\gg 1$. (3) Finally, the cross-sectional area and the elevation are higher for the glacial valleys compared to the fluvial ones. These glacial valleys often originate with a topographic hollow which have the same properties than terrestrial glacial cirque. The glacial landscapes identified in southern Terra Sabaea are restricted to elevations > 1000 m and are dated by crater counting to be 3.6 Ga. This study strongly supports glacial processes as the origin of these valleys and cirques, and is the first morphometric evidence of glacial valleys associated with glacial cirques in the southern highlands in agreement with the climatic models. We propose that the martian climate during the late Noachian/early Hesperian was characterized by glaciated highlands at elevations greater than 1500 m and at lower elevations where fluvial valley network has been identified (< 1500 m) the climate was more temperate allowing liquid water to be stable and creating fluvial valley

networks.

Keywords: Glacial landscape, Late Noachian/Early Hesperian, Morphometry, Early Mars.

1. Introduction

The presence of valley network is one of the best lines of evidence for prolonged surface water on Mars, and they are located preferentially in the southern highlands. These valleys have V-shaped or U-shaped cross-profile shapes and commonly include inlet and outlet valleys of Noachian-aged basins (Fassett and Head, 2008b). The valleys width ranges is from 50 m to 10 km, their median depth is 80 m and their length is usually less than few hundred kilometers. The origin of the valley networks remains uncertain and four hypotheses are proposed: (1) precipitation-fed surface runoff (Craddock and Howard, 2002); (2) runoff fed by surface ice melting (Segura, 2002); (3) runoff fed by surface or near surface melting by magmatic intrusions (Gulick, 2001); (4) sapping from subsurface aquifers (Carr, 1995). Whatever their formation process(es), the presence of valley networks similar to those on Earth (Baker, 2001; Hynek et al., 2010), clay minerals (Bibring et al., 2006), lakes, alluvial fans, and deltas (Ramirez and Craddock, 2018) show that during the Noachian (4.5-3.7 Ga), a hydrosphere was active on the surface of Mars with relatively warm and wet conditions. Some of these valley networks, are dated to the early Hesperian around 3.6 Ga (Fassett and Head, 2008a; Bouley and Craddock, 2014). During the Hesperian, there was the formation of outflow channels (Carr and Malin, 2000). The abrupt emergence of outflow channels into the landscape indicates a formation by the rapid release of large volumes of water stored as subsurface groundwater or as an aquifer under pressure (Carr and Head, 2010). In addition, the observed surface alteration products changed, the Noachian clays gave way to sulfates from the late Noachian to the Hesperian, which indicates a global change in the aqueous chemistry of Mars (Bibring et al., 2006). These mineralogical and geomorphological lines of evidence show that the active Noachian hydrosphere lost its intensity and changed to a cryosphere during the Hesperian (Carr and Head, 2010).

Currently, the distribution of valley networks appears to be controlled by the topography induced by the Tharsis dome. Based on this correlation, Phillips (2001) suggested that the valley networks were formed after the formation of Tharsis, during the Noachian. However, recent geodynamic modeling showed that without Tharsis, the valley networks would have the same distribution as observed today, in a south tropical band from 40°S to 0°S (Bouley et al., 2016). The growth of the Tharsis dome started during the Noachian era

(more than 3.7 billion years ago). Its position has induced a reorientation of the planet with respect to its spin axis (true polar wander, TPW), which is responsible for the present equatorial position of the volcanic province (Bouley. et al., 2016). It has been suggested that the Tharsis load on the lithosphere affected the orientation of the valley networks (Bouley. et al., 2016). Moreover, climate modeling has shown that with Noachian/ early Hesperian conditions, with an atmospheric pressure less than 1 bar, a reduced Tharsis bulge topography, and an obliquity of 45° , there is a preferential deposition of ice in the southern highlands in the same area as the valley networks (Wordsworth et al., 2013; Bouley. et al., 2016). This globally sub-zero scenario called “icy-highlands” for the late Noachian climate may be sufficient to explain most of the fluvial morphology and geology without the need to invoke additional long-term warming mechanisms or an early warm and wet Mars (Wordsworth et al., 2013; Head and Marchant, 2014). Therefore, it is postulated that the valley networks could have been formed in a cold climate.

So, on the one hand, several studies invoke a wet and warm climate allowing the formation of the valley networks (Carr, 1995; Craddock and Howard, 2002; Bibring et al., 2006; Carr and Head, 2010). And on the other hand, the new models invoke the “icy-highlands” scenario for early Mars (Wordsworth et al., 2013; Bouley. et al., 2016).

The purpose of this study is to seek geomorphologic evidence of this hypothesised cold climate in the southern highlands. To achieve this, we studied an area in Terra Sabea where ice should have been accumulated according to the models (Wordsworth et al., 2013; Bouley. et al., 2016). We performed a comparison between morphologies found in this area and those found in previously studied martian and terrestrial glacial and fluvial valleys. By studying the geometry and the morphology of the features we can deduce whether the origin of the valleys is liquid water or flowing ice.

2. Glacial landforms on Earth and Mars

2.1. Characteristics of glacial landforms on Earth

Glacial landforms can be recognized based on their geometry and morphology. Penck (1905) and de Martonne (1910) were the first to compare the morphology of alpine glacial valleys with fluvial valleys. Firstly, the study of glacial valleys revealed that their morphometry is very different from fluvial valleys (Section 4.2). Secondly, it showed that glacial valleys are often associated with other structures characteristic of glacial activity. These valleys are characterized by an accumulation of snow at the valley head forming a cirque. The

snow then compacts and sinters to ice, and by the action of gravity the ice mass flows down the slope above the equilibrium line, the accumulation zone. Below the equilibrium line, the glacier enters in the ablation zone. Here, the ice melts and/or sublimates and meltwater and sediment are delivered on the proglacial plains (Bennett and Glasser, 2011). The depositional features created are: (1) moraines resulting from debris entrained during glacial erosion that are transported and deposited at the glacier side and/or the glacier front when the glacier is stable and then retreats. The frontal moraine indicates the maximum advance of the glacier (Andersson, 1998; Ewertowski and Tomczyk, 2015). (2) Eskers which are a type of straight-to-sinuous ridge composed of sand and gravel resulting from the flow of glacial meltwater in predominantly subglacial and englacial conduits (Bennett and Glasser, 2011). Eskers are generally formed under warm-based glaciers, the core being formed in a tunnel inside the ice (Brennand, 2000). At and beyond the margin of the glacier, ice blocks buried in the esker will melt and form (3) kettle holes (Fitzsimons, 1991). Kettle holes are enclosed topographic depressions that are formed at the surface of outwash deposits in recently deglaciated surfaces (Corti et al., 2012).

This landform assemblage, making up a classic glacial landscape, is composed of a glacial cirque, a glacial valley, and associated deposits. This assemblage is found in regions which have experienced glacial activity, and their distributions are linked to paleoclimate (Barr and Spagnolo, 2015).

2.2. Past and recent martian glaciations

Evidence of past glaciations have been extensively reported on Mars. In the southern hemisphere, at latitudes higher than 30° , some craterwall valleys have been interpreted as glacial valleys in two Noachian-aged craters and in one Hesperian-aged crater (Hobbs et al. 2016; Fig. 1). These glacial valleys exhibit a U-shaped cross-section and a length to width ratio >1 while fluvial valleys have a length to width ratio $\gg 1$ (Hobbs et al., 2016). In addition, evidence of old glacial land systems (3.5 Ga) in Ius Chasma and Central Candor Chasma in Valles Marineris have been identified using paraglacial structures (Mège and Bourgeois, 2011; Gourronc et al., 2014).

Evidence of Amazonian glaciation has been extensively reported in the mid-latitudes. This takes the form of viscous flow features (VFF) that often appear on the slopes of high-relief features and exhibit morphologies indicative of glacial viscous flow (Souness and Hubbard, 2012). They are elongated flow-like features composed of essentially pure glacial ice below a protective layer of debris (Holt et al., 2008; Plaut et al., 2009). VFF

can be divided into three types: (1) glacier-like forms (GLF) are visually similar to terrestrial valley glaciers, showing signs of downpositive relief viscous deformation (Hubbard et al., 2014) (2) lobate debris aprons (LDA) are characterized by lobate features surrounding massifs and are often observed at the base of crater walls, in that case it is called concentric crater fill (CCF; Squyres 1979) (3) lineated valley fills (LVF) are formed on valley floors from the convergence of two or more LDA-type flows (Squyres, 1979). Finally, previous work has reported deposit features similar to terrestrial eskers (Kargel and Strom, 1992; Fastook et al., 2012; Gallagher and Balme, 2015; Butcher et al., 2016) and moraines like-ridges (MLR) at the foot of many mid-latitude crater walls (Arfstrom and Hartmann, 2005; Conway et al., 2018). These landforms are in many cases similar to glacial landforms on Earth and allow analogue-based comparisons to be made (Souness and Hubbard, 2012).

3. Study area in Terra Sabaea

3.1. Description of the area

We focused our study on Terra Sabaea. Terra Sabaea is located northwest of Hellas planitia (Fig. 1a). This area is characterized by a high density of valley networks dated of the late Noachian/early Hesperian (Hynek et al. 2010; Bouley. and Craddock 2014; Fig. 1b). The majority of these valley networks are located in the inter crater plains, but some of them are located on the inner wall of impact craters in the study area (Fig. 2a). We noted that some valley-like features, unmapped by Hynek et al. (2010), could be found on both negative relief features, such as impact craters, but also on positive relief features, such as mountains (Fig. 2b,c,d). Terra Sabaea has a mean elevation of 1740 m and is located where ice is predicted to have been deposited in the Noachian according to the models described above (Wordsworth et al., 2013; Bouley. et al., 2016). To seek geomorphologic evidence for this hypothesised cold climate, we studied three sites: Dawes crater, an unnamed crater we called “crater 1” and a unnamed mountain we called “mountain 1” (Fig. 2).

3.1.1. Mountain 1

This feature is an isolated mountain 2 km high with a summit at 3.5 km in elevation above the MOLA reference datum. It is located 425 km to the northeast of Dawes crater (42°17'E, 2°55'S; Fig. 2a). The south

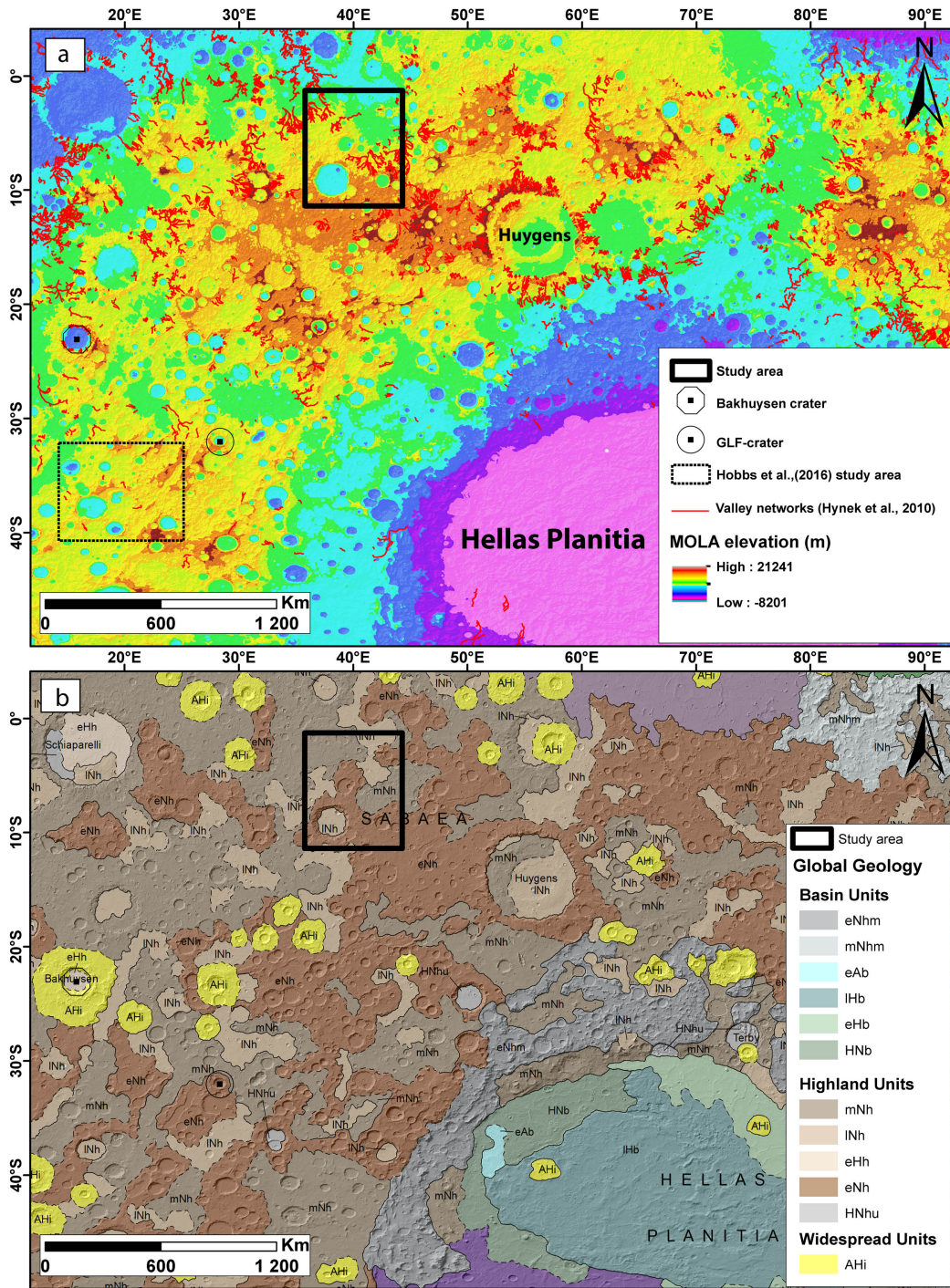


Fig. 1. Terra Sabaea and Noachis Terra in the southern highlands. (a) Study area and areas used for comparison. The red line represents the valley networks mapped by Hynek et al. (2010). Mars orbiter laser altimeter (MOLA) digital elevation background. (b) USGC geological map of the area (Tanaka, 2014). Images credit NASA/JPL/University of Arizona.

facing slope appears topographically bland and the north facing slope is dissected by valleys running from the summit to the base with lengths on the order of tens of kilometers (Fig. 2b).

3.1.2. Crater 1

This unnamed crater is located at 150 km to the east of Dawes crater (42°34'E, 9°10'S; Fig. 2a). It has a diameter of 74 km and a depth of 2 km. It is dated to the early Noachian (Tanaka, 2014). Its walls have some unmapped valleys of tens of kilometers in length (Fig. 2c).

3.1.3. Dawes crater

Dawes crater is a large impact crater (38°8'E, 8°55'S; Fig. 2a) with a diameter of 200 km, a depth of 2.5 km and has walls with steep inner slopes $> 20^\circ$ (Fig. 2d). Its walls have 35 valleys mapped by Hynek et al. (2010) as valley networks, located on the southern wall (Fig. 2a). The northern wall has some unmapped valleys. Dawes crater is dated to the late Noachian (Tanaka, 2014).

4. Data and methods

4.1. Imagery

The purpose of the study is to define if the valleys in the study area are glacial or fluvial. To achieve this we compared the studied valleys with known cases on Earth and Mars. We used Context Camera image (CTX) with a resolution of 6 m/pixel (Fig. 3a; Malin and Edgett 2001) to characterize the valleys. This first step was the most important because it allowed us to identify the morphologies to be studied in more detail. Then, to constrain their geometry, we used the Digital Terrain Map Reduced Data Record (DTMRDR) data with 1 m numeric height resolution from High-Resolution Stereo Camera (HRSC) with a resolution of 10-20 m/pixel depending on the ground resolution of the respective image (Gwinner et al., 2016) and MOLA gridded global digital elevation data with a resolution of $1/64^\circ$ in latitude x $1/32^\circ$ in longitude (Fig. 3b; Smith et al. 2001). We made our measurements using ArcGIS software. The projection systems used was "SimpleCylindrical_Mars" for CTX, with this projection, distortion increases as the distance from the

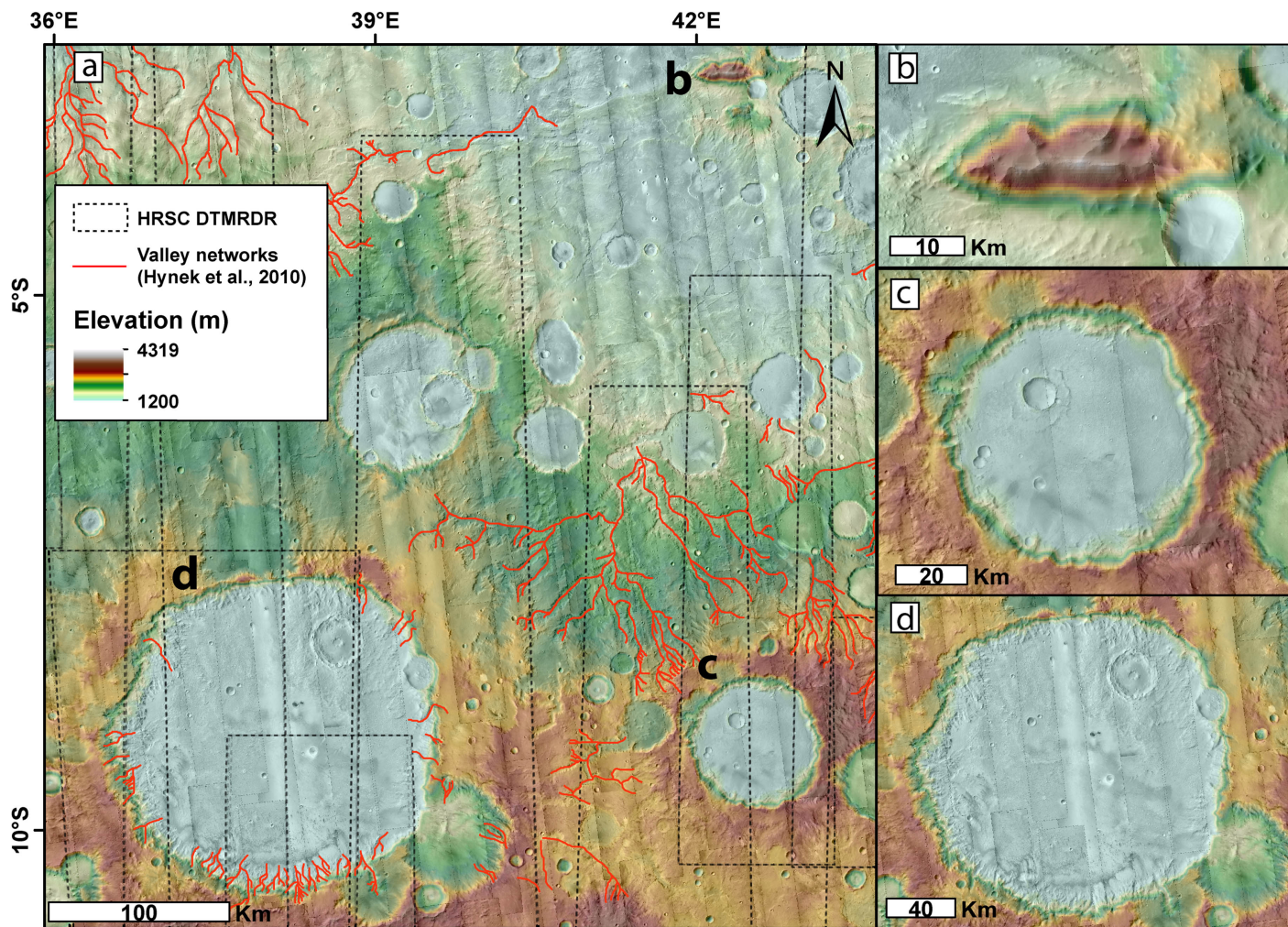


Fig. 2. Location of the three study areas. (a) Context camera (CTX) mosaic of the study area with MOLA digital elevation map. The red lines are the valley networks identified by Hynek et al. (2010) (b) Mountain 1 CTX images with MOLA background . (c) Crater 1 CTX images with MOLA background . (d) Dawes crater CTX images with MOLA background . All the images and data used are sum up in the supplementary (Table 3). Images credit NASA/JPL/University of Arizona.

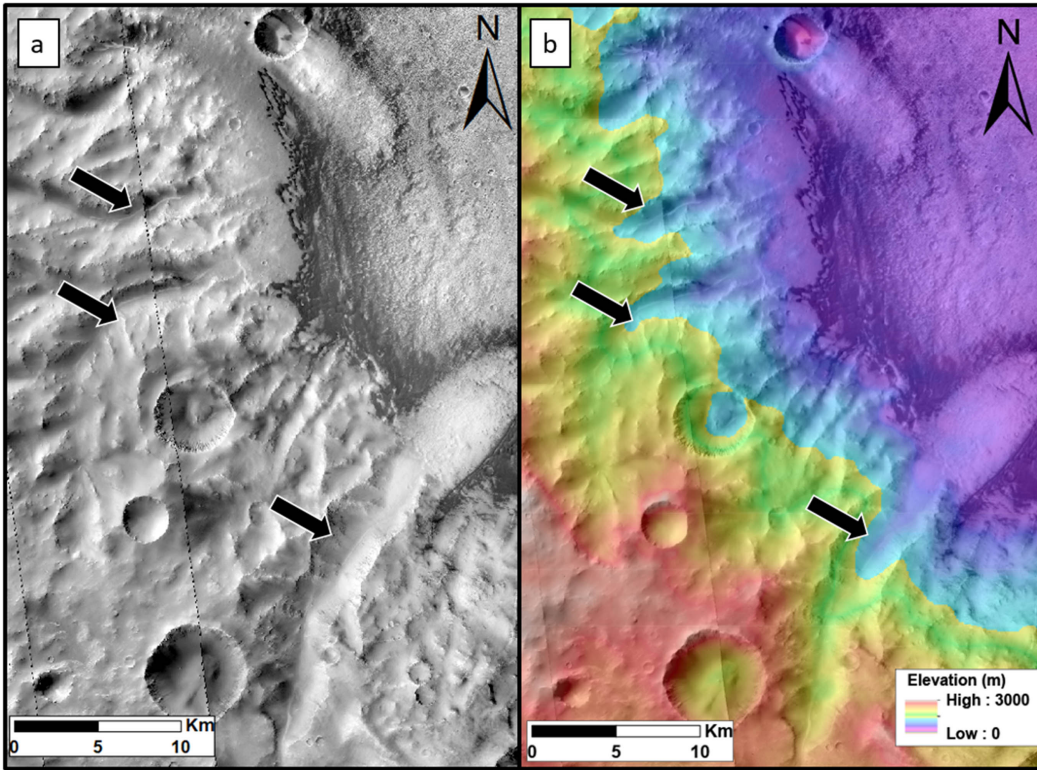


Fig. 3. Example of studied valleys. The west rim of Dawes crater visualised using (a) CTX images P11_005461_1706_XI_09S323W; P17_007742_1708_XN_09S323W (b) MOLA colorised data overlain on CTX images. The black arrows indicate the location of the valleys. Images credit NASA/JPL/University of Arizona.

standard parallels increases. We used “SINUSOIDAL_MARS” for DTMRDR, the scale along all parallels and the central meridian of the projection is accurate. And “Mars2000_ECylindrical_clon0” for MOLA. Our study areas are near the equator (between 2° and 9°S), which is a standard parallels so the distortions can be neglected. To measure valleys on Earth, we used data from the Institut national de l’information géographique et forestière (IGN). We used the 25m/pixel DEM.

4.2. Morphometrical analysis of terrestrial glacial landscapes

4.2.1. Terrestrial glacial and fluvial valleys

Penck (1905) showed that the cross-section area of alpine glacial valleys increases down to the equilibrium line and then decreases downstream to the end of the valley. This is the “law of adjusted cross-sections” (Penck, 1905). Since 1905, numerous authors have studied the morphological and geometrical differences between

fluvial and glacial terrestrial valleys using various parameters: length, width, slope, elevation, drainage area, and cross-section. The own properties of ice and liquid water (state of matter, velocity, rate of abrasion...) make that glacial valleys are different from fluvial valleys by the footprint they leave in the landscape. Generally, a glacial valley is U-shaped with a wide flat floor, steep walls and symmetric shoulders (Penck, 1905; Livers and Wohl, 2015). These characteristics come from the processes of glacial erosion: (1) Glacial quarrying is the means by which a glacier removes larger chunks and fragments from its bed and walls (Bennett and Glasser, 2009). (2) Glacial abrasion is the process by which rock particles transported at the base of a glacier are moved across a bedrock surface scratching and wearing it away (Bennett and Glasser, 2009). A fluvial valley is V-shaped with a narrow floor, gentle walls and symmetric shoulders (Montgomery, 2002; Livers and Wohl, 2015). These characteristics come from the process of fluvial erosion: (1) Water abrasion generate detachment of soil particles by flowing water under the influence of both drag and lift forces (Léonard and Richard, 2004). These differences of erosion have influences on morphology and geometry of these two kinds of valleys. Then, from literature, we created a list of morphological and geometrical characteristics that allow the distinction of glacial valleys from fluvial ones (Table 1).

4.2.2. *Terrestrial glacial cirques*

Terrestrial glacial valleys have often valley heads upstream where the ice accumulates. When these valley heads are a hollow, open downstream but bounded upstream by the crest of a steep slope a ‘headwall’ ($>27^\circ$) which is arcuate in plan around a more gently sloping floor ($<27^\circ$), They are called glacial cirque. It is glacial if the floor has been affected by glacial erosion while part of the headwall has developed subaerially, and a drainage divide was located sufficiently close to the top of the headwall (the cirque crest) for little or none of the ice that fashioned the cirque to have flowed in from outside, (Barr and Spagnolo, 2015; Evans and Cox, 2017). The characteristics of cirques are readily measurable due to in the absence of ice and can include: (1) their spatial distribution, (2) the length (L), (3) the width (W), (4) the amplitude (A), (5) the height range (H), (6) the size ($\sqrt[3]{LWH}$), and (7) the axial gradient ($\arctan(A/L)$). This parameter approximates the surface slope of a former glacier just filling the cirque (Barr and Spagnolo, 2015; Evans and Cox, 2017). Often, cirque size is calculated in order to assess whether cirques have developed isometrically (whether the rate of growth has been equal in all three orthogonal dimensions) or allometrically (whether the rate of cirque lengthening, widening and deepening has been unequal, and cirques have therefore changed shape

Morphology	References
Glacial valleys are U-shaped while fluvial valley are V-shaped	Roberts and Rood, 1984 Livers and Wohl, 2015
Glacial valleys have a wide flat floor unlike fluvial valley which are steeper	Penck, 1905 Montgomery, 2002
Glacial valleys have symmetric shoulders that delimit the drainage area	Montgomery, 2002 Livers and Wohl, 2015
Above the shoulders glacial valleys have a cirque-like niche	Penck, 1905 Barr and Spagnolo, 2015
Glacial valleys have a longitudinal profile which has a gentle slope with slope failures	Roberts and Rood, 1984 Augustinus, 1992
Glacial valleys have steep walls unlike fluvial valleys which have gentle walls.	Penck, 1905 Livers and Wohl, 2015
Geometry	
Glacial valleys are wider than fluvial ones	Roberts and Rood, 1984 Augustinus, 1992 Livers and Wohl, 2015
The law of adjusted cross-sections	Penck, 1905
The elevation of glacial valleys is higher than fluvial one	Roberts and Rood, 1984 Montgomery, 2002
For drainage area > 50 km ² the cross section ratio is four times bigger for glacial valley than for fluvial valleys	Montgomery, 2002

Table 1. Morphological and geometrical criteria used to distinguish fluvial and glacial valley in this study based on terrestrial studies.

during development; Olyphant 1981; Evans 2010). To assess this, length, width and altitudinal range are plotted against cirque size. They can provide information about the duration and intensity of the glacial conditions that formed them (Delmas et al., 2015).

4.3. Morphometrical analysis of valleys on Mars

We used all the criteria described in Table 1 and in Table 2 to study the mapped valley networks and unmapped valleys in our study area. Authors studying terrestrial landscapes generally use only three or four parameters to characterize valleys and emphasis is placed on the shape of the valley, U-shaped for glacial valleys and V-shaped for fluvial ones. The shape is an important indicator of the origin of the valley, but it is not always a discriminating parameter, for example, a V-shaped valley can be filled by deposits and become more U-shaped. In order to circumvent this problem, in this paper, we studied the morphometry of the martian valleys using as many parameters as possible to interpret the origin of the valleys.

4.3.1. Morphological identification of the valleys and their drainage area

The first step in the analysis was to define the outline of the studied valleys using two criteria: (1) The shoulders of the valley should be well preserved and should be continuous over hundred of meters. As for terrestrial measurements, we chose to stop the valley when we can no longer follow the crest (Livers and Wohl, 2015). (2) The overall morphology should be the same along the whole length of the valley. For the valley networks, we do not consider the entire network as a single valley but as a set of tributary valleys. The shapefile thus obtained allowed us to define the outline of the valley, but also to obtain the drainage area within which the erosion (by ice or liquid water) took place (Fig. 4a).

4.3.2. Valley length and width

The length of the valley was defined using a longitudinal line extending from the furthest upstream part of the valley to the downstream part of the valley, sub-parallel to the valley shoulders (Fig. 4a). Then, in order to have a wide range of measurement, we divided the length into four segments of equal length. The width was measured at each segment boundary (5 width measurements per valley), perpendicular to the length line and crossed the crest on each side of the valley (Fig. 4a).

Valley parameters	Abbreviation	Definition
Length (m)	L	Longitudinal line extending from the upstream part to the downstream part.
Width (m)	W	Perpendicular to the length line.
Slope (°)	Sl	Average values of all pixel in the valley shape.
Elevation (m)	El	Average values of all pixel in the valley shape.
Depth (m)	Dp	Difference between the highest and lowest point from a cross-sectional profile.
V-index (dimensionless)	V-index	Deviation from an ideal V-shaped valley.
Cross-section (m ²)	CS	Calculated from the cross-sectional profiles.
Length/width ratio (dimensionless)	L/W	Length/ width.
Valley head parameters		
Length (m)	L	Length of the median axis.
Width (m)	W	Maximum dimension measured perpendicular to the length line.
Amplitude (m)	A	Difference in altitude between the highest and lowest point on length line.
Height range (m)	H	Difference between the highest and lowest point.
Axial gradient (°)	Axgrad	Arctan(A/L).
Size (m)	S	$\sqrt[3]{LWH}$.
Length/height ratio (dimensionless)	L/W	Length/height.

Table 2. Parameters measured for the valleys and valley heads used in this study. Selected from several terrestrial studies (Johnson, 1904; Penck, 1905; de Martonne, 1911; Graf, 1970, 1976; Olyphant, 1981; Roberts and Rood, 1984; Augustinus, 1992; Montgomery, 2002; Amerson et al., 2008; Evans, 2010; Zemp et al., 2011; Barr and Spagnolo, 2015; Delmas et al., 2015; Livers and Wohl, 2015; Hobbs et al., 2016; Evans and Cox, 2017; Zimmer and Gabet, 2018).

4.3.3. Valley slope and elevation

The slope was calculated for every pixel of the HRSC DTMRDR that fell within the valleys using the ArcGIS tool “slope”. Then to extract the average slope and elevation values for each valley we used the ArcGIS tool “extract by mask”. This tool allow to compute the average values of all pixel that fell within the outline previously drawn for the valley (Fig. 4a-b).

4.3.4. Valley cross-sectional area and V-index

The cross-sectional area was calculated from the transverse profile at the start and end of each segment (0%, 25%, 50%, 75%, 100% of the valley length). The profile crossed the two shoulders of the valley. From this profile, we extracted the maximum depth of the valley (Fig. 4e). Five cross-sectional areas were calculated, one for each segment we measured, and the average valley cross-sectional area was calculated from these five values. In order to characterize the shape of the valleys we used the V-index (Zimmer and Gabet, 2018). This V-index is the measure of the deviation from an ideal V-shaped valley. It is calculated by comparing the valley cross-sectional area (A_x) between the valley bottom and a specified height above the valley floor to that of an ideal V-shaped cross-section with the same height and width as the subject cross section (A_v , Zimmer and Gabet, 2018).

$$V - index = (A_x/A_v) - 1 \quad (1)$$

When V-index = 0, the ideal V-shaped valley is the same that the mesured one. If the valley is U-shaped the V-index > 0 whereas V-shaped valleys have a V-index < 0 (Zimmer and Gabet, 2018). We chose to calculate the V-index for each valleys at 50% of the valley length.

4.4. Morphometrical analysis of valley heads on Mars

Some valley heads on Mars have an theater-like form. For these valley heads we defined the outline, using the same method as described in section 4.3.1. Then, we measured its width and length (Fig. 4c). The altitudinal range was obtained by using the same method described previously for the valleys (Section 4.3.3; Fig. 4c,d,f). The amplitude was obtained by mesuring the difference in altitude between highest and lowest points on the length line (Evans and Cox, 2017). The size of the valley heads was calculated using the

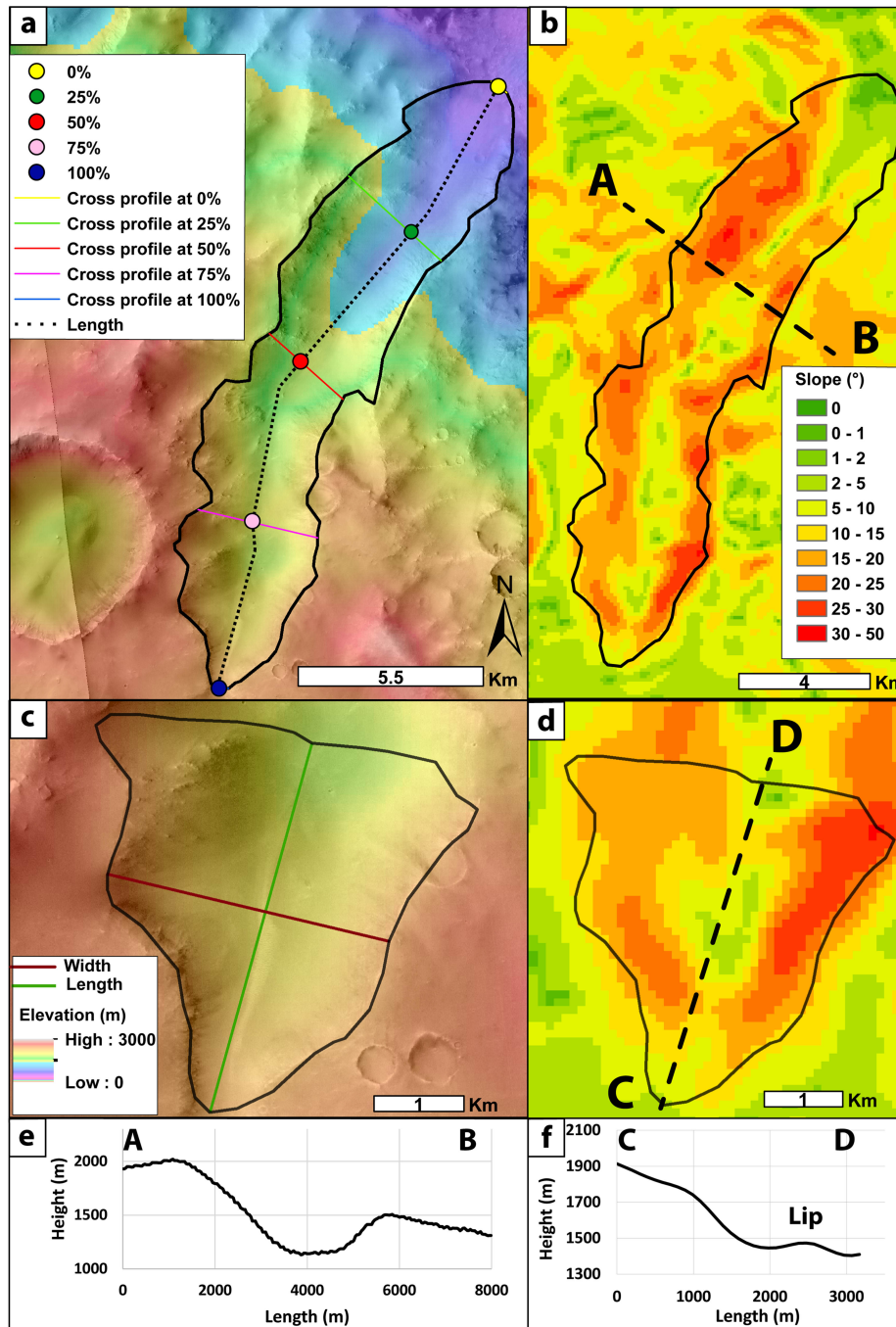


Fig. 4. Valley and valley head morphometric measurement. (a) A valley in Dawes crater and its associated valley head, where 0% correspond to the furthest point downstream and 100% the furthest point upstream. Background is CTX images (P17_007742_1708_XN_09S323W; P11_005461_1706_XI_09S323W) and MOLA elevation data. (b) Slope map of the valley in (a) (calculated from HRSC DTMRDR: h1950_0000_b13) where the dashed line shows the position of the cross-sectional profile shown in (e). (c) Detailed view of the valley head shown in (a). (d) Slope map of the valley head, where the dashed line shows the position of the longitudinal profile shown in (f). Images credit NASA/JPL/University of Arizona.

relation

$$Size = \sqrt[3]{LWH} \quad (2)$$

(with L: Length, W: Width, H: Height), and the axial gradient using the relation

$$Axgrad = arctan(A/L) \quad (3)$$

(with A: Amplitude, L: Length). The boundary between the valley head and the valley is not always very clear. To be consistent between the different studied valleys, we chose to set this boundary to the change in topographic break in slope that marks the transition between the upstream valley head and the downstream main valley (Fig. 4f).

4.5. Comparative morphometrical analysis with known valleys on Earth and Mars

4.5.1. Comparison with Mars

Two craters in the southern highlands, that have already been studied, have been chosen as reference for our comparison (Fig. 1). Bakhuisen crater (15.39°E, 23.9°S) has 35 valley networks mapped by Hynes et al. (2010) and are interpreted as fluvial valleys by Moore (2005) (Fig. 5). A crater, referred as “GLF-crater” in this study (28°16'E, 31°58'S), defined by Souness and Hubbard (2012) as a crater with Amazonian GLFs (Fig. 6). We supposed that the valleys in this crater were mainly shaped by the GLFs present in this crater. We applied our method to the valleys in these craters. The results thus obtained allowed us to verify if our method is consistent with the interpreted origin of the valleys (Moore, 2005; Hynes et al., 2010; Souness and Hubbard, 2012). Moreover, with the data obtained, we were able to build a database large enough to compare these known cases with the valleys in our study areas.

4.5.2. Comparison with the Earth

In order to compare the martian results for the valleys, we decided to apply the method described above (Section 4.3) in the area of Chamonix in the French Alps (Fig. 7). This terrestrial glacial landscape present several glaciated valleys and contrary to our study area, the glacial valleys in Chamonix still have their glacier (Mer de Glace, Argentière glacier...; Zemp et al. 2011; Frezzotti and Orombelli 2013). Then some measured parameters such as the depth and the cross-sectional are distorted, they should increase without the glacier.

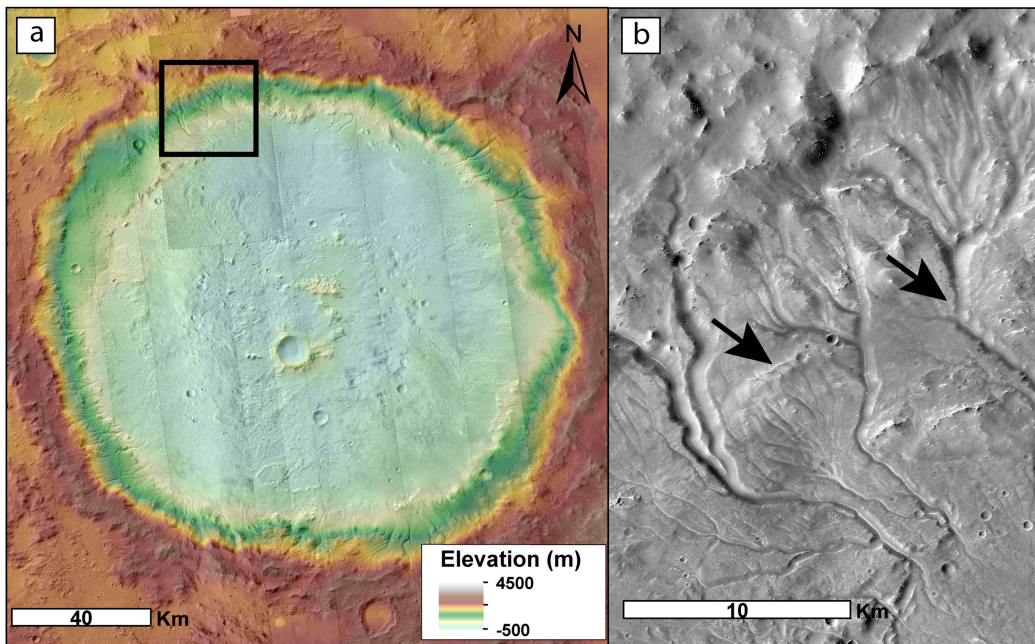


Fig. 5. Bakuysen crater (a) Background using CTX images (G05_020309_1568_XN_23S343W; G12_022933_1578_XI_22S344W; B18_016551_1566_XN_23S344W; B20_017263_1573_XI_22S343W; B18_016617_1562_XI_23S345W; B17_016195_1563_XN_23S345W; P11_005475_1569_XN_23S343W) and MOLA elevation data. (b) Detailed view of the fluvial valleys shown in (a) (G12_022933_1578_XI_22S344W). Images credit NASA/JPL/University of Arizona.

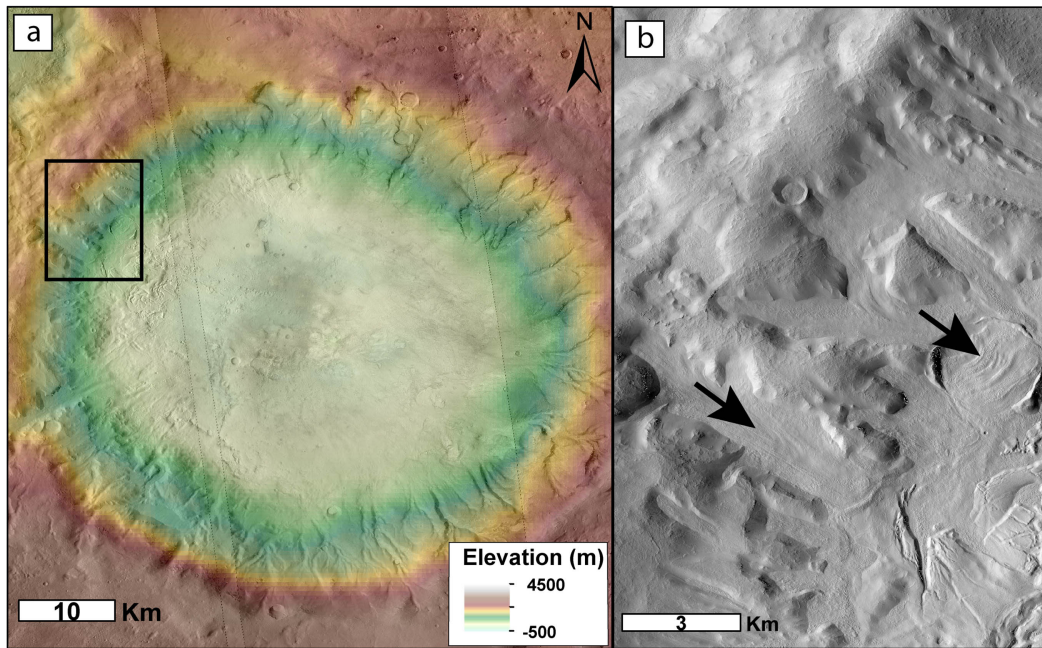


Fig. 6. GLF-crater (a) Background using CTX images (P07_003589_1466_XN_33S331W; B11_013966_1476_XN_32S331W; B06_011909_1480_XN_32S332W) and MOLA elevation data. (b) Detailed view of the valleys and GLF shown in (a) (B06_011909_1480_XN_32S332W). Images credit NASA/JPL/University of Arizona.

However, the other parameters are measurable even if a glacier is present. Indeed, the current presence of a glacier does not influence the length and the width of the valleys because the main glacial erosion phase is over since the Holocene which correspond to the maximum glacier extent (Zemp et al., 2011).

4.6. Summary of measured parameters

4.6.1. Valleys in Terra Sabaea

Using our morphometric analysis we characterized 140 valleys with different origins, namely 36 fluvial valleys in Bakhuisen crater (Moore, 2005; Hynek et al., 2010), 23 glacial valleys in GLF-crater (Souness and Hubbard, 2012) and a suite of valleys with unknown origin: 42 from Dawes crater, 33 from Crater 1 and 6 from mountain 1. We constructed a database with more than 2500 usable measurements to determine whether the valleys of Dawes crater, Crater 1 and mountain 1 are fluvial or glacial in origin. We plotted frequency distributions for each measured parameters (Fig. 8a-d). The average value for each studied parameter is presented in Table 10 in the supplementary. Hynek et al. (2010) identified 35 fluvial valleys in Bakhuisen crater and 29 fluvial valleys in Dawes crater. We re-examined these valleys using more morphometric parameters and we added new valleys to this dataset (Fig. 9).

4.6.2. Valley heads in Terra Sabaea

We identified 100 valley heads in the study area, namely 75 valley heads in Dawes crater and 25 in Crater 1. We plotted frequency distributions for each measured parameters (Fig. 10a-f). The average value for each of the studied parameters is presented in Table 11 in the supplementary. We did not find any valley heads in mountain 1. We constructed a database, with more than 700 usable measurements, to characterise these valley heads and to compare them with terrestrial morphologies (Fig. 11).

4.6.3. Glacial valleys in Chamonix valley

We identified 13 glacial valleys in Chamonix valley. The values for each studied parameter is presented in Table 9 in the supplementary. We constructed a database, with more than 250 measurements, usable as terrestrial reference from our method. The tables containing all the measured parameters for each area are in the supplementary material (Table 4-9).

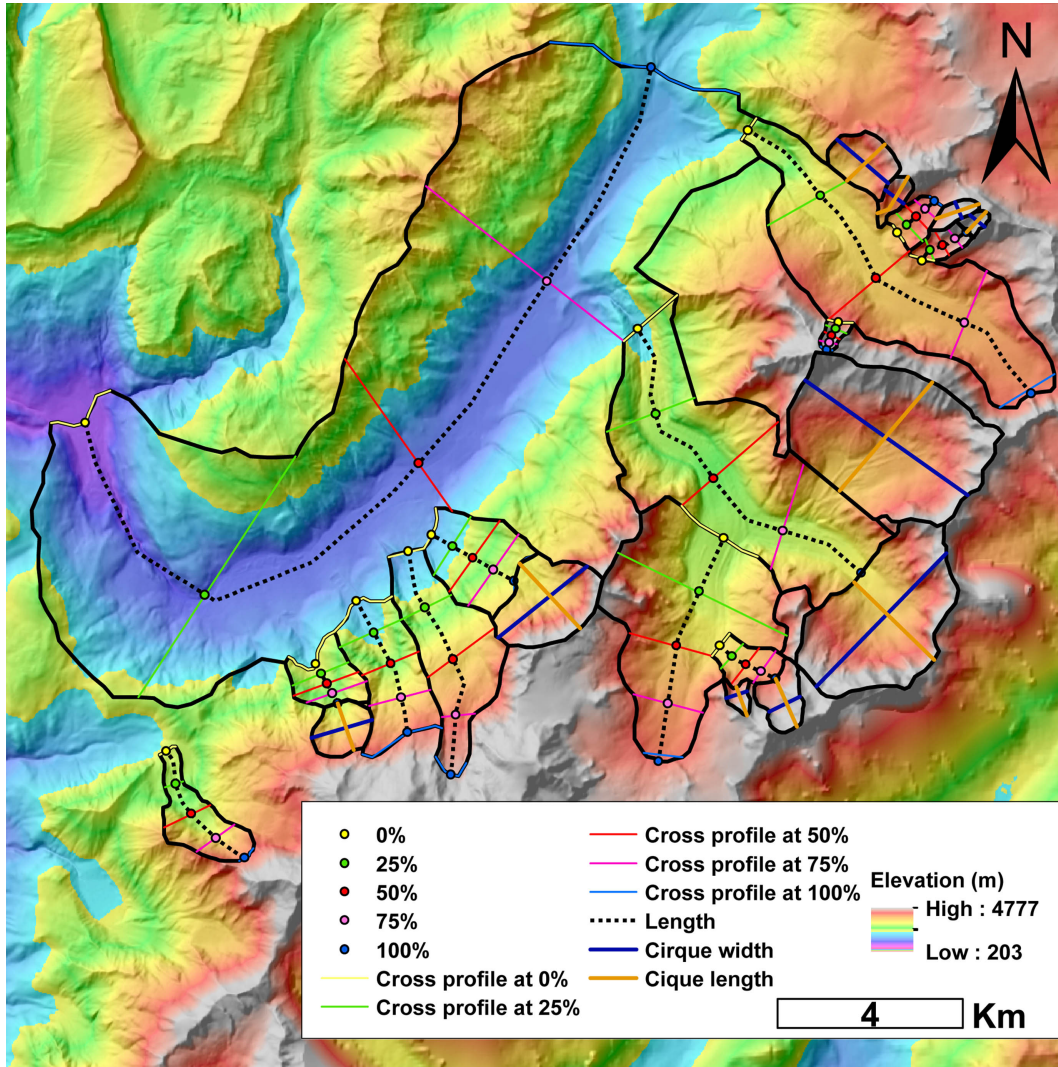


Fig. 7. Study area of Chamonix in the French Alps on Earth. Colorized elevation data from 25m/pixel DEM BDALTr_2-0_ASC_25M_LAMB93_IGN69_D073. Images credit IGN-F

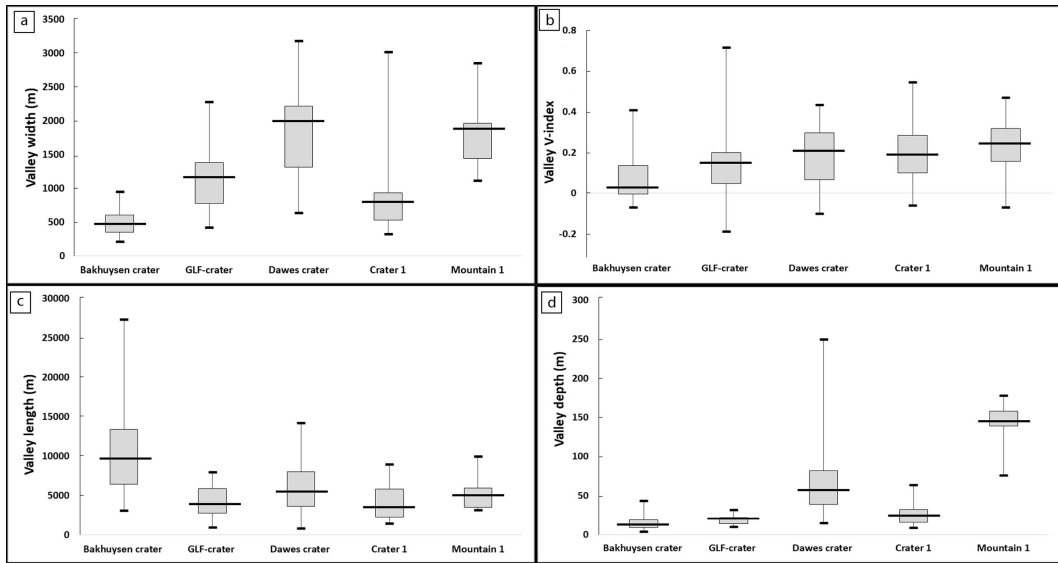


Fig. 8. Box and whisker plot of valley (a) width, (b) V-index, (c) length and (d) depth. The short black lines represents the maximum and minimum for each dataset. The box represent the interquartile range, with Q1 and Q3 the bottom and top of the box. The median is represented by the long black lines in the boxes.

4.7. Age estimation of Dawes crater

In order to constrain the age of the valleys, we performed a crater size-frequency analysis, or “crater counting”. We measured the crater size-frequency distribution (the number and size of craters accumulated on surface units) using CTX images to estimate the age for Dawes crater (Hartmann and Neukum, 2001; Ivanov, 2001). We observed that the floor of Dawes crater is covered by materials that partially overlaps the base of the crater wall. This deposit partially covers the valleys showing that this material was deposited after valley formation. Hence, the valleys and valley heads are younger than the crater walls but older than the filling material that covers them. Therefore, estimating the age of the crater floor and the craters inner walls allowed us to bracket the maximum and minimum age of the valleys and valley heads. We defined two count areas, the first one is the crater inner walls delimited by the crater rim and the break in slope with the crater floor. This area is characterized by the presence of valleys and valleys heads. The second is the crater floor characterized by a flat floor, strongly cratered and the complete absence of valleys and valley heads. We measured all impact craters > 1 km, except secondary and ghost crater using CraterTools in ArcGIS (Kneissl et al., 2011) in these two areas. Dawes crater has 96 superposed craters > 1 km over an area of 28439 m². The crater size-frequency distributions was plotted with Craterstats 2.1 software using a cumulative plot and using the function chronology from Hartmann and Neukum (2001) and Hartmann (2005). The crater

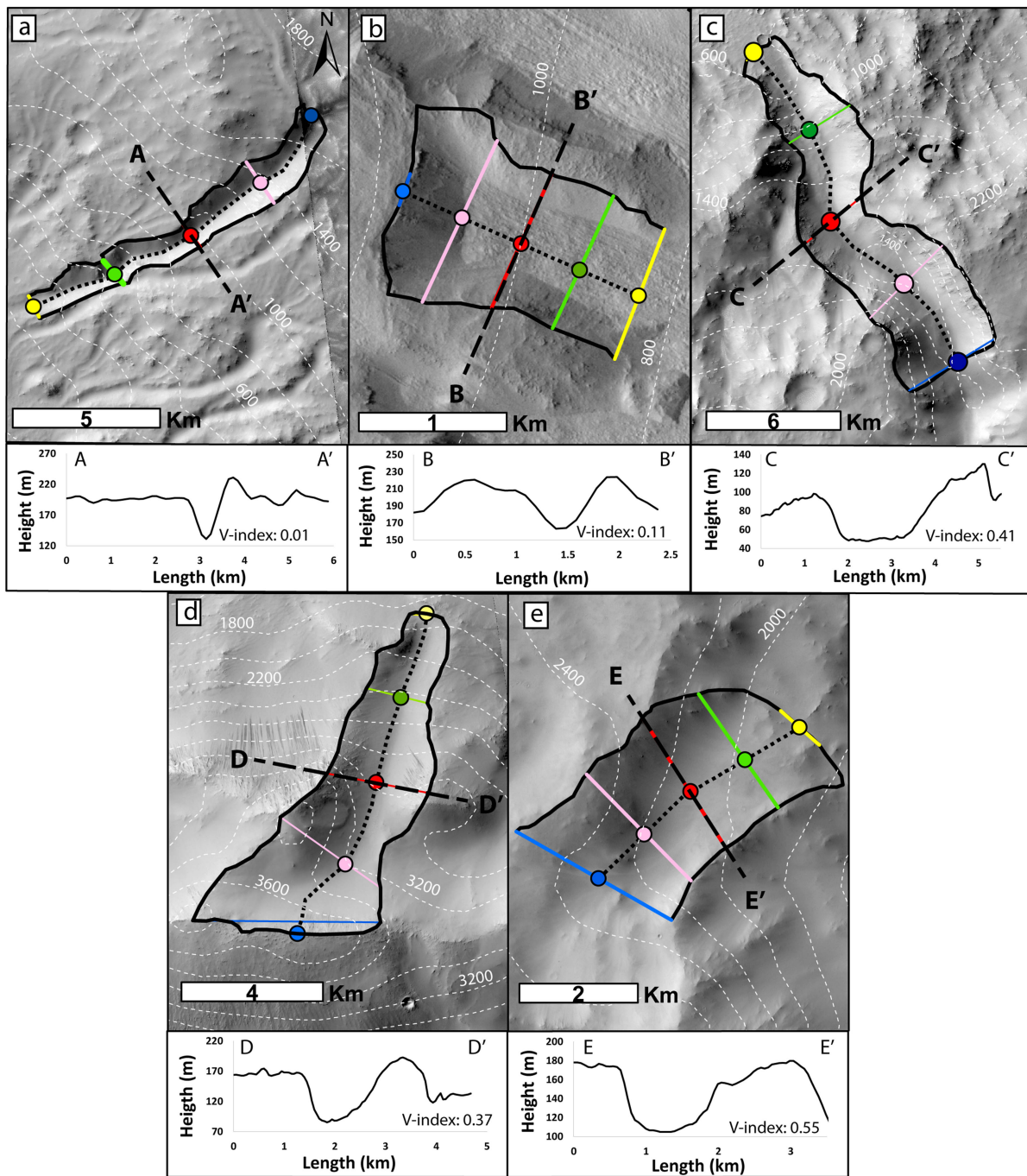


Fig. 9. Example of studied valleys and their associated V-index. The dashed line shows the cross-section at 50% of the downstream valley length extract from HRSC elevation data. Valley examples from (a) Bakhuisen crater (CTX: B20_017263_1573_XI_22S343W), (b) GLF-crater (CTX: B06_011909_1480_XN_32S332W), (c) Dawes crater (CTX: B01_010102_1699_XN_10S321W), (d) mountain 1 (CTX: G19_025833_1759_XN_04S317W), (e) Crater 1 (CTX: G02_019174_1705_XN_09S318W). The legend is the same as Fig. 4a. Images credit NASA/JPL/University of Arizona.

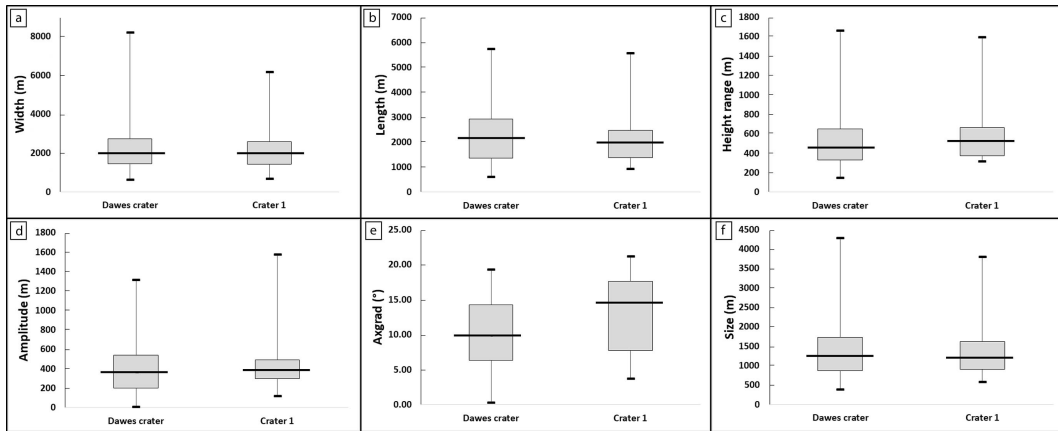


Fig. 10. Box and whisker plot of valley head: (a) width, (b) length, (c) altitudinal range, (d) amplitude, (e) axial gradient and (f) size.

size-frequency distribution is not significant for crater 1, in fact, the plot obtained does not fit with any of the established crater density boundaries (Tanaka, 1986; Hartmann, 2005). However, in order to constrain the age of the valley in crater 1, we counted the craters with diameter > 1 km and calculated the $N(1)$ to determine the formation period of the valleys using established crater density boundaries (Bouley. and Craddock, 2014). $N(1)$ is the density of craters with a diameter > 1 km normalized to an area of 10^6km^2 . This method was realized in two count areas in crater 1, the floor and the crater inner walls defined as the same way described above. We also applied the “ $N(1)$ method” to Dawes crater in order to check if the two ages found with the different methods are consistent. Mountain 1 only have 3 craters > 1 km it is not enough to realize a significant crater size-frequency analysis.

5. Results

5.1. Morphometric comparison: Valleys

5.1.1. Length to Width ratio

The valleys from Dawes crater, Crater 1, mountain 1, and GLF-crater have a mean length to width ratio of 2.5, being only slightly longer than they are wide (Fig. 12). The Bakhuisen valleys are significantly longer compared to their width, with a mean length to width ratio of 22 (Fig. 12). The difference between the length to width ratio suggests that the formation process was not the same for Bakhuisen crater as for the

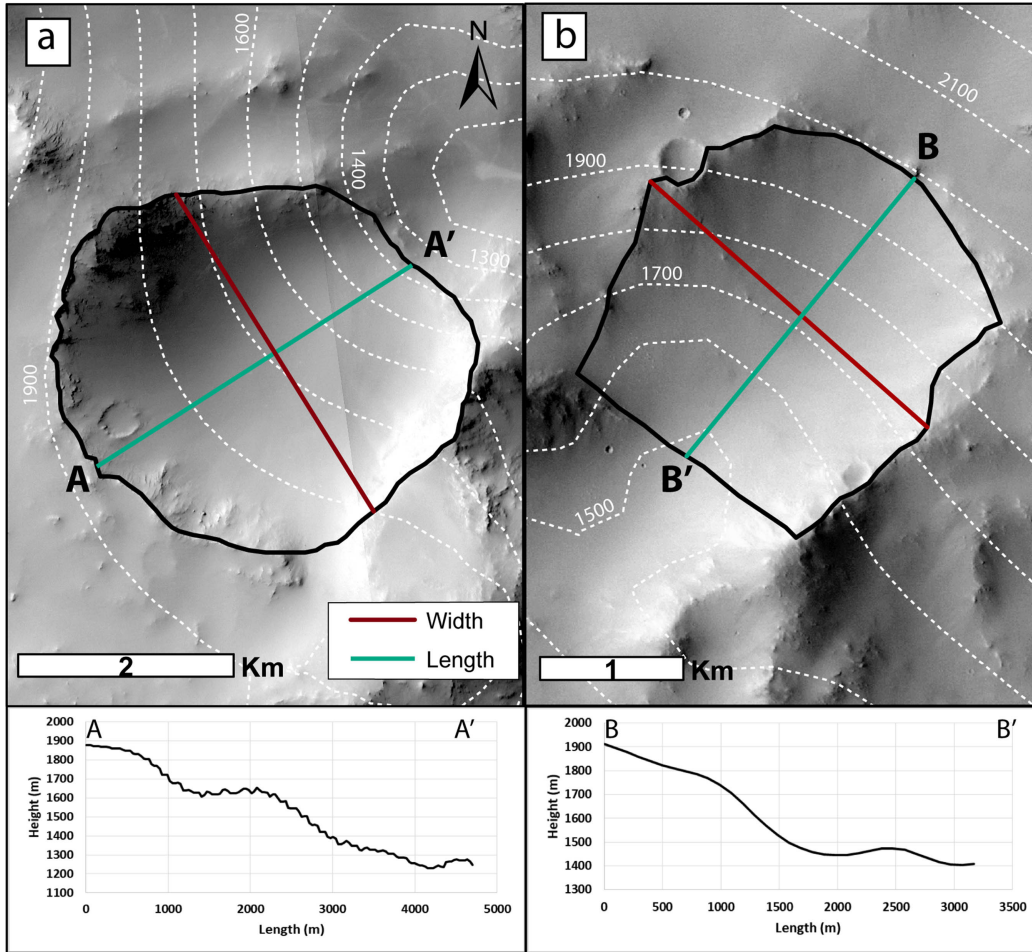


Fig. 11. Example of studied valley heads. The length line shows the location of the longitudinal cross section included underneath each image. Valley head from (a) Dawes crater south-east inner rim (CTX B19_017104_1709_XN_09S323W) (b) Crater 1 northwest inner rim (CTX: B16_015917_1710_XN_09S317W). Images credit NASA/JPL/University of Arizona.

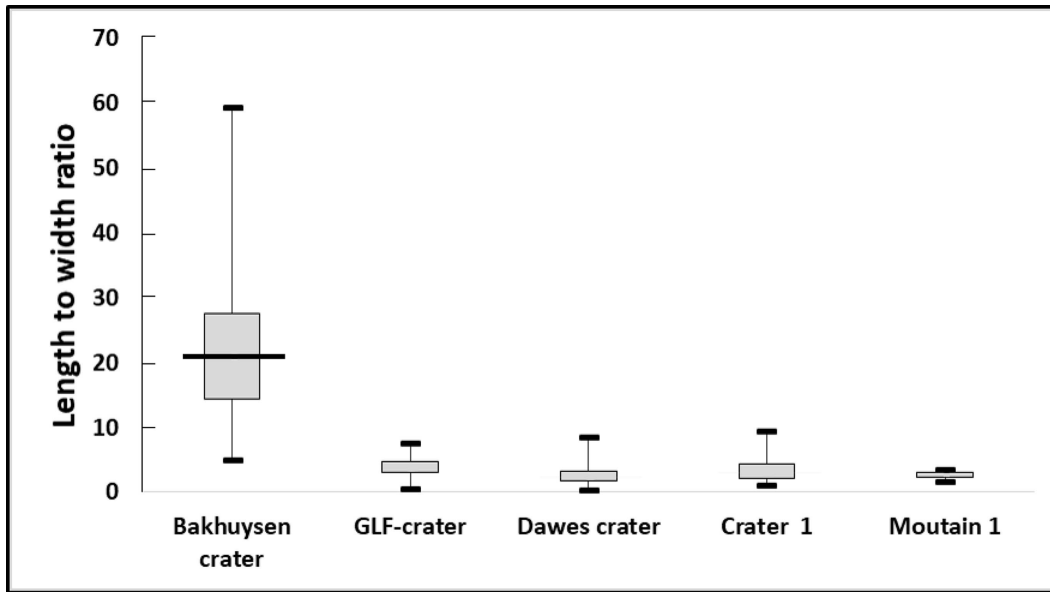


Fig. 12. Box and whisker plot of length to width ratio for valleys in each study areas. 140 valleys have been plotted, 36 from Bakhuisen crater, 23 from GLF-crater, 42 from Dawes crater 33 from crater 1 and 6 from mountain 1 . The median values are respectively: 20.8; 3.6; 2.3; 2.8 and 2.7.

other valleys. Long and narrow valleys are formed by fluvial processes and have an aspect ratio $\gg 1$ while short stubby valleys are generally formed by glacial erosion with an aspect ratio > 1 (Hobbs et al., 2016). Thus, our analysis supports the fluvial interpretation for the Bakhuisen valleys and suggests the origin of the valleys from GLF-crater, Dawes crater, Crater 1, and mountain 1 are different.

5.1.2. Cross-sectional area

Based on our analysis of the valley ratio cross-sectional area/ drainage area we can distinguish two groups (Fig. 13a). The first one is composed of Bakhuisen crater valleys, the ratio between the cross-sectional area and the drainage area is low with an average value of 0.001. The second group is composed of Dawes crater, Crater 1, mountain 1, and GLF-crater, the ratio between the cross sectional area and the drainage area is higher than for Bakhuisen. The average values is about 0.004, that is four times higher than Bakhuisen one (Fig. 13a). On Earth, this value of four is the characteristic difference between the glacial and fluvial valleys (Montgomery, 2002). Moreover, the cross-sectional profiles reveal that Bakhuisen valleys have a V-shape characteristic of a fluvial erosion (Penck, 1905; Roberts and Rood, 1984; Livers and Wohl, 2015) and that Dawes crater, Crater 1, mountain 1, and GLF-crater valleys have a U-shape which is characteristic of a

glacial erosion (Fig. 9). In order to confirm this result, we realized a statistical test to verify if the data are statistically different. The five populations are not normally distributed so we chose to use the Mann-Whitney U test. This method is used to test whether two samples are likely to derive from the same population. This nonparametric test is applicable when the samples are small ($N < 40$), not normally distributed and independent which is the case for this study. To achieve this, the first step was to rank the cross-sectional area/drainage area values to obtain the critical value of U and compare it with the values in Mann-Whitney table for a given N (Table 12 in supplementary). To give an example, let compare the two populations of valleys from Bakhuisen crater ($N = 35$) and Mountain 1 ($N=6$). After ranking, we obtained a critical U value of 6. For these populations, the U value in the table is 37. The critical U value from our data is strictly inferior than the U given in the Mann-Whitney table. So we can confirm that the valleys from Bakhuisen crater and Mountain 1 are statistically separated, that mean that the cross-sectional area/drainage area for these two population of valley do not follow the same trend. In other words, the erosion processes between these two populations of valleys are not the same. We applied this test to the other populations and we found the same result.

The Fig. 13b shows the variation of the cross-sectional areas all along the valleys in the different areas. From the top of the valley (100%) down to the middle of the valley (50%) the cross-sectional area increases and then decreases downstream to the end of the valley (0%). This variation follows the law of a justed cross section described by Penck (1905) for the alpine glacial valleys on Earth.

5.1.3. Elevation

Based on the elevation of the valleys, we can distinguish two groups. The first, comprises valleys in Bakhuisen crater, are found at an elevation < 1000 m, 168 m on average (Fig. 14). The second group is made up of valleys from GLF-crater, Dawes crater, Crater 1 and mountain 1, where 95% the valleys are located at an elevation higher than 1000 m with an average of 1722 m (Fig. 14). These valleys are at an elevation 10 times higher than the valleys in Bakhuisen crater. On Earth, the elevation of glacial valleys is higher than fluvial ones (Roberts and Rood, 1984; Montgomery, 2002).

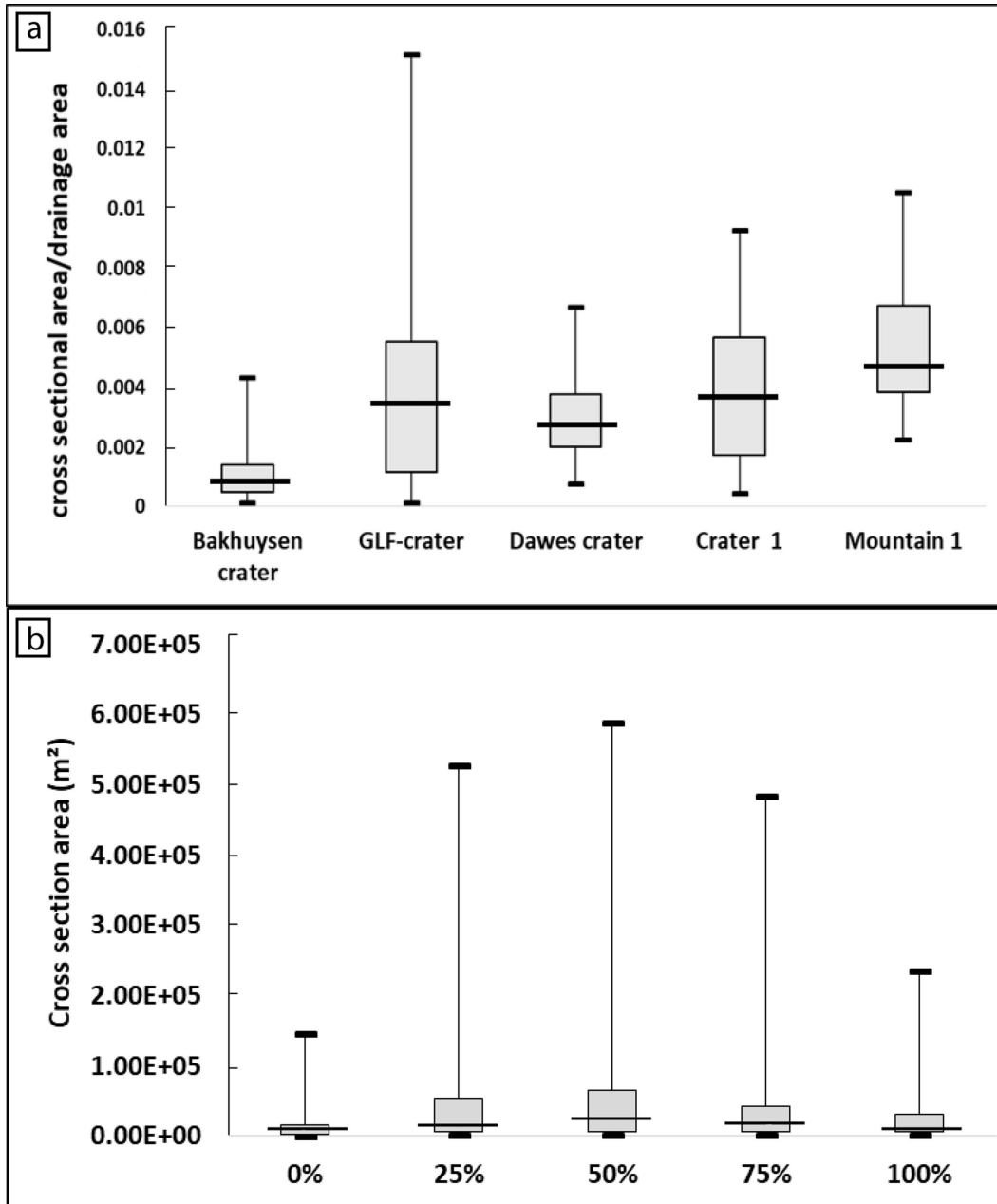


Fig. 13. (a) Box and whisker plot of cross-sectional area/ drainage area for the studied valleys. We can observe two groups, one composed of the valley from Bakhuyzen crater with a mean cross sectional area/drainage area of 0.001 and the second composed of GLF-crater, Dawes crater, Crater 1, and mountain 1 with a mean cross sectional area/drainage area of 0.004. (b) Box and whisker plot of cross-section area at 0%, 25%, 50%, 75% and 100% of the valley length for Dawes crater, Crater 1 and Mountain 1.

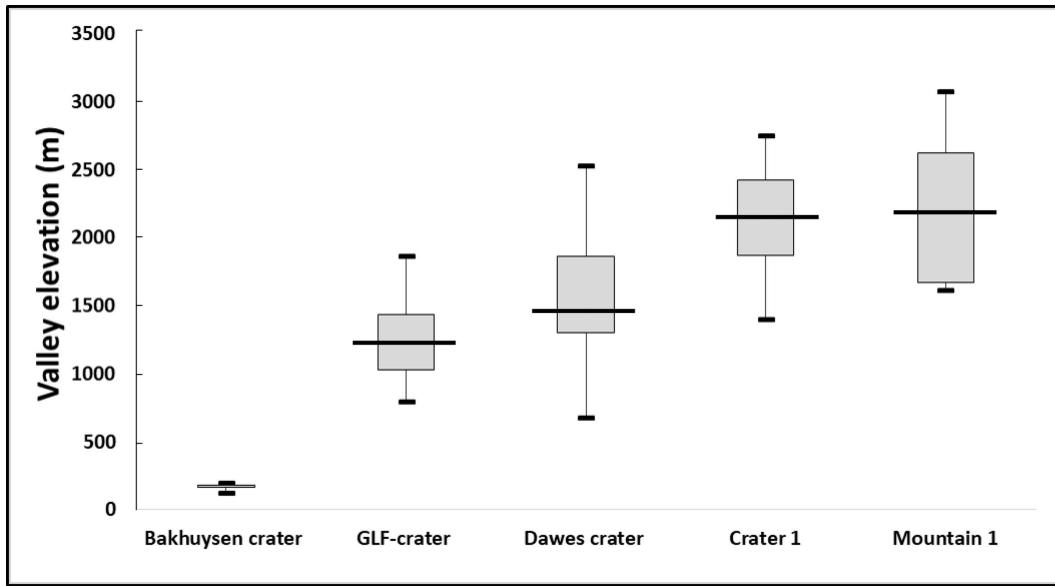


Fig. 14. Box and whisker plot of elevation of the identified valleys from MOLA elevation data.

5.2. Morphometric comparison: valley heads

The valley heads in Dawes crater and Crater 1 have a sizes ranging from 372 m to 4282 m (Fig. 10 f). Furthermore, the longitudinal profile shows a steep upstream slope, between 26° to 28° , and a gentle downstream slope between 17° to 20° (Fig. 15 a-b). On the 75 valley heads identified in Dawes crater 32 presents a topographical lip and 43 do not. For Crater 1, 13 valleys heads have a topographical lip on 25 measured valley heads. These topographical lips have a height between 20 and 100 m (Fig. 15a-b). The average value for each compared parameters is presented in Table 11 in the supplementary.

5.3. Morphometric comparison: glacial valleys in Chamonix

In order to compare the measurement made on Mars with known case on Earth, we plotted length against width for each valley in our study areas and compared them with the results we obtained on 13 glacial valleys in Chamonix (Fig. 16). This plot reveals two groups, the first, comprises valleys in Bakhuisen crater that are longer than wider (Section 5.1.1). The second comprises valleys in Dawes crater, Crater 1, GLF-crater, mountain 1. The point here is that valleys from the second group follow the same trend than Chamonix ones. The V-index is also comparable, in fact Dawes crater, Crater 1 and mountain 1 have a mean V-index of 0.20, 0.21, 0.23 respectively and the glacial valleys from Chamonix have a mean V-index of 0.21. Moreover, the mean length to width ratio is 3.21 (Table 10 in the supplementary). These results suggest that the

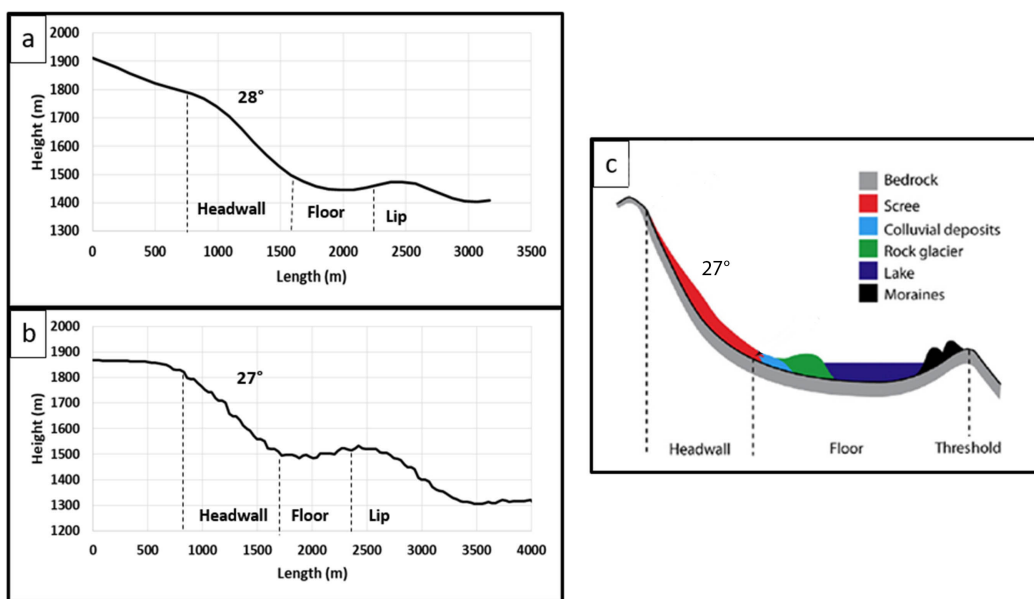


Fig. 15. Longitudinal profile of valley heads from HRSC DTMRDR. (a) In Dawes crater (h5184_0000_da4), (b) In Crater 1 (h1961_0000_bl3), (c) Longitudinal profile of a typical terrestrial glacial cirque. Modify from Barr and Spagnolo (2015)

valleys from Dawes crater, Crater 1 and mountain 1 are eroded by the same processes than glacial valleys from Chamonix.

6. An interpreted glacial landscape in Terra Sabaea

6.1. Characteristics of glacial valleys in Terra Sabaea

The measured parameters of the valleys in Dawes crater, Crater 1, and on mountain 1 are similar to terrestrial glacial valleys:

1. Dawes crater, Crater 1 and mountain 1 valleys have a length to width ratio >1 , which more similar to the GLF-crater valleys than to Bakhuyzen fluvial valley which have a length to width ratio $\gg 1$ (Fig. 12b)
2. Dawes crater, Crater 1 and mountain 1 valleys have a cross-sectional areas that are four times larger than Bakhuyzen fluvial valleys and a similar cross-sectional area to the GLF-crater valleys (Fig. 13a)

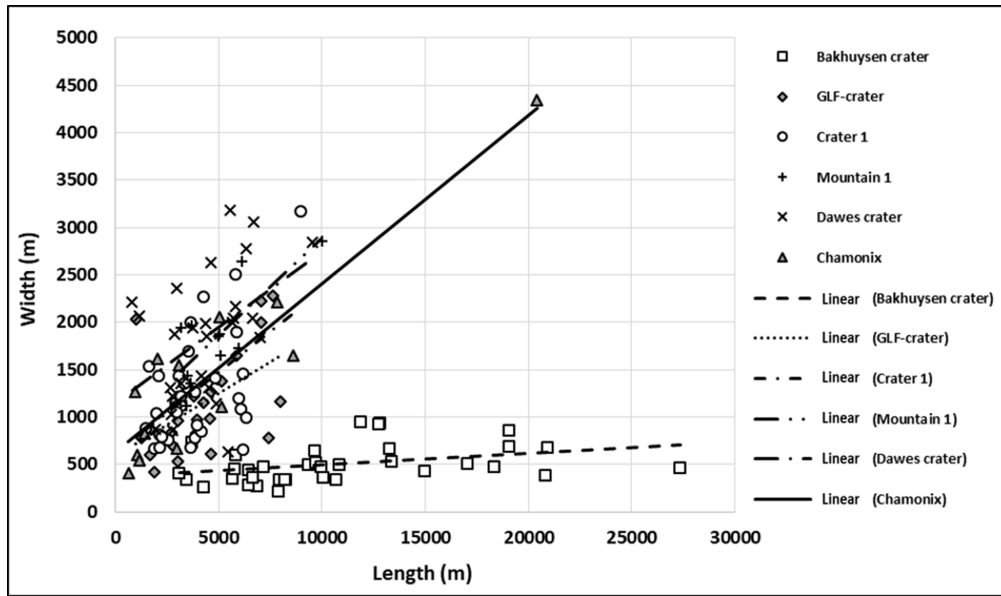


Fig. 16. Length versus width for all the valleys from the different study areas.

3. Dawes crater, Crater 1 and mountain 1 valleys have a V-index around 0.20 while Bakhuisen fluvial valleys have a V-index around 0.07 (Fig. 8b)
4. Dawes crater, Crater 1 and mountain 1 valleys have an elevation 10 time higher than Bakhuisen and a similar elevation to GLF-crater valleys (Fig. 14)
5. Dawes crater, Crater 1 and mountain 1 valleys have a U-shape while Bakhuisen morphologies have a V-shape (Fig. 9c-e)
6. Dawes crater, Crater 1 and mountain 1 valleys respect the cross-section law characteristic of terrestrial glacial valleys (Fig. 13b)

6.2. Characteristics of valley heads in Terra Sabaea

The longitudinal profiles of valley heads in Dawes crater and Crater 1 are similar to typical longitudinal profiles of glacial cirques on Earth (Fig. 15c). They have a steep upstream slope of about 28° in the headwall, then a gentle downstream slope about 20° on the floor, with a topographic lip marking the end of the feature (Fig. 15). The other measured parameters, reported in Fig. 10 and in Table 11 in the supplementary, are within the range of the highest terrestrial glacial cirques measured (Barr and Spagnolo, 2015; Evans and Cox, 2017). The mean axial gradient measured is low, 9.97° in Dawes crater valley heads and 13.18° in Crater

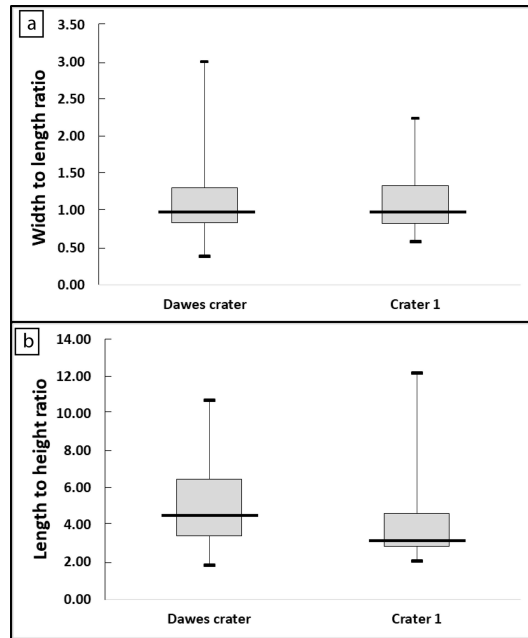


Fig. 17. Box and whisker plot of (a) valley head width to length ratio, (b) valley head length to height ratio.

1 valley heads (Fig. 10e) compared to the mean axial gradient measured on Earth but still in the range of terrestrial glacial cirque (Barr and Spagnolo, 2015; Evans and Cox, 2017). The width to length ratio is around one, which correspond to terrestrial glacial cirque (Fig. 17a) and the length to height ratio is in the range of terrestrial glacial cirques measured on Earth by Barr and Spagnolo (2015) and Evans and Cox (2017; Fig. 17b).

The morphological and geometrical similarities of the valley heads and the valleys to terrestrial glacial cirques and valleys, strongly suggests that the origin of the valleys in Dawes crater, Crater 1 and on mountain 1 is glacial. Moreover, the fact that the valleys in Dawes crater and Crater 1 are also associated with features strongly resembling glacial cirques strengthens the interpretation that Dawes crater and Crater 1 exhibit relict glacial landscapes (Fig. 18a-f).

6.3. Timing of the formation of the glacial landscape

In order to constrain the potential age of the glacial landscape, undertook an analysis of the crater-size frequency distribution for Dawes crater. The crater size-frequency distribution for the floor of Dawes crater gives a best-fit age of 3.52 ± 0.05 Ga and 3.66 ± 0.03 Ga for the inner wall with Hartmann and Neukum (2001) chronology function (Fig. 19a). With Hartmann (2005) chronology function, the best-fit age is 3.34

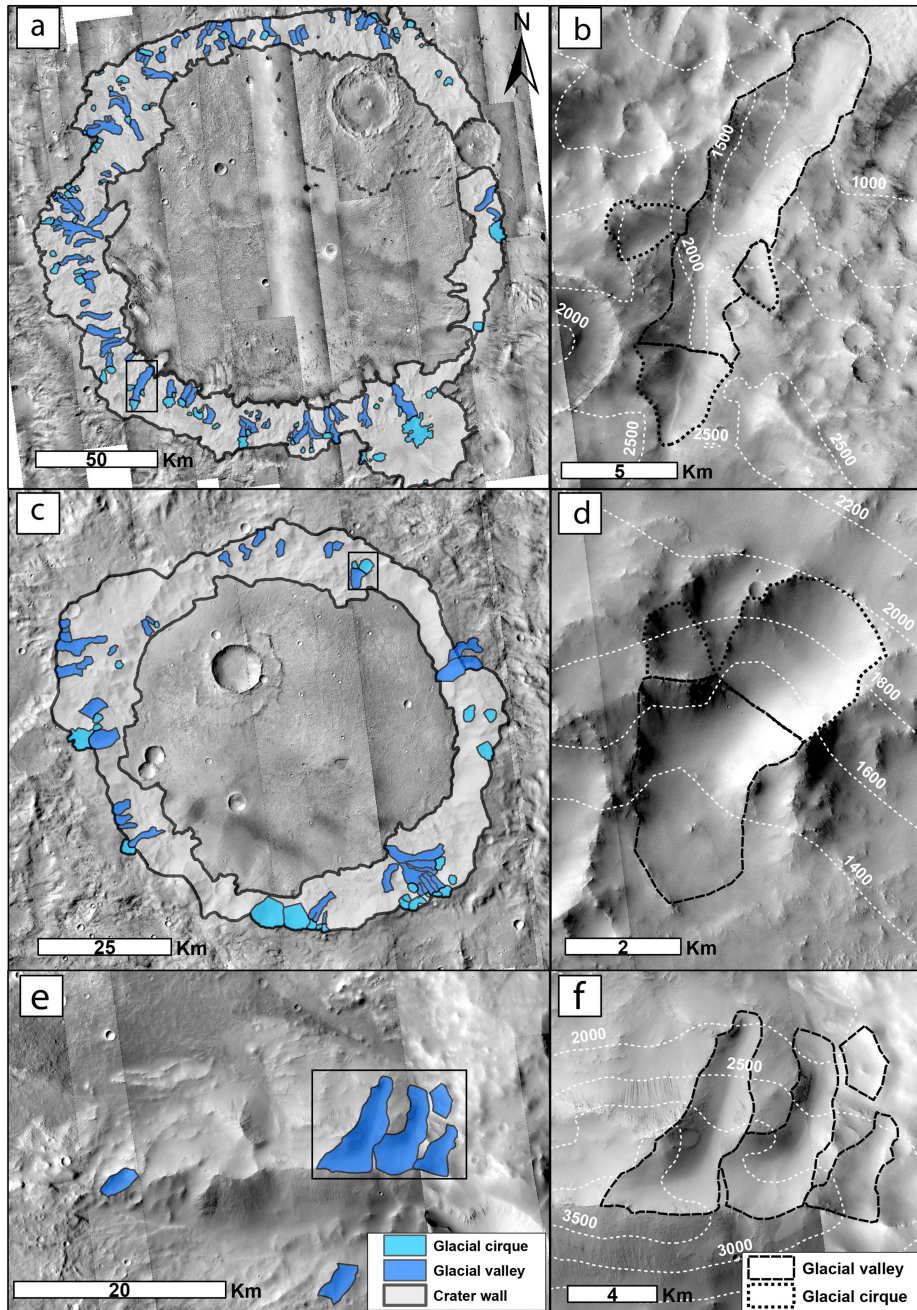


Fig. 18. Geomorphological map of the proposed glacial landscape. (a) Dawes crater distribution of the glacial valleys and cirques on the inner wall of the crater overlain on CTX images. (b) Detail of glacial assemblage, the main glacial valley is surrounded by three glacial cirques. (c) Crater 1 distribution of the glacial valleys and cirques on the inner wall of the crater overlain on CTX images. (d) Detail of glacial assemblage, the main glacial valley is surrounded by two glacial cirques. (e) Mountain 1 distribution of the glacial valleys on the wall of the mountain overlain on CTX images. (f) Detail of glacial valleys, we can not found glacial cirque on that mountain. Images credit NASA/JPL/University of Arizona.

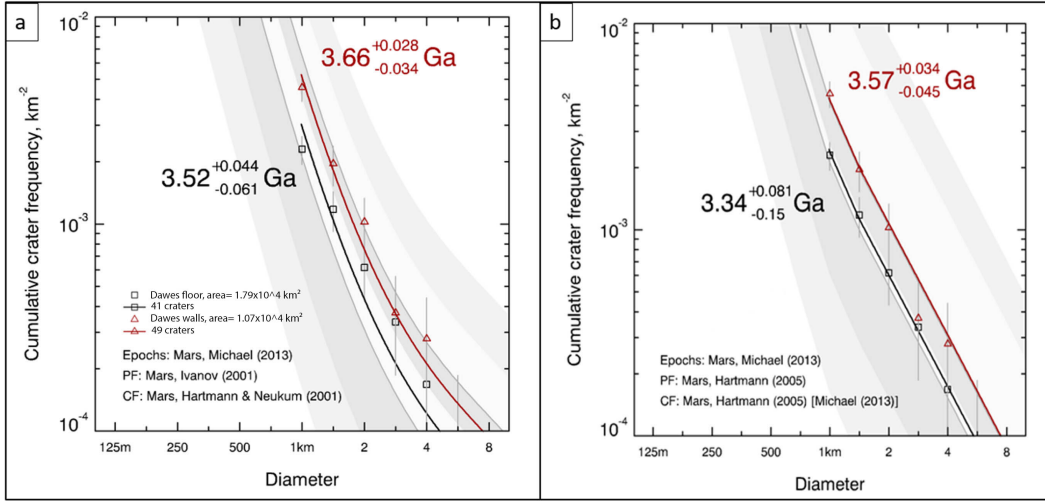


Fig. 19. Timing of formation of the glacial landscape in Daves crater. (a) Results are for crater with diameter > 1 km with Hartmann and Neukum (2001) chronology function. The red triangles represent the counts performed on the inner wall (3.66 Ga) and the black squares the counts performed on the crater floor (3.52 Ga). (b) Results are for crater with diameter > 1 km with Hartmann (2005) chronology function. The red triangles represent the counts performed on the inner wall (3.57 Ga) and the black squares the counts performed on the crater floor (3.34 Ga). A detail map of the count area is in the supplementary (Fig. 21).

± 0.06 Ga for the floor, and 3.57 ± 0.03 Ga for the inner wall (Fig. 19b). So the age of the Daves crater glacial landscape is probably between 3.34 and 3.66 Ga (Late Noachian/ Early Hesperian).

Daves crater has $N(1) = 4579$ for the walls and $N(1) = 2291$ for the floor. We applied this method to Crater 1 and we found $N(1) = 4167$ for the walls and $N(1) = 3297$ for the floor. In the two craters, the crater densities correspond to the Late Noachian/Early Hesperian for the inner walls and to the Hesperian for the floor according to the established crater density boundaries (Tanaka, 1986; Hartmann, 2005). These ages are consistent with the age found by Bouley, and Craddock (2014) with the basin age-dating method for the basins and subbasins within Terra Sabaea of 3.61 ± 0.02 Ga. So, we hypothesize that from the Late Noachian to the Early Hesperian, the climate was cold enough to have deposition and preservation of ice leading to formation of glaciers and for the crater walls to be shaped by ice processes and form a glacial landscape.

7. Discussion

7.1. Allometry and origin of the glacial cirque in Terra Sabaea

The glacial cirque distribution in Daves crater and Crater 1 shows that some of them are located at lower elevations than some glacial valleys. On Earth, glacial cirques are usually at higher elevations than the

downstream glacial valleys. The sizes and allometric coefficients of the cirques provides information which can explain the differences in the topographic characteristic of cirques on Mars compared to the Earth. Cirque size is calculated in order to assess whether cirques have developed isometrically or allometrically and it is plotted against the length, width and altitudinal range (Barr and Spagnolo, 2015). The allometric coefficients of logarithmic regressions indicate if the cirque growth equally in the three dimensions (isometric) or unequally (allometric), when the allometric coefficients are close to 1 the cirque population displays isometric properties and when they are significantly different from 1 the cirque population displays allometric properties. The sum of these coefficients must be 3 (Evans, 2010; Barr and Spagnolo, 2015; Delmas et al., 2015). The allometric coefficients for all the three dimension are close to 1 in Dawes crater and Crater 1 and they sum to 3 (Fig. 20a-b). So the glacial cirques identified in Dawes crater and Crater 1 are isometric. The apparent isometry of cirque indicate that former glacier rarely extended beyond their cirques because a glacier confined to its cirque may naturally result in isometric developement, but, on Earth, glaciers often grow beyond cirque confines and shape glacial valley downstream (Barr and Spagnolo, 2015). In our study, we found both, cirques connected and unconnected to a glacial valley. Delmas et al. (2015) proposed that the isometric character of cirques could be interpreted as a process by which nonglacial topographic depressions with allometric properties were progressively shaped by ice to form isometric landforms. We proposed that on Mars, this nonglacial topographic depressions could be a pre-existant impact crater filled later by the ice. This hypothesis could explain (1) the isolated cirques which are not linked with a glacial valley and (2) the fact that some glacial cirques are found at lower elevations than glacial valleys. Moreover, if some of glacial cirques have an impact crater as origin, the impact crater diameter should be >2 km (Fig. 10a-b, Table 11). These craters later filled by the ice became glacial cirques with high size. So this hypothesis can also explain (3) the fact that the measured parameters are high but within the range of the highest terrestrial glacial cirques.

7.2. *Type of glaciation*

On Earth, cold-based glaciers have temperatures below the pressure-melting point at near their base (Nagle and Witherick, 2002; Cogley et al., 2010). Their movement is a result of internal plastic deformation inside the ice, and only little, if any, basal abrasion occurs. Warm-based glaciers have at their base temperatures at pressure melting points, they melt from their bed, resulting in basal sliding in which a water film lubricates the surface. Extensive basal abrasion occurs (Hargitai and Kereszturi, 2015). These differences of erosion involve that glacial depositional features such as moraines, kames, eskers, or kettles hole are generally typical

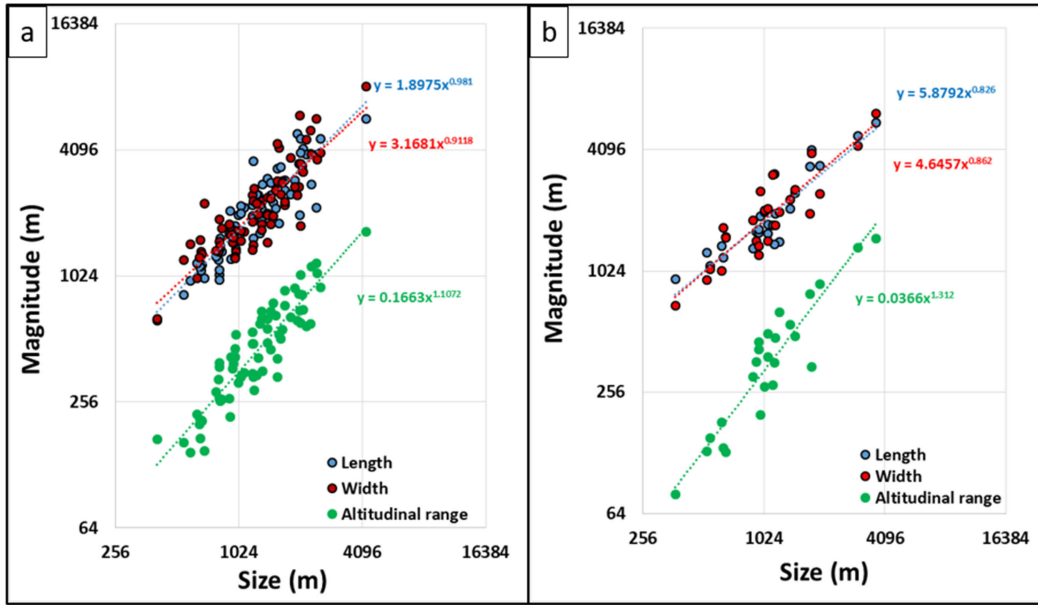


Fig. 20. Valley head morphometry. (a) Allometric (double log (4)) plot of valley heads from Dawes crater (N=77). the allometric coefficients are 0.98 (length), 0.91 (width) and 1.1 (altitudinal range). (b) Allometric (double log (4)) plot of valley heads from Crater 1 (N=25) the allometric coefficients are 0.82 (length), 0.86 (width) and 1.3 (altitudinal range). The size is calculated from $\sqrt[3]{LWH}$ and the magnitude is the different values from the length, width and altitudinal range.

of warm-based glacier. In Terra Sabaea, the glacial valleys do not have any of these features. This absence could be because these depositional features are composed of easily erodable unconsolidated sediment, and have been removed by subsequent erosional episodes like, erosion by wind, meteoritics impacts or run-off. When a glacier melts, a large amount of liquid water flows down the slope. We propose that the water thus liberated could have eroded and transported away these characteristic depositional features. Therefore, it is difficult to infer if the glaciers that created these valleys were warm or cold based. However, the morphometric properties highlighted in this study allow us to differentiate between the types of glaciation responsible for there valleys (alpine glacier or ice cap). Our morphological and geometrical results are consistent with terrestrial alpine glaciers as defined by Jackson et al. (2005) as any glacier in a mountain range except an ice cap, ice sheet, or ice field. Such glaciers usually originate in a cirque and may flow down into a valley (Section 6.2).

7.3. Late Noachian/early Hesperian glacial landscape versus Amazonian VFFs

An important point to discuss is the difference between late Noachian/early Hesperian glacial landscape versus Amazonian VFFs. Even if they are both formed by glacial processes, their distribution and their formation conditions are different. These differences are mainly controlled by the orbital parameters and atmospheric conditions that are completely different between the late Amazonian and the late Noachian/early Hesperian. Several studies indicate that the formation of VFF seems to be linked with an orbital obliquity increase (Madeleine et al., 2009; Hubbard et al., 2011; Souness and Hubbard, 2012). In fact, Amazonian climatic models suggested that an atmospheric pressure of 0.007 bar and high (45°) to medium obliquity (30°) are favourable conditions to form VFFs (Montmessin, 2004; Forget, 2006). Moreover, the geomorphologic mapping of these features, show that they are only locally found between 30° to 50° in latitudes, on crater slopes > 20° (Milliken, 2003; Hubbard et al., 2011; Souness and Hubbard, 2012; Hubbard et al., 2014). So the VFFs have a latitudinal and slope dependence and are formed under particular conditions. The late Noachian/early Hesperian glacial landscape we found in the three sites are at elevations > 1000 m (Fig. 14). Climatic models suggested that, with an obliquity of 45° and under a 1 bar CO₂ atmosphere with cloud, radiative effects and active water cycle, water ice could deposit in area > 1000 m in elevation without latitudinal dependence (Forget et al., 2013; Wordsworth et al., 2013). At this high obliquity, the exchange in water ice and CO₂ become more intense, and surface ice are predicted to become stable even at equatorial latitudes (Conway et al., 2018). Moreover, even if we analyzed only three sites on Terra Sabaea, a preliminary mapping of the whole area seems to indicate that more structures seem to have glacial landscape. A future detailed study of these features will be done in order to characterize the regional distribution of these landscapes. However, our observations linked with the climatic models suggested that the late Noachian/early Hesperian glacial landscape have an altitudinal dependence and are formed under less particular conditions and on larger scale than VFFs.

7.4. Paleoclimatic implications

Almost all the valleys identified in this study as being glacial in origin are located at elevations between 1000 m and 3000 m (Fig. 14). The glacial valley elevations we found are consistent with the previous modeling studies which predicted the deposition of water ice at elevations > 1000 m during the late Noachian (Wordsworth et al., 2013; Bouley et al., 2016). Nevertheless, on Earth, the equilibrium line altitude (ELA)

for a glacier, which separates area where the ice is stable (upper accumulation zone) from the area where the ice is not stable (lower ablation zone), is approximated as the elevation which corresponds to the 1/3 of the length of the valley (Anderson et al., 2006). If we apply this rule to Terra Sabaea, we find that the elevation of the ELA is at about 1800 m for Dawes crater and 2000 m for Crater 1. These paleo-ELA are higher than the predicted 1000 m elevation stability of ice in the climatic models (Wordsworth et al., 2013; Bouley. et al., 2016).

Ramirez and Craddock (2018) reviewed the debate between the wet and warm early martian climate versus the icy highlands scenario. They suggested that the icy highlands scenario is not possible because of the complete absence of glacial features in Noachian terrains. However, our study demonstrates, for the first time the presence of a glacial landscape composed of glacial valleys associated with glacial cirques in Noachian terrains in the south of Terra Sabaea (Fig. 18). The observed sequence of Al-bearing clays being deposited over Mg-Fe-bearing clays in ancient terrains has also been interpreted to be consistent with a frozen early martian surface (Ehlmann et al., 2011).

Independently of the debate, we suggest that these two climates could have coexisted. On the Earth, it is common to find places where the ice is stable at high elevation and not stable at lower elevation. The southern highlands have evidence of glacial landscape at elevations > 1000 m, but also some nearby fluvial valley networks at elevations < 1000 m, these two kinds of landscapes seem to be linked together by their ages and their distribution. The catchment of Naktong Vallis, one of the biggest valley networks on Mars (located at 850 km at the north of Dawes crater at an elevation of 1200 m), extends up to a large plateau located at more than 2000 m elevation near Dawes crater (Bouley et al., 2009) and is dated at 3.6 Ga (Fassett and Head, 2008a; Bouley et al., 2009; Bouley. and Craddock, 2014). This age is consistent with the age found for the glacial landscape in Dawes crater and show that the liquid and water ice could have coexisted. Moreover, the glacial landscapes are located at altitudes where the valley network density is known to be low (elevations > 1500 m; Table 10 and Fig. 2a). For elevations < 1500 m the valley network density is known to be higher (Fig. 2a; Bouley et al. 2009). In order to explain this altitudinal relationship between the glacial landscape and the valley networks we propose two hypotheses:

(1) These two climates scenarios are complementary, indeed to form these two types of valley morphologies, a high atmospheric humidity is necessary. Several studies have proposed snowfall and melting snow as the source of water for the valley networks (Head et al., 2005; Bouley et al., 2009; Fastook et al., 2012). Moreover, at the lowest elevations (< 1500 m), the high density of V-shaped valleys, suggests that precipitation played

a role in their formation (Carr, 1995; Baker, 2001; Bibring et al., 2006; Ramirez and Craddock, 2018). Thus, at higher elevations (> 1500 m), snow could have accumulated to form glaciers. We propose that the martian climate during the late Noachian/early Hesperian was characterized by glaciated highlands at > 1500 m according to the glacial landscape we highlighted and temperate lowlands at < 1500 m where liquid water was stable. Thus, a water cycle similar to the Earth could have existed allowing the deposition of snow and glacier formation in the highlands and the precipitation of liquid water for an elevation < 1500 m.

(2) The variations in Mars' orbital obliquity could have changed the global climate and created glacial-interglacial cycles (Laskar et al., 2004). During cold climate periods accumulation and preservation of large amount of water ice could have occurred thus forming glacial landscape at elevations > 1500 m. Then during interglacial periods this ice could have melted and liquid water flowed down shaping the valley networks at an elevations < 1500 m.

In any case, we suggest that the melting of ice could be an important factor to consider for valley network formation. The glaciated highlands could allow the formation of local ice sheet around craters where we found glacial landscapes. We suggest that, the ice flowed down on the inner crater slopes to form alpine glacier and shaped the glacial valleys. But outside the crater, where the slope is gentle and where we did not observe alpine glacier morphologies, these supposed local ice sheet could have melted (Fastook and Head, 2015). This melting water could be a source and/or a reservoir of lowest elevations valley networks and feed the open-basin lake observed in this area by Fassett and Head (2008b). These scenarios would be sufficient to explain most of the valley networks, glacial landscape, and geology in Terra Sabaea. The water liberated could have contributed to the formation of valley networks and the hydration of the soil. Our geomorphological observations provide evidence for a glaciated highlands > 1500 m and temperate lowlands < 1500 m during the late Noachian/ early Hesperian in Terra Sabaea. These results and interpretations are verified in our study area, and bring new elements to the debate about the early Mars climate, but we did not apply our method to the entire highlands in Terra Sabaea. However, a preliminary mapping have been done and it seems like other impact crater presents morphologies similar to those described in this study. A future study in the whole highlands > 1500 m, applying this method, will be done to better constrain the distribution of this supposed glacial landscape and the link they could have with the martian paleo-climate.

8. Conclusion

Our morphometrical analyses allowed us to identify glacial valleys and glacial cirques distributed across three sites in Terra Sabaea. These glacial landforms have similar characteristics to glacial landforms on Earth. The altitude of this glacial landscape is > 1000 m in agreement with numerical climate simulations that have predicted deposition of ice in the southern hemisphere during the late Noachian. We constrain the timing of the formation of these glacial landscapes to about 3.6 Ga, which corresponds to the late Noachian/early Hesperian. This study supports a glacial erosive agent for the origin of these valleys and brings the first morphometric evidence of an ancient glacial landscape composed of glacial valleys associated with glacial cirques in the southern highlands. Finding similar glacial landscapes in other impact craters or in the inter-crater plains in the southern highlands would allow better constraint on the distribution of the ice for early Mars.

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Supplementary material

CTX/ HRSC

Studied Structures	CTX	HRSC
Dawes crater	B21_017816_1708_XN_09S322W B20_017394_1735_XN_06S321W B19_017104_1709_XN_09S323W P17_007742_1708_XN_09S323W P14_006529_1708_XN_09S321W P13_006239_1706_XN_09S323W P11_005461_1706_XI_09S323W P11_005395_1717_XI_08S320W P11_005250_1714_XI_08S322W G23_027376_1684_XN_11S320W B18_016827_1684_XN_11S319W G22_026743_1724_XN_07S321W D15_033257_1689_XN_11S319W D10_031055_1703_XN_09S320W P21_009179_1697_XN_10S322W G01_018739_1714_XN_08S322W B01_010102_1699_XN_10S321W D07_030132_1718_XN_08S320W	h1961_0000_bl3 h1950_0000_bl3 h1928_0000_re3 h1928_0000_nd3
Crater 1	J01_044980_1713_XN_08S316W B08_012594_1713_XN_08S316W F02_036448_1716_XN_08S317W D01_027455_1729_XN_07S318W B19_016906_1705_XN_09S317W B16_015917_1710_XN_09S317W P15_006753_1707_XN_09S317W F03_037015_1729_XN_07S318W G02_019174_1705_XN_09S318W	h5184_0000_da4 h5202_0000_da4
GLF-crater	P07_003589_1466_XN_33S331W B11_013966_1476_XN_32S331W B09_013254_1466_XI_33S331W B06_011909_1480_XN_32S332W	h2540_0000_nd3 h2540_0000_da4 h2540_0000_nd3 h2540_0000_bl3 h2540_0000_gr3
Positive relief	P12_005619_1752_XI_04S317W D22_035815_1762_XN_03S318W G19_025833_1759_XN_04S317W F05_037582_1752_XN_04S316W F05_037793_1760_XN_04S318W F04_037516_1812_XN_01N317W D15_033191_1757_XN_04S318W	h5184_0000_gr3 h8412_0000_ir3
Bakhuysen crater	G05_020309_1568_XN_23S343W G12_022933_1578_XI_22S344W B18_016551_1566_XN_23S344W B20_017263_1573_XI_22S343W B18_016617_1562_XI_23S345W B17_016195_1563_XN_23S345W P11_005475_1569_XN_23S343W	h6445_0000_da4 h6445_0000_gr3 h6488_0000_dt4 h6488_0000_da4

Table 3. CTX images and HRSC elevation data used for this study

Bakhuysen valleys

Length 0% (m)	Length 25%	Length 50%	Length 75%	Length 100%	Width 0% (m)	Width 25%	Width 50%	Width 75%	Width 100%	Average Width	Surface (m ²)	Slope (%)	Depth (m)	Elevation (m)	Cumulative volume (m ³)	Cross-section 0 % (m)	Cross-section 25%	Cross-section 50%	Cross-section 75%	Cross-section 100% (Average cross-section)
0.00	4767.50	9535.00	14302.50	19070.00	146.00	679.00	1854.00	704.00	888.00	886.20	20574190.00	4.13	11.67	194.96	89073075.16	1431.51	9085.14	5068.05	15176.14	5195.13
0.00	2966.50	5933.00	8899.50	11866.00	799.00	1019.00	541.00	1669.00	305.00	946.60	13422022.00	3.38	37.00	186.63	232058515.27	13897.70	14190.05	32316.76	18610.12	18796.16
0.00	2940.75	4681.50	7022.25	9866.00	169.00	775.00	597.00	777.00	216.00	494.80	5571520.00	3.12	19.33	190.73	59406668.93	4809.40	17055.80	962.23	18704.83	9655.74
0.00	3204.50	6409.00	9613.50	13818.00	708.00	1036.00	775.00	1692.00	470.00	956.20	14495773.00	2.89	12.80	178.99	67424271.27	4809.40	17055.80	962.23	18704.83	9655.74
0.00	1711.00	3422.00	5133.00	6844.00	0.00	280.00	215.00	531.00	328.00	270.80	2955588.00	3.61	19.75	155.88	67534195.98	2414.44	1081.31	29607.12	7051.38	9906.56
0.00	1610.75	3221.50	4832.25	6443.00	35.00	218.00	340.00	419.00	409.00	283.80	2430728.00	2.73	7.90	135.29	26686572.89	1470.44	3897.20	3382.97	3382.97	4094.72
0.00	1996.75	3993.50	5990.25	7987.00	17.00	138.00	213.00	319.00	419.00	211.40	2430728.00	2.73	7.90	135.29	26686572.89	1470.44	3897.20	3382.97	3382.97	4094.72
0.00	1673.25	3346.50	5019.75	6693.00	48.00	348.00	261.00	659.00	464.00	514.60	5795568.00	5.13	15.92	111.48	63293980.13	7459.82	21062.20	3814.58	4501.41	10140.75
0.00	5311.50	10623.00	15934.50	20916.00	434.00	488.00	1433.00	318.00	318.00	676.20	14851886.00	6.81	33.43	146.63	31405420.17	8782.63	14710.41	20919.14	17113.41	13508.46
0.00	4589.25	9178.50	13767.75	18557.00	578.00	609.00	633.00	779.00	0.00	477.80	11755544.00	4.89	24.60	140.18	270265915.04	3742.36	4921.90	11278.77	46944.21	14723.61
0.00	3243.25	6486.50	9729.75	13082.00	285.00	619.00	354.00	579.00	0.00	367.40	5191379.00	4.30	12.25	168.00	38471511.04	354.30	5175.05	3180.16	6550.03	3815.88
0.00	3343.25	6686.50	10029.75	13373.00	487.00	489.00	590.00	888.00	214.00	533.60	781643.00	3.96	14.20	170.96	53740022.58	1139.24	3410.47	2857.75	11938.74	746.53
0.00	3184.00	6368.00	9552.00	12776.00	168.00	753.00	979.00	1870.00	858.00	925.60	15555448.00	4.38	16.67	166.20	75997687.11	9092.26	6638.39	6978.62	6978.62	7636.42
0.00	1459.75	2919.50	4379.25	5839.00	0.00	500.00	777.00	1094.00	638.00	598.80	4405470.00	4.55	30.00	180.92	30672388.87	2793.59	1623.92	2784.81	1623.92	2400.77
0.00	2674.75	5349.50	8024.25	10699.00	0.00	549.00	292.00	518.00	368.00	345.40	5401413.00	4.19	9.00	171.62	26150891.07	3005.97	7463.70	14439.04	10851.37	10851.37
0.00	1809.00	3618.00	5427.00	7236.00	370.00	475.00	304.00	394.00	161.00	348.80	3308866.00	3.21	10.00	164.56	21146406.27	2037.24	6705.92	387.35	1236.85	2591.84
0.00	2474.25	4948.50	7422.75	9896.00	144.00	574.00	848.00	1747.00	343.00	731.20	3918979.00	4.25	36.50	156.36	50373799.97	249.16	3910.04	23326.40	13616.22	13616.22
0.00	2417.25	4834.50	7251.75	9666.00	601.00	588.00	819.00	801.00	393.00	640.40	6778504.00	2.92	9.80	168.36	23825733.69	744.59	538.09	1041.08	6584.76	3907.58
0.00	857.25	1714.50	2571.75	3429.00	302.00	447.00	345.00	318.00	318.00	345.20	1192484.00	2.04	4.25	169.95	26676111.99	1071.3	1682.81	1682.81	1682.81	1777.96
0.00	1415.00	2830.00	4245.00	5662.00	0.00	282.00	430.00	434.00	605.00	380.20	2013593.00	2.18	5.25	171.76	9714408.04	2737.56	2319.28	2319.28	2319.28	2319.28
0.00	1797.00	3594.00	5391.00	7186.00	115.00	705.00	677.00	730.00	196.00	476.60	4139483.00	2.24	2.67	172.98	8741813.67	3049.37	1466.85	1829.90	351.68	1216.14
0.00	1721.75	3443.50	5165.25	6907.00	216.00	475.00	311.00	445.00	438.60	438.60	1509431.00	2.83	3.00	172.89	31695981.03	2018.74	6777.25	1081.74	6081.02	3031.02
0.00	1673.25	3346.50	5019.75	6693.00	43.00	432.00	451.00	568.00	159.00	448.80	3670814.11	3.85	10.70	168.80	32093814.11	93.28	13418.49	1544.63	9719.91	7351.89
0.00	4360.25	8720.50	13080.75	17451.00	372.00	466.00	712.00	689.00	236.00	511.00	9315417.00	3.94	17.20	176.74	168070981.26	3930.46	4645.00	26470.04	4740.19	9921.42
0.00	1443.25	2886.50	4329.75	5773.00	224.00	464.00	561.00	638.00	172.00	451.80	3069941.00	3.99	11.50	165.61	11275513.26	3930.46	2054.64	2148.18	3031.94	1617.14
0.00	5204.00	10408.00	15616.00	20816.00	0.00	335.00	533.00	810.00	258.00	387.20	13009497.00	3.84	5.40	165.51	11571503.86	411.55	5768.24	442.21	5067.94	773.71
0.00	1981.50	3963.00	5944.50	7926.00	0.00	364.00	749.00	378.00	211.00	344.40	3570194.00	2.41	11.00	185.33	22076031.48	357.03	1398.45	4768.79	4616.80	2785.27
0.00	1071.25	2142.50	3213.75	4285.00	0.00	273.00	259.00	554.00	201.00	257.40	1435109.00	2.80	8.00	177.96	5809592.36	177.96	5809592.36	1355.80	1355.80	1355.80
0.00	2047.75	4095.50	6143.25	8191.00	316.00	173.00	426.00	550.00	236.00	338.20	3146176.00	2.81	9.50	186.11	20437155.63	323.78	668.84	3144.67	5843.06	2495.09
0.00	3749.25	7498.50	11247.75	14997.00	249.00	574.00	510.00	521.00	305.00	431.80	7436760.00	2.85	17.20	188.46	87150111.65	514.23	8177.87	3475.83	5472.47	11603.78
0.00	1667.25	3334.50	5001.75	6669.00	151.00	433.00	396.00	670.00	185.00	365.00	3728810.00	4.67	20.00	177.89	55599597.18	2554.11	12817.56	9959.40	12817.56	8337.02
0.00	6836.75	13673.50	20510.25	27347.00	251.00	521.00	488.00	701.00	355.00	461.20	16235891.00	3.41	7.25	187.74	83460088.78	1084.20	2487.25	6833.57	2487.25	3051.89
0.00	3314.50	6629.00	9943.50	13288.00	505.00	874.00	680.00	920.00	371.00	670.00	11260219.00	6.18	43.33	161.58	388507991.93	3713.26	24316.07	28736.45	28736.45	3057.93

Table 4. All measured parameters for Bakhuysen crater valleys

GLF-crater valleys

Length 0% (m)	Length 25%	Length 50%	Length 75%	Length 100%	Width 0% (m)	Width 25%	Width 50%	Width 75%	Width 100%	Average Width	Surface (m ²)	Slope (°)	Depth (m)	Elevation (m)	Cumulative volume (m ³)	Cross-section 0.5(m)	Cross-section 25%	Cross-section 50%	Cross-section 75%	Cross-section 100%	Average cross-section
0	1995	380	575	750	750	228	233	341	423	277	1847852	8.75	315	1233.97	16599788.4	934.187646	6175.96583	4025.18602	2198.63421	1742.46971	2114.1469
0	417.26	834.5	1251.75	1669.0	1669.0	327	327	486	612	474	3114677	12.36	87.1	1514.17	3194567.07	1514.17	6175.96583	4025.18602	2198.63421	1742.46971	1092.24753
0	447.26	834.5	1251.75	1669.0	1669.0	307	307	456	582	456	2845571	12.36	213.3333333	1370.18	3194567.07	4522.85356	1444.43524	1823.89226	1428.34725	1103.87722	1092.24753
0	944.5	1889	2833.5	3778	3778	634	634	951	1201	768	5046093.14	10.2	212	1284.32	40465093.14	634.2387	7628.73566	2123.82681	1821.76098	1478.89541	4378.89541
0	1230	2460	3690	4920	4920	1743	1727	2623	3322	2228	1458304	11.84	17.75	1230.84	39138703.06	1303.43827	1503.43827	1390.33003	8988.80105	6988.80105	7965.020847
0	1158	2316	3474	4632	4632	1578	1578	2367	3024	2016	1345904	8.79	20.6	982.08	7749494.32	2307.42585	2858.56966	1262.18817	30482.23398	30482.23398	1670.71837
0	1852.5	3705	5557.5	7410	7410	2421	2421	3631.5	4539	3026	1972943	10.75	15	1223.5	42242393.32	3311.95513	3201.40838	1229.31588	3482.36391	3482.36391	5038.08847
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	19445483.1	10.1	21.2	1132.33	4445483.1	6388.08874	6252.35474	3238.04485	2452.26392	2452.26392	2452.26392
0	1824.75	3649.5	5474.25	7300	7300	2368	2368	3552	4440	2961.33	194										

Dawes crater valleys and valley heads

Length (m)	Width (m)	Depth (m)	Volume (m³)	Cross-section (%)	Average cross-section		
1033.00	1353.00	363.00	394.00	19.36	0.34	2.62	
1371.00	1331.00	390.00	537.00	15.88	0.28	2.55	
1225.00	1603.00	311.00	419.00	14.25	0.25	2.92	
3341.00	2890.00	354.00	411.00	6.05	0.11	8.13	
2000.00	1673.00	244.00	315.00	6.36	0.12	6.35	
1986.00	2473.00	104.00	643.00	3.00	0.05	5.69	
1866.00	1798.00	647.00	393.00	19.12	0.33	2.69	
1830.00	4194.00	416.00	534.00	12.81	0.22	3.43	
627.00	636.00	125.00	163.00	11.27	0.20	3.71	
3530.00	2713.00	470.00	837.00	7.58	0.13	4.22	
2930.00	2723.00	770.00	892.00	14.72	0.26	3.28	
2880.00	1983.00	321.00	490.00	6.36	0.11	5.88	
1932.00	5975.00	636.00	697.00	17.71	0.31	2.86	
1081.00	1332.00	191.00	210.00	10.02	0.17	5.15	
1222.00	1341.00	212.00	328.00	3.84	0.17	3.73	
2140.00	1639.00	549.00	638.00	14.33	0.25	3.35	
369.00	1446.00	84.00	147.00	4.35	0.09	6.59	
2087.00	1751.00	12.00	218.00	0.33	0.01	3.57	
2787.00	2341.00	208.00	360.00	4.27	0.07	7.74	
2293.00	1971.00	643.00	757.00	15.80	0.28	3.03	
2634.00	2231.00	750.00	870.00	15.89	0.28	3.03	
2923.00	2302.00	503.00	741.00	3.76	0.17	3.94	
978.00	1494.00	141.00	376.00	8.20	0.14	2.60	
1636.00	2231.00	470.00	603.00	16.03	0.28	1.36	2.71
2143.00	2619.00	577.00	659.00	15.07	0.26	1.22	3.25
3392.00	2506.00	448.00	512.00	7.52	0.13	0.74	6.63
1544.00	1423.00	170.00	259.00	6.28	0.11	0.92	5.96
1770.00	1262.00	308.00	420.00	3.87	0.17	0.71	4.21
395.00	2260.00	31.00	150.00	5.23	0.09	2.27	6.63
1270.00	1348.00	253.00	286.00	11.27	0.20	1.06	4.44
3610.00	1432.00	186.00	337.00	2.95	0.05	0.40	10.71
2280.00	2679.00	203.00	291.00	5.09	0.09	1.18	7.84
4870.00	2485.00	386.00	627.00	4.53	0.08	0.51	7.77
4641.00	1778.00	557.00	1032.00	6.84	0.12	0.38	4.50
3235.00	3422.00	735.00	828.00	12.80	0.22	1.06	3.91
3934.00	5055.00	373.00	603.00	5.42	0.09	1.28	6.52
2234.00	1364.00	398.00	552.00	10.10	0.18	0.61	4.05
2801.00	3891.00	854.00	1137.00	16.36	0.30	1.39	2.46
1334.00	1721.00	189.00	264.00	8.06	0.14	1.29	5.05
2157.00	5745.00	636.00	1171.00	17.88	0.31	2.66	1.84
2976.00	1479.00	581.00	640.00	11.05	0.19	0.50	4.65
4641.00	3370.00	430.00	902.00	6.03	0.11	0.86	5.15
2475.00	2008.00	278.00	417.00	6.41	0.11	0.81	5.94
1152.00	1301.00	204.00	207.00	10.04	0.18	1.13	5.57
1130.00	1512.00	135.00	172.00	6.81	0.12	1.34	6.57
2168.00	1667.00	173.00	351.00	4.56	0.08	0.77	6.18
1589.00	1471.00	347.00	370.00	12.32	0.22	0.93	4.29
1540.00	2335.00	442.00	485.00	16.01	0.28	1.52	3.18
2209.00	1510.00	293.00	341.00	7.56	0.13	0.68	6.48
2501.00	3747.00	591.00	648.00	13.30	0.23	1.50	3.86
2630.00	4361.00	201.00	337.00	4.27	0.07	1.62	7.98
831.00	1219.00	140.00	164.00	3.56	0.17	1.47	5.07
1132.00	1250.00	163.00	200.00	8.19	0.14	1.10	5.66
1172.00	1001.00	134.00	223.00	3.40	0.16	0.85	5.26
3863.00	4601.00	511.00	528.00	7.52	0.13	1.19	6.58
1474.00	1563.00	364.00	391.00	13.87	0.24	1.06	3.77
1922.00	1852.00	380.00	483.00	11.88	0.20	0.96	3.98
1673.00	1247.00	457.00	458.00	15.28	0.27	0.75	3.65
2911.00	2854.00	526.00	566.00	10.24	0.18	0.98	5.14
2041.00	2414.00	540.00	571.00	14.82	0.26	1.18	3.57
3892.00	3670.00	326.00	1058.00	4.79	0.08	0.94	3.68
5741.00	8214.00	1317.00	1665.00	12.92	0.23	1.43	3.45
3943.00	3518.00	542.00	611.00	7.83	0.14	0.89	6.45
2512.00	2260.00	292.00	344.00	6.63	0.12	0.90	7.30
2857.00	2397.00	363.00	454.00	7.24	0.13	0.84	6.29

Table 6. All measured parameters for Dawes crater valleys and valley heads

Crater 1 valleys and valley heads

Length 0% (m)	Length 25%	Length 50%	Length 75%	Length 100%	Width 0% (m)	Width 25%	Width 50%	Width 75%	Width 100%	Average Width	Surface (m²)	Slope (°)	Depth (m)	Elevation (m)	Cumulative volume (m³)	Cross-section 0% (m²)	Cross-section 25%	Cross-section 50%	Cross-section 75%	Cross-section 100%	Average cross-section
0	3806	2178	1432	824	1632	1089	632	384	224	752	2622	3.25	32	1617	195824.36	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3811	2183	1437	829	1637	1094	637	389	229	757	2627	3.30	37	1622	196333.46	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3816	2188	1442	834	1642	1104	642	394	234	762	2632	3.35	36	1627	196842.56	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3821	2193	1447	839	1647	1109	647	399	239	767	2637	3.40	35	1632	197351.66	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3826	2198	1452	844	1652	1114	652	404	244	772	2642	3.45	34	1637	197860.76	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3831	2203	1457	849	1657	1119	657	409	249	777	2647	3.50	33	1642	198369.86	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3836	2208	1462	854	1662	1124	662	414	254	782	2652	3.55	32	1647	198878.96	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3841	2213	1467	859	1667	1129	667	419	259	787	2657	3.60	31	1652	199388.06	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3846	2218	1472	864	1672	1134	672	424	264	792	2662	3.65	30	1657	199897.16	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3851	2223	1477	869	1677	1139	677	429	269	797	2667	3.70	29	1662	200406.26	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3856	2228	1482	874	1682	1144	682	434	274	802	2672	3.75	28	1667	200915.36	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3861	2233	1487	879	1687	1149	687	439	279	807	2677	3.80	27	1672	201424.46	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3866	2238	1492	884	1692	1154	692	444	284	812	2682	3.85	26	1677	201933.56	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3871	2243	1497	889	1697	1159	697	449	289	817	2687	3.90	25	1682	202442.66	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3876	2248	1502	894	1702	1164	702	454	294	822	2692	3.95	24	1687	202951.76	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3881	2253	1507	899	1707	1169	707	459	299	827	2697	4.00	23	1692	203460.86	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3886	2258	1512	904	1712	1174	712	464	304	832	2702	4.05	22	1697	203969.96	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3891	2263	1517	909	1717	1179	717	469	309	837	2707	4.10	21	1702	204479.06	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3896	2268	1522	914	1722	1184	722	474	314	842	2712	4.15	20	1707	204988.16	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3901	2273	1527	919	1727	1189	727	479	319	847	2717	4.20	19	1712	205497.26	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3906	2278	1532	924	1732	1194	732	484	324	852	2722	4.25	18	1717	206006.36	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3911	2283	1537	929	1737	1199	737	489	329	857	2727	4.30	17	1722	206515.46	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3916	2288	1542	934	1742	1204	742	494	334	862	2732	4.35	16	1727	207024.56	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3921	2293	1547	939	1747	1209	747	499	339	867	2737	4.40	15	1732	207533.66	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3926	2298	1552	944	1752	1214	752	504	344	872	2742	4.45	14	1737	208042.76	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3931	2303	1557	949	1757	1219	757	509	349	877	2747	4.50	13	1742	208551.86	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3936	2308	1562	954	1762	1224	762	514	354	882	2752	4.55	12	1747	209060.96	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3941	2313	1567	959	1767	1229	767	519	359	887	2757	4.60	11	1752	209570.06	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3946	2318	1572	964	1772	1234	772	524	364	892	2762	4.65	10	1757	210079.16	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3951	2323	1577	969	1777	1239	777	529	369	897	2767	4.70	9	1762	210588.26	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3956	2328	1582	974	1782	1244	782	534	374	902	2772	4.75	8	1767	211097.36	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3961	2333	1587	979	1787	1249	787	539	379	907	2777	4.80	7	1772	211606.46	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3966	2338	1592	984	1792	1254	792	544	384	912	2782	4.85	6	1777	212115.56	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3971	2343	1597	989	1797	1259	797	549	389	917	2787	4.90	5	1782	212624.66	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3976	2348	1602	994	1802	1264	802	554	394	922	2792	4.95	4	1787	213133.76	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3981	2353	1607	999	1807	1269	807	559	399	927	2797	5.00	3	1792	213642.86	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3986	2358	1612	1004	1812	1274	812	564	404	932	2802	5.05	2	1797	214151.96	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3991	2363	1617	1009	1817	1279	817	569	409	937	2807	5.10	1	1802	214661.06	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	3996	2368	1622	1014	1822	1284	822	574	414	942	2812	5.15	0	1807	215170.16	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	4001	2373	1627	1019	1827	1289	827	579	419	947	2817	5.20	0	1812	215679.26	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	4006	2378	1632	1024	1832	1294	832	584	424	952	2822	5.25	0	1817	216188.36	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	4011	2383	1637	1029	1837	1299	837	589	429	957	2827	5.30	0	1822	216697.46	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	4016	2388	1642	1034	1842	1304	842	594	434	962	2832	5.35	0	1827	217206.56	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	4021	2393	1647	1039	1847	1309	847	599	439	967	2837	5.40	0	1832	217715.66	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	4026	2398	1652	1044	1852	1314	852	604	444	972	2842	5.45	0	1837	218224.76	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	4031	2403	1657	1049	1857	1319	857	609	449	977	2847	5.50	0	1842	218733.86	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	4036	2408	1662	1054	1862	1324	862	614	454	982	2852	5.55	0	1847	219242.96	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	4041	2413	1667	1059	1867	1329	867	619	459	987	2857	5.60	0	1852	219752.06	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	4046	2418	1672	1064	1872	1334	872	624	464	992	2862	5.65	0	1857	220261.16	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	4051	2423	1677	1069	1877	1339	877	629	469	997	2867	5.70	0	1862	220770.26	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	4056	2428	1682	1074	1882	1344	882	634	474	1002	2872	5.75	0	1867	221279.36	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	4061	2433	1687	1079	1887	1349	887	639	479	1007	2877	5.80	0	1872	221788.46	145.07857	205.84272	383.42076	563.42076	693.03686	383.03686
0	4066	2438	1692	1084	1892	1354	892	644	484	1012	2882	5.85	0	1877	222297.56	145.07857	205.84272	383.42076	563.42076		

Moutain 1 valleys

Length (m)	Leak 50%	Leak 60%	Leak 70%	Leak 80%	Width 50%	Width 60%	Width 70%	Width 80%	Average 50%	Surface (m ²)	Stress (t)	Depth (m)	Elevation (m)	Cumulative volume (m ³)	Cross-section 0.50m	Cross-section 0.60m	Cross-section 0.70m	Cross-section 0.80m	Average cross-section
0	544	544	544	544	249	249	249	249	249	1352.96	6.8	63	249.5	8647.91	1634.94	1634.94	1634.94	1634.94	1634.94
0	986.6158	986.6158	986.6158	986.6158	318.157	318.157	318.157	318.157	318.157	1019.037	6.8	63	318.5	10244.614	3074.612	3074.612	3074.612	3074.612	3074.612
0	1078.1175	1078.1175	1078.1175	1078.1175	336	336	336	336	336	1102.07	6.8	63	336.5	11147.329	3369.329	3369.329	3369.329	3369.329	3369.329
0	1170.6192	1170.6192	1170.6192	1170.6192	354	354	354	354	354	1195.11	6.8	63	354.5	12200.044	3719.044	3719.044	3719.044	3719.044	3719.044
0	1263.1209	1263.1209	1263.1209	1263.1209	372	372	372	372	372	1278.15	6.8	63	372.5	13252.759	4073.759	4073.759	4073.759	4073.759	4073.759
0	1355.6226	1355.6226	1355.6226	1355.6226	390	390	390	390	390	1361.19	6.8	63	390.5	14305.474	4428.474	4428.474	4428.474	4428.474	4428.474
0	1448.1243	1448.1243	1448.1243	1448.1243	408	408	408	408	408	1444.23	6.8	63	408.5	15358.189	4783.189	4783.189	4783.189	4783.189	4783.189
0	1540.6260	1540.6260	1540.6260	1540.6260	426	426	426	426	426	1527.27	6.8	63	426.5	16410.904	5137.904	5137.904	5137.904	5137.904	5137.904

Table 8. All measured parameters for Moutain 1 valleys

	Bakhuysen crater	GLF-crater	Dawes crater	Mountain 1	Crater 1	Chamonix
Number of valleys identified	36	23	42	6	33	13
Average length (km)	10	4.2	4.4	5	3.8	4.7
Average width (km)	0.5	1.2	2	1.8	1.3	1.5
Average aspect ratio length:width	21.5	3.7	2.4	2.7	2.9	3.2
Average elevation (m)	170	1280	1600	2200	2150	2500
Average depth (m)	15	20	56	143	25	308
Average cross-sectional area (m ²)	6537	12647	24568	45591	13631	480793
Average V-index	0.07	0.15	0.20	0.21	0.23	0.21

Table 10. Average values for each measured parameter for valleys in each studied zone.

	Dawes crater	Crater 1	Evans and Cox (2017)	Barr and Spagnolo (2015)
Number of valley heads identified	75	25	1593	10362
Average width (m)	2398	2177	656	749
Average length (m)	2317	2120	625	744
Average amplitude (m)	388	493	260	
Average altitudinal range (m)	519	452	310	309
Average size (m)	1377	1242		
Average width to length ratio	1.05	1.02	1.05	1.03
Lip average height (m)	75	35		
Average axgrad (°)	9.97	13.18	23.1	24.2
Average length to height ratio	4.94	3.87	2.03	2.58
Number of valley head linked with the valley	41	13		

Table 11. Average values for each of the measured parameters for valley heads in each of studied areas and average values from terrestrial cirque from Barr and Spagnolo (2015); Evans and Cox (2017)

$n_1 \backslash n_2$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
2																			0	0
3								0	0	0	1	1	1	2	2	2	2	3	3	
4					0	0	1	1	2	2	3	3	4	5	5	6	6	7	8	
5				0	1	1	2	3	4	5	6	7	7	8	9	10	11	12	13	
6			0	1	2	3	4	5	6	7	9	10	11	12	13	15	16	17	18	
7			0	1	3	4	6	7	9	10	12	13	15	16	18	19	21	22	24	
8			1	2	4	6	7	9	11	13	15	17	18	20	22	24	26	28	30	
9		0	1	3	5	7	9	11	13	16	18	20	22	24	27	29	31	33	36	
10		0	2	4	6	9	11	13	16	18	21	24	26	29	31	34	37	39	42	
11		0	2	5	7	10	13	16	18	21	24	27	30	33	36	39	42	45	46	
12		1	3	6	9	12	15	18	21	24	27	31	34	37	41	44	47	51	54	
13		1	3	7	10	13	17	20	24	27	31	34	38	42	45	49	53	56	60	
14		1	4	7	11	15	18	22	26	30	34	38	42	46	50	54	58	63	67	
15		2	5	8	12	16	20	24	29	33	37	42	46	51	55	60	64	69	73	
16		2	5	9	13	18	22	27	31	36	41	45	50	55	60	65	70	74	79	
17		2	6	10	15	19	24	29	34	39	44	49	54	60	65	70	75	81	86	
18		2	6	11	16	21	26	31	37	42	47	53	58	64	70	75	81	87	92	
19	0	3	7	12	17	22	28	33	39	45	51	56	63	69	74	81	87	93	99	
20	0	3	8	13	18	24	30	36	42	46	54	60	67	73	79	86	92	99	105	
21	0	3	8	14	19	25	32	38	44	51	58	64	71	78	84	91	98	105	112	
22	0	4	9	14	21	27	34	40	47	54	61	68	75	82	89	96	104	111	118	
23	0	4	9	15	22	29	35	43	50	57	64	72	79	87	94	102	109	117	125	
24	0	4	10	16	23	30	37	45	52	60	68	75	83	91	99	107	115	123	131	
25	0	5	10	17	24	32	39	47	55	63	71	79	87	96	104	112	121	129	138	
26	0	5	11	18	25	33	41	49	58	66	74	83	92	100	109	118	127	135	144	
27	1	5	12	19	27	35	43	52	60	69	78	87	96	105	114	123	132	142	151	
28	1	5	12	20	28	36	45	54	63	72	81	91	100	109	119	128	138	148	157	
29	1	6	13	21	29	38	47	56	66	75	85	94	104	114	124	134	144	154	164	
30	1	6	13	22	30	40	49	58	68	78	88	98	108	119	129	139	150	160	170	
31	1	6	14	22	32	41	51	61	71	81	92	102	113	123	134	145	155	166	177	
32	1	7	14	23	33	43	53	63	74	84	95	106	117	128	139	150	161	172	184	
33	1	7	15	24	34	44	55	65	76	87	98	110	121	132	144	155	167	179	190	
34	1	7	16	25	35	46	57	68	79	90	102	113	125	137	149	161	173	185	197	
35	1	8	16	26	37	47	59	70	82	93	105	117	129	142	154	166	179	191	203	
36	1	8	17	27	38	49	60	72	84	96	109	121	134	146	159	172	184	197	210	
37	1	8	17	28	39	51	62	75	87	99	112	125	138	151	164	177	190	203	217	
38	1	9	18	29	40	52	64	77	90	102	116	129	142	155	169	183	196	210	223	
39	2	9	19	30	41	54	66	79	92	106	119	133	146	160	174	188	202	216	230	
40	2	9	19	31	43	55	68	81	95	109	122	136	150	165	179	193	208	222	237	

Table 12. Mann-Whitney table for a bilateral test.

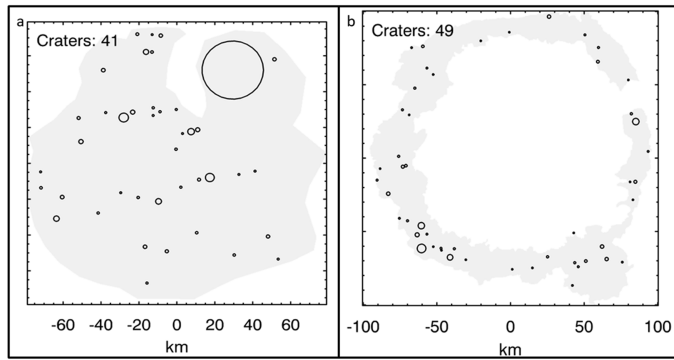
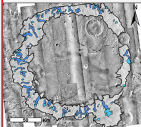


Fig. 21. Map of the count-areas of craters $> 1\text{km}$ in Dawes crater. (a) Dawes crater floor. (b) Dawes crater inner walls.

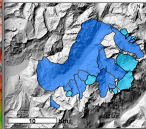
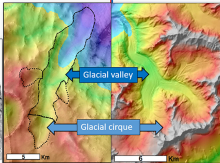
Morphometric evidence of 3.6 Ga glacial valleys and glacial cirques in martian highlands: south of Terra Sabaea

- Early Mars
- Glacial landscape
- Morphometric comparison

- Morphological parameters
- Geometrical parameters
- Comparison with Mars



Dawes crater



Chamonix valley