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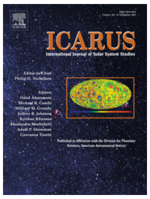

Former extent of glacier-like forms on Mars

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A B S T R A C T

Mars' mid-latitude glacier-like forms (GLFs) have undergone substantial mass loss and recession since a hypothesised last martian glacial maximum (LMGM) stand. To date, there is a lack of knowledge of the nature and timing of the LMGM, the subsequent mass loss and whether this mass loss has been spatially variable. Here, we present the results of a population-scale inventory of recessional GLFs, derived from analysis of 1293 GLFs[3] identified within Context Camera (CTX) imagery, to assess the distribution and controls on GLF recession. A total of 436 GLFs were identified showing strong evidence of recession: 197 in the northern hemisphere and 239 in the southern hemisphere. Relative to their parent populations, recessional GLFs are over-represented in the low latitude belts between 25 and 40° and in areas of high relief, suggesting that these zones exert some control over GLF sensitivity and response to forcing. This analysis is complemented by the reconstruction of the maximum extent and morphology of a specific GLF for which High Resolution Imaging Science Experiment (HiRISE) derived digital elevation data are available. Using Nye's (Nye, J.F. [1951] *Proc. Roy. Soc. Lond, Ser. a—Mat. Phys. Sci., 207,* 554–572) perfect plastic approximation of ice flow applied to multiple flow-lines under an optimum yield strength of 22 kPa, we calculate that the reconstructed GLF has lost an area of 6.86 km^2 with a corresponding volume loss of 0.31 km^3 since the LMGM. Assuming the loss reconstructed at this GLF occurred at all mid-latitude GLFs yields a total planetary ice loss from Mars' GLFs of 135 km^3, similar to the current ice volume in the European Alps on Earth.

1. Introduction

Although water ice is not presently stable across much of Mars' mid-latitudes (Mellon and Jakosky, 1995; Mellon et al., 2004), evidence of pervasive ice-rich landforms between 30 and 60° latitude has been presented (Sharp, 1973; Squyres, 1978, 1979; Lucchitta, 1984; Mangold, 2003; Milliken et al., 2003; Levy et al., 2007; Baker et al., 2010; Dickson et al., 2010; Head et al., 2010; Souness et al., 2012; Hubbard et al., 2014; Brough et al., 2016; Sinha and Murty, 2015). Based on evidence from the Shallow Radar (SHARAD) instrument on board the Mars Reconnaissance Orbiter (MRO), the composition of these ice-rich deposits is consistent with water ice (Holt et al., 2008; Plaut et al., 2009), and their surface morphologies are indicative of viscous flow of that ice (e.g. Squyres, 1979; Mangold, 2003; Head et al., 2005). Collectively, these ice-rich deposits have become known as viscous flow features, or VFFs (Milliken et al., 2003), and are hypothesised to have been formed during a previous 'ice age' as a result of changes in orbital and atmospheric parameters providing preferential conditions for mid-latitude ice accumulation during periods of high (>30°) obliquity (Head et al., 2003; Forget et al., 2006; Madeleine et al., 2009; Fassett et al., 2014). The last major change from a high (~35°) to low (~25°) mean obliquity period occurred ~4–6 Ma BP (Laskar et al., 2004), perhaps causing the end of the hypothesised last martian glacial maximum, or LMGM (Souness and Hubbard, 2013). The persistence of VFFs to the present day is therefore probably due, at least partly, to their ubiquitous debris cover protecting the underlying ice from sublimating into the atmosphere (Bryson et al., 2008; Holt et al., 2008; Plaut et al., 2009; Fastook et al., 2014).

Glacier-like forms (GLFs) are a distinctive subtype of VFFs, similar in planform appearance to terrestrial valley glaciers or debris-covered glaciers (e.g. Arfstrom and Hartmann, 2005; Hubbard et al., 2011; Souness et al., 2012). GLFs form in cirque-like alcoves or valleys and appear to flow downslope, generally coalescing from a wide upper basin to a narrow elongate tongue

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[3] In their inventory Souness et al. (2012) identified 1309 GLFs. We refine the number of GLFs to 1293, due to the identification of duplicate entries.

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that is often confined by raised latero-terminal ridges. GLFs may or may not feed into pre-existing VFFs and form what Head et al. (2006, 2010) described as Mars' integrated glacial landsystem. Following this model, GLFs represent the smallest component of this glacial landsystem and may converge downslope to form broad, rampart-like lobate debris aprons (LDAs). Where LDAs converge or coalesce, complex and contoured surfaces termed lineated valley fill (LVF) are commonly observed (Squyres, 1978, 1979; Lucchitta, 1984).

GLFs and other VFFs (LDA or LVF) have been interpreted as relict remains of once far larger ice masses (Dickson et al., 2008; Sinha and Murty, 2013; Hubbard et al., 2014; Brough et al., 2016), that were most extensive during a hypothesised LMGM (Souness and Hubbard, 2013). For example, in a two-dimensional planform analysis of a GLF in Phlegra Montes, Hubbard et al. (2014) noted a set of pronounced ridges resembling terrestrial moraines, encompassing a texturally distinct 'arcuate' terrain, devoid of many impact craters, in the forefield of a GLF. The contrast between this distinct landform and the wider surface led the authors to suggest that the proglacial arcuate terrain represented a phase of expanded glaciation, and that the GLF had subsequently receded by up to ∼3.3 km. Such an expanded former extent has also been identified on GLFs elsewhere on Mars (Hubbard et al., 2011; Hartmann et al., 2014), as well as on the regional scale of Mars' integrated glacial landsystem (e.g. Head et al., 2006; Dickson et al., 2008; Fastook et al., 2014), where surface lowering of up to ∼900 m has been inferred (Dickson et al., 2008). Indeed, the identification of relict landforms of glacial origin across large areas of Mars has led to inferences of former regional- to continental-scale ice sheet glaciation (Kargel et al., 1995; Hobley et al., 2014; Souček et al., 2015). Furthermore, several studies have noted the superposed relationship of some GLFs to the underlying ice-rich terrain (LDA or LVF) onto which they appear to have flowed, leading to suggestions of recurrent glacial phases with at least one 'local' glacial phase advancing over an earlier 'regional' glaciation (Levy et al., 2007; Dickson et al., 2008; Baker et al., 2010; Sinha and Murty, 2013; Brough et al., 2016). Despite these inferred changes, we currently have limited knowledge of the nature and timing of Mars' LMGM, the volume of ice lost since that time and whether such GLF recession has been spatially variable (e.g. Hubbard et al., 2014).

On Earth, the vast majority of valley glaciers have experienced an expanded former extent, or glacial maximum, and have receded since that time (Zemp et al., 2009; Radić and Hock, 2014; Fischer et al., 2015). The visible imprint of such recession, or in some cases complete deglaciation, is recorded to varying degrees in the geomorphic and sedimentary record. Detailed investigation of these remnant landform and sediment assemblages can therefore be used to reconstruct former glacier limits and thermal conditions (e.g. Kleman et al., 1997; Hambrey and Glasser, 2012). Furthermore, due to their short response times, valley glaciers have become important indicators of climatic change (Hambrey et al., 2005; Raper and Braithwaite, 2009; Carrivick et al., 2015). Thus, if the processes and responses of martian GLFs are broadly equivalent to their terrestrial counterparts, they may represent (i) effective geomorphic agents, through both erosion and deposition, and (ii) important archives of recent climatic change on Mars.

The aim of this paper is to advance our understanding of the glacial history of Mars' GLFs by assessing and quantifying the distribution of, and controls on, GLF recession. Specifically we (i) provide a population-scale inventory detailing the locations of GLFs that show evidence of recession; (ii) analyse the environmental settings of recessional GLFs to assess likely controlling variables on their spatial distribution; and (iii) provide a high-resolution three-dimensional reconstruction of a typical recessional GLF to calculate its volume and area change.

2. Data and methods

2.1. Population-scale recessional GLF inventory

2.1.1. Mapping distribution and morphology

Identification of recessional GLFs was based on analysis of all GLFs in the database of Souness et al. (2012). This database contains the Context Camera (CTX [6 m per pixel]) image ID, coordinate information and basic morphometric and environmental data for all identified GLFs. All GLFs in the database were manually examined by eye using Arizona State University's Mars Image Explorer (http://viewer.mars.asu.edu/) and JMARS software (https://jmars.asu.edu/). GLFs showing evidence of an expanded former extent (Fig. 1) were recorded into a separate database (published as supplementary material to this manuscript) and subsequently imported and plotted, based on the coordinate data of Souness et al. (2012), using ESRI's ArcMap 10.1 Geographic Information System (GIS) software.

2.1.2. Spatial distribution

To determine what, if any, controls are responsible for the observed spatial distribution of recessional GLFs, several environmental parameters were extracted and analysed. These include latitude (°), longitude (°), elevation (m relative to Mars datum), relief (m) and orientation (°). Following Souness et al. (2012) relief was calculated as the standard deviation of elevation values extracted from a 5 km radius buffer from the GLF's head. As well as plotting recessional GLF counts against these variables, both the recessional GLF population and the total GLF population were normalised against their total counts (436 and 1293, respectively), and the subsequent normalised ratio of recessional GLFs relative to total GLF population plotted to evaluate the relative abundance of recessional GLFs (with a ratio >1 indicating over-representation and <1 indicating under-representation).

The normalised ratio plots for global and hemispheric GLF coverage are presented herein. The global and hemispheric recessional GLF counts can be found in the accompanying supplementary material to this manuscript (Figs. S1–S4).

2.2. Case study: Crater Greg GLF reconstruction

The presence of overlapping High Resolution Imaging Science Experiment (HiRISE) satellite imagery allows high-resolution digital elevation models (DEMs) to be created (e.g. Kirk et al., 2008). Here we utilise a 2 m per pixel DEM (stereo pair PSP_002320_1415_RED and PSP_003243_1415_RED [see Hubbard et al., 2011 for details]) and corresponding orthorectified HiRISE image, with a resolution of ∼0.25 m per pixel, to reconstruct the former extent of a well-studied GLF (e.g. Hartmann et al., 2003; Marchant and Head, 2003; Milliken et al., 2003; Kargel, 2004; Hubbard et al., 2011 [Fig. 2d]).

2.2.1. Study site

Our case study reconstruction is based on the analysis of a GLF located in Crater Greg, eastern Hellas Planitia (Fig. 2). This crater is located in a climatically important zone with global climate models suggesting that it was positioned in one of two regions of high ice deposition outside of the polar ice-caps during periods of high obliquity (Forget et al., 2006; Hartmann et al., 2014).

Several lobate tongues classified as GLFs are located on the northern wall of Crater Greg (Arfstrom and Hartmann, 2005; Hubbard et al., 2011; Souness et al., 2012; Hartmann et al., 2014 [Fig. 2c]). The GLF studied herein (Fig. 2d), is ∼4 km long and ∼1–2 km wide, extends down-slope at an angle of ∼10°, and according to Hartmann et al. (2014) is likely younger than ∼50 Ma BP, with a best estimate of ∼2–9 Ma BP. Several arcuate ridges