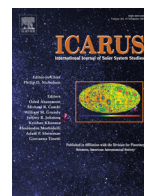




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Ice-rich (periglacial) vs icy (glacial) depressions in the Argyre region, Mars: a proposed cold-climate dichotomy of landforms

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ABSTRACT

On Mars, so-called “scalped depressions” are widely observed in Utopia Planitia (*UP*) and Malea Planum (*MP*). Typically, they are rimless, metres- to decametres-deep, incised sharply, tiered inwardly, polygonised and sometimes pitted. The depressions seemingly incise terrain that is *icy* and possibly thermokarstic, i.e. produced by the thermal destabilisation of the icy terrain. Agewise, the depressions are thought to be relatively youthful, originating in the Late Amazonian Epoch.

Here, we report the presence of similar depressions in the Argyre region (*AR*) (30–60° S; 290–355° E). More importantly, we separate and differentiate these landforms into two groups: (*ice-rich*) periglacial depressions (Type-1); and, (*icy*) glacial depressions (Type-2a-c). This differentiation is presented to the Mars community for the first time.

Based on a suite of morphological and geological characteristics synonymous with *ice-complexes* in the Lena Peninsula (eastern Russia) and the Tuktoyaktuk Coastlands (Northwest Territories, Canada), we propose that the Type-1 depressions are *ice-rich* periglacial basins that have undergone volatile depletion largely by sublimation and as the result of thermal destabilisation. In keeping with the terms and associated definitions derived of terrestrial periglacial-geomorphology, *ice-rich* refers to permanently frozen-ground in which ice lenses or segregation ice (collectively referenced as *excess ice*) have formed.

We suggest that the depressions are the product of a multi-step, cold-climate geochronology:

- (1) Atmospheric precipitation and surface accumulation of an *icy* mantle during recent high obliquities.
- (2) Regional or local triple-point conditions and thaw/evaporation of the mantle, either by exogenic forcing, i.e. obliquity-driven rises of aerial and sub-aerial temperatures, or endogenic forcing, i.e. along Argyre impact-related basement structures.
- (3) Meltwater migration into the regolith, at least to the full depth of the depressions.
- (4) Freeze-thaw cycling and the formation of *excess ice*.
- (5) Sublimation of the *excess ice* and depression formation as high obliquity dissipates and near-surface ice becomes unstable.

The Type-2 depressions exhibit characteristics suggestive of (*supra-glacial*) *dead-ice basins* and *snow/ice suncups* observed in high-alpine landscapes on Earth, e.g. the Swiss Alps and the Himalayas. Like the Type-1 depressions, the Type-2 depressions could be the work of sublimation; however, the latter differ from the former in that they seem to develop within a glacial-like *icy* mantle that blankets the surface rather than within an *ice-rich* and periglacially-revised regolith at/near the surface.

Interestingly, the Type-2 depressions overlie the Type-1 depressions at some locations. If the periglacial/glacial morphological and stratigraphical dichotomy of depressions is valid, then this points to recent glaciation at some locations within the *AR* being precursed by at least one episode of periglaciation. This also suggests that periglaciation has a deeper history in the region than has been thought

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hitherto. Moreover, if the hypothesised differences amongst the Argyre-based depressions are mirrored in Utopia Planitia and Malea Planum, then perhaps this periglacial-glacial dichotomy and its associated geochronology are as relevant to understanding late period landscape-evolution in these two regions as it is in the AR?

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1. Introduction

On Mars so-called “scalped depressions” are widely observed in both hemispheres, i.e.: Utopia Planitia (*UP*), one of the great northern-plains (Costard and Kargel, 1995; Seibert and Kargel, 2001; Morgenstern et al., 2007; Soare et al., 2007, 2008, 2009; Lefort et al., 2009a; Séjourné et al., 2011, 2012; Ulrich et al., 2010); and, Malea Planum (*MP*), a large volcanic plain at and below the southern rim of the Hellas basin (Lefort et al., 2009b; Zanetti et al., 2010; Willmes et al., 2012). Typically, they are rimless, metres- to decametres-deep, incised sharply, tiered inwardly, polygonised and sometimes pitted. The depressions are thought to: a) have formed in the very Late Amazonian Epoch, given the sharpness of their incision, the highly-muted terrain in which they occur, and sparse cratering; b) reside in icy terrain; and, c) be thermally destabilised and ice-depleted – *thermokarstic* – as the result of near-surface and obliquity-driven ice instability (Costard and Kargel, 1995; Morgenstern et al., 2007; Soare et al., 2007, 2008, 2009; Lefort et al., 2009a,b; Zanetti et al., 2010; Ulrich et al., 2010; Willmes et al., 2012). Similar depressions are observed in and around the Argyre impact-basin region (*AR*) in the southern hemisphere (30–60° S; 290–355° E). Some workers suggest that this is a region where near-surface water ice and surface liquid-water could be metastable even under current conditions (Haberle et al., 2001; Zent et al., 1986, also, Hecht et al., 2002).

In the Lena Peninsula (eastern Russia) (e.g. Schirrmeister et al., 2002, 2013; Grosse et al., 2007) and the Tuktoyaktuk Coastlands (Northwest Territories, Canada) (e.g. Washburn, 1973; Mackay, 1979; Murton, 1996; Dallimore et al., 2000; Hill et al., 2001; French, 2007) depressions of the type observed in the *AR*, as well in *UP* and *MP*, often occur in *ice-complexes*. These complexes or landform assemblages are: *ice-rich* (i.e. containing *ice lenses* and *segregation ice*, collectively referenced as *excess ice*, from metres to decametres of depth); incised by ice-wedge polygons and polygon trough/junction ponds or pits; punctuated by thermokarstic-terrain (i.e. terrain underlain by excess ice) and rimless depressions or *alases* (where the excess ice has been lost by evaporation or drainage) (e.g. Schirrmeister et al., 2002, 2013; Grosse et al., 2007).

Other depressions in the *AR* show morphologies and traits similar in some ways to those presented above; however, they are distinguishable by the absence of polygonisation, trough/junction pits and inward-oriented terraces and the presence of sharp rims (in some instances), bowl-like shape and dense honeycomb-like clustering. Collectively, this second group of depressions is suggestive of *supra-glacial lake basins* and of *snow/ice suncups* as observed, for example, in the Swiss Alps (Kääb and Haeberli, 2001; Paul et al., 2007) and the Himalayas (Benn et al., 2000; Reynolds, 2000).

Supra-glacial lakes occur in debris-covered *dead-ice* (ice that has been decoupled from an originating glacier) (Kääb and Haeberli, 2001); here, irregularly-shaped crevasses formed by the stress of glacial advance and retreat fill with water, derived of melted snow or ice, and evolve into small metres-deep lakes that are metres to decametres in (long-axis) diameter (Kääb and Haeberli, 2001). Meltwater drainage or evaporation exposes floor or basin morphologies similar to those associated with the second group of Mars depressions. Small-sized polygons have not been re-

ported in the terrain adjacent to the *dead-ice lakes* or *basins* on Earth.

Suncups comprise sharply-narrow and sub-metre high ridges separated by smoothly-concave sub-metre bowls or hollows (Betterton, 2001; Herzfeld et al., 2003); it is thought that they form by the differentiated albeit highly-localised ablation (sublimation or evaporation) of dirty vs clean snow (Betterton, 2001; Herzfeld et al., 2003; Mitchell and Tiedje, 2010).

In this article we have three main aims:

- (1) Map the distribution of (Fig. 1) and describe the polygonised, tiered and sometimes-pitted depressions in the *AR*, defined as Type-1 depressions (Fig. 2); discuss their morphological and geological synonymy with the thermokarst terrain on Earth where *ice-complexes* are observed (Fig. 3); and, propose a possible periglacial-origin for these depressions.
- (2) Map the distribution of (Fig. 1) and describe morphologically similar but unpolygonised, untiered and unpitted Type-2 depressions in the region (Fig. 4); we propose that these depressions are glacial in origin and analogous to alpine *dead-ice lake* basins and *suncups* on Earth (Fig. 5).
- (3) Hypothesise that an endogenic influence could be responsible, at least in part, for the thermal de-stabilisation required to form the Type-1 depressions.

Numerous studies have identified landforms in the *AR* during the Late Amazonian Epoch that could have been formed by water-based freeze-thaw cycling: a) clastically sorted, small-sized ($\leq \sim 25$ m in diameter) polygons (Banks et al., 2008; Soare et al., 2016); b) clastically unsorted, small-sized and low-centred polygons (Soare et al., 2014a); c) (possible) hydraulic or open-system pingos (Soare et al., 2014b,d) gelifluction-like lobes (Johnsson et al., 2015; Soare et al., 2015,2016). The proposed dichotomy of landforms and associated geochronology presented here is consistent with this premise and underlines the extent to which relatively-recent boundary conditions in the *AR* might have been less uniformly cold and dry, perhaps even to the present day, than is generally thought.

2. Definition of key periglacial terms

The proposed differentiation of periglacial from glacial depressions in the Argyre region can be meaningful only in as much as the key referential or framing terms are identified and then defined clearly. Towards this end, the generally-accepted usage of these terms in terrestrial geology and periglacial-geomorphology is our benchmark. We recognise that some workers in the Mars community of planetary scientists believe that the relevance and viability of definitions derived of terrestrial systems or landscapes is contingent upon their adaptation to the Martian context (e.g. Byrne et al., 2009; Dundas et al., 2015; Sizemore et al., 2014). However, until a discrete and thorough discussion on appropriate periglacial-terms and -definitions for Mars appears in the scholarly literature, deference to the current lexicon of terrestrial geology and periglacial-geomorphology might be the most prudent course to plot.

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