Geogr. Fis. Dinam. Quat.
40 (2017). 19-27, 3 figg.

DOI 10.4461/GFDQ.2017.40.2

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AMAZONIAN THERMOKARST WITHIN A TROUGH OF NOCTIS LABYRINTHUS, MARS

Abstract: Baioni D., Tramontana M. & Murana A., *Amazonian thermokarst within a trough of Noctis Labyrinthus, Mars.* (IT ISSN 0391-9839, 2017).

This paper describes the possible ice-related landforms observed on the floor of a trough located in the western part of Noctis Labyrinthus, centred at -6.8° S, 98.9° W, in the equatorial region of Mars.

A morphological survey of the study area and of the landforms was investigated through an integrated analysis of Mars Reconnaissance Orbiter (MRO) High Resolution Imaging Science Experiment (HiRISE) and Context Camera (CTX) data.

The analysis highlighted the presence of landforms interpreted as being due to thermokarst processes, resembling similarly ice-related landforms found both in the cold-climate non-glacial regions of Earth and in other areas of Mars.

These landforms, which are attributed to melting processes of ground ice, suggest significant climatic changes and climatic conditions differing from those existing now. Moreover, they appear to display young erosional age, suggesting that they are probably of Amazonian age.

Key Words: Thermokarst, Noctis Labyrinthus, climate changes, Amazonian, Mars

INTRODUCTION

Mars is currently a hyperarid, hypothermal desert and its largest reservoirs of surficial water ice are located at the poles (Bibring & *alii*, 2004). However, general atmospheric circulation models suggest that ice migrates directly to the near-equatorial regions during periods of higher obliquity (Levrard & *alii*, 2004; Chamberlain & Boynton, 2007). In particular, climate models have shown that near-equatorial glaciation could be induced episodically as Mars reaches high obliquities (Forget & *alii*, 2006; Head & *alii*, 2003, 2006).

Studies based on the Mars Global Surveyor and Mars Odyssey data have identified both stratigraphical evidence of glaciation and periglaciation (Soare & Osinski, 2009; Soare & *alii*, 2012) and a landscape assemblage consistent with periglacial activity (Soare & *alii*, 2008) in non-polar regions of Mars.

Analysis of the most recently acquired high-resolution satellite images provided evidence for the possible presence of ice in the planet's tropical and equatorial regions (Megè & Bourgeois, 2011; Shean, 2010), and features attributed to present or previous permafrost or ground-ice-related processes at low latitudes and/or equatorial areas of the planet have been identified (Balme & Gallangher, 2009; Megè & Bourgeois, 2011; Warner & *alii*, 2010).

Canyon troughs, as well as impact craters, are useful targets for the identification of periglacial features because their interiors function as cold traps, shielding volatile elements from the ablative effects of insolation or wind and preserving icy bodies that would otherwise be removed in an open plain (Levy & *alii*, 2009; Shean, 2010).

Noctis Labyrinthus (denoted as NL hereafter) (fig. 1) is an intricate system of Late Hesperian and early Amazonian linear troughs and rounded pits connecting the Tharsis volcanic rise and western Valles Marineris (Tanaka & *alii*, 2014; Rodriguez & *alii*, 2016). We focused our study on a trough located in the western part of NL (fig. 1A and 1B), centred at -6.8° S, 98.9° W, approximately 60 × 50 km in size and with a depth of 5 km below the adjacent plateau (Weitz & *alii*, 2013). The north-western part of the trough floor (fig. 1C and 1C1) is characterized by chaotic terrain (Weitz & *alii*, 2013), where the widespread presence of shallow depression morphologies that display different shapes and sizes, whose origin is still unknown, can be observed.

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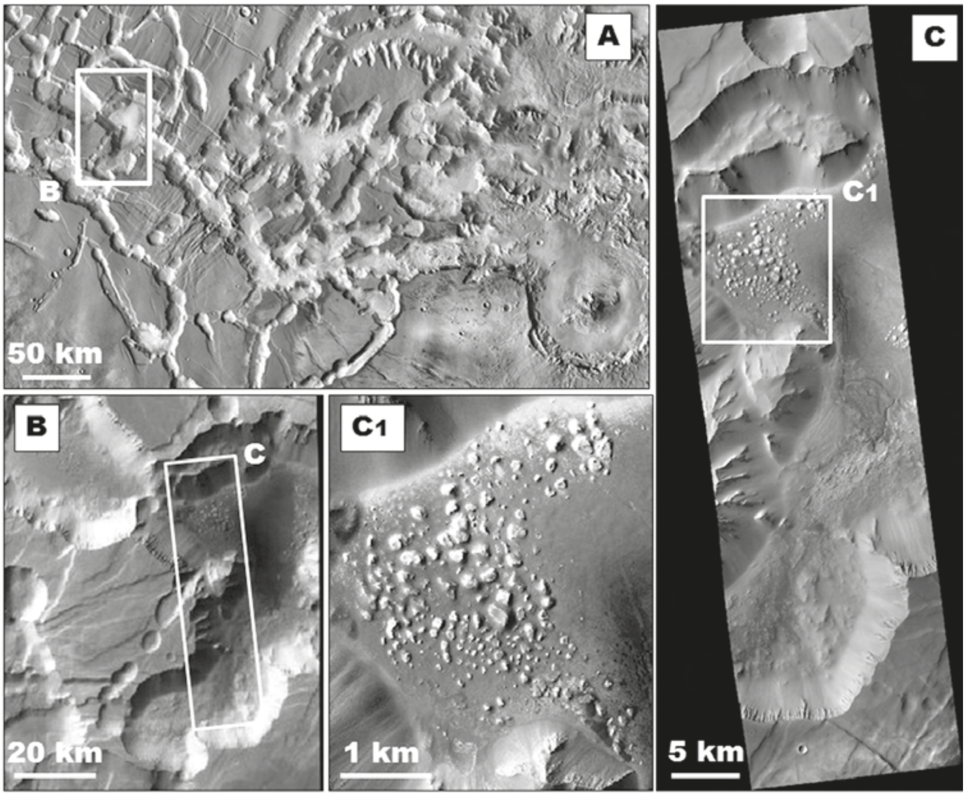

FIG. 1 - A) Image of Noctis Labyrinthus, Mars, with the location of the trough object of the study (white box) (image THEMIS daytime IR mosaic modified by Weitz et al., 2013) (north toward up). B) Image of the trough object of the study. Image (modified) HRSC ID:H3155_0000_ND3 taken from the website http://viewer.mars.asu.edu (north toward up). C) Location of the study area (white box) within the trough in western NL (image CTX ID:G03_019311_1728_XN_07S099W) (north toward up). C1) Image of the study area located in the north-western part of the trough (image CTX ID:G03_019311_1728_XN_07S099W) (north toward up).

The goals of this study were to describe, for the first time, these morphologies located in the north-western area floor of this trough of NL and to investigate their possible origins and paleoclimatic significance.

Landform features were investigated through an integrated visual analysis of data from the Mars Reconnaissance Orbiter (MRO) High-Resolution Imaging Science Experiment (HiRISE) (McEven & *alii*, 2007) and the Context Camera (CTX) (Malin & *alii*, 2007). The CTX images analysed (B20_017610_1731_XN_06S099W; B21_017966_1731_XN_06S099W; G03_019311_1728_XN_07S099W; G03_019522_1728_XN_07S099W) have a spatial resolution of 6 m per pixel, and the HiRISE images analysed (PSP_007101_1730; PSP_008393_1730; ESP_017610_1730; ESP_018533_1730) have a spatial resolution ranging between 26 and 26.2 cm per pixel (objects between 78 and 79 cm across are resolved). HiRISE images (including enhanced RGB, IRB, and derived stereo anaglyph images) give enough detail to observe even small characteristics of the landforms.

STUDY AREA

NL (fig. 1A), on the eastern edge of the Tharsis Plateau, consists of a network of intersecting valleys that merge and coalesce with pit chains and larger troughs connecting the Tharsis volcanic rise and the western Valles Marineris. This intricate system of Late Hesperian and Early Amazonian linear troughs and rounded pits (Tanaka & Davis, 1988; Tanaka & *alii*, 2014) distributed in alignment with pre-existing faults and grabens oriented concentrically and radially to the elevated volcanic plains of Syria Planum is unique in that it constitutes the only Valles Marineris boundary terrain thought to retain collapsed structures produced by groundwater-flow-induced conduit formation (Tanaka & Davis, 1988; Witbeck & *alii*, 1991) or alternatively by the withdrawal of subsurface magmatic reservoirs (Mège & *alii*, 2003). A very recent study (Rodrigues & *alii*, 2016) showed that NL retains geologic evidence of conduit development associated with structurally controlled groundwater flow through salt-rich upper crustal deposits, consistent with aquifer drainage from the Tharsis volcanic rise region.

The trough investigated in this paper (fig. 1B and 1C), is located in the western part of NL, centred at 6.81° S, 98.89° W, and is approximately 60 × 50 km in size with a depth of 5 km below the adjacent plateau (Weitz & *alii*, 2013). The trough floor is characterized mainly by fissure vents and hummocky lava flows (Weitz & Bishop, 2011); the age of these lava flows, which display a pyroxene-rich mineralogy, is thought to be Late Amazonian (Mangold & *alii*, 2010).

The north-western part of the trough (fig. 1C1) is a flat area 2 km below the plateau that represents a break in the slope along the wall rock. It is surrounded by chasma walls on the north, south, and west sides, while on the east side it is cut by a deep slope because part of the original floor of the trough was lowered by an additional collapse and widened to the current floor depth (Weiz & *alii*, 2013).

This flat area is characterized by the presence of mesas displaying tilted and sloped tops and by mounds comprising chaotic terrain that seems to be covered by more dust and/or aeolian debris (Weitz & *alii*, 2013).

At the base of several mesas and exposed between them, light-toned and sometimes layered deposits can be observed. Some of these deposits display Al-phyllosilicates and/or hydrated silica spectra extracted from CRISM data, while other light-toned units lack spectral features that might enable identification of their mineralogical composition (Weitz & *alii*, 2013). These layered and light-toned materials are interpreted to represent relatively older sediments deposited within the trough and it is likely that they are more extensive at depth than the exposures that can be observed along the surface. Younger lava flows cover much of the trough floor, burying the light-toned layered materials and embaying the mesas (Weitz & *alii*, 2013).

Moreover, a unit characterized by polygonal fracturing, for which CRISM spectra show no diagnostic features or hydrated signatures, can be observed. The lighter reflectance and the type of fracturing of this unit appear to be uncharacteristic of lava flows, resembling, from the morphological point of view, features seen in association with hydrated units on Mars (Weitz & *alii*, 2013).

In this area, the widespread presence of depressions of different shapes and sizes that display marked differences from the impact craters from the morphological point of view can be observed. These landforms, on which this work focuses, are described below.

MORPHOLOGICAL ANALYSIS OF NL DEPRESSION FEATURES

The present morphological analysis revealed the presence of many shallow rimless depressions of various sizes and shapes. These depressions are closed, surrounded entirely by unbroken plains (figs. 2 and 3), and unrelated to geological units.

The depressions display a variety of plan forms ranging from rounded (figs. 2A, 2D, 2E), elliptical (figs. 2B, 3D), elongated (fig. 3E), and polygonal (fig. 3A) to drop-like (fig. 3B). Some depressions display typical coalescence with a rounded-elongated outline (fig. 2C). These depressions display generally well-defined continuous margins that often appear sharp (figs. 2A, 2B, 2D, 3B), showing very little or no sign of erosion or slumping, while a few cases display signs of moderate erosion (figs. 3A, 2A, 2D, 2E). The depressions have both symmetrical and asymmetrical sides with very steep sloping to vertical walls. The sides appear

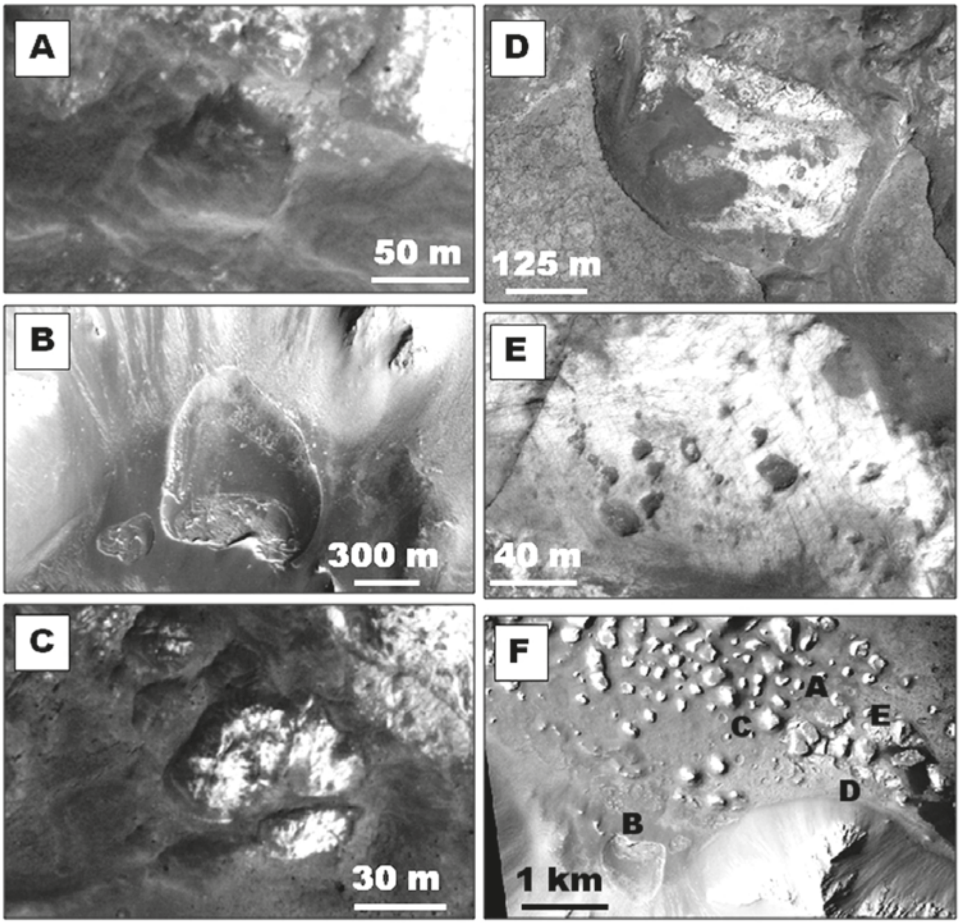

FIG. 2 - A) Rounded depression displaying asymmetrical sides located in the central part of the study area (HiRISE PSP_007101_1730) (north toward up). B) Elliptical (center) and rounded (left) depressions showing very steep sides and flat bottom located in the southern part of the study area (CTX_B20_017610_1731_XN_06S099W) (north toward up). C) Rounded depressions displaying coalescence located in the central part of the study area (HiRISE PSP_007101_1730) (north toward up). D) Rounded depression displaying steep sides and flat bottom slighty shifed toward one side, located in the central part of the study area (HiRISE PSP_007101_1730) (north toward up). E) Rounded and elliptical depressions located in the central part of the study area (HiRISE PSP_007101_1730) (north toward up). F) Location of the depressions shown in the images A-F (CTX_B20_017610_1731_XN_06S099W) (north toward up).

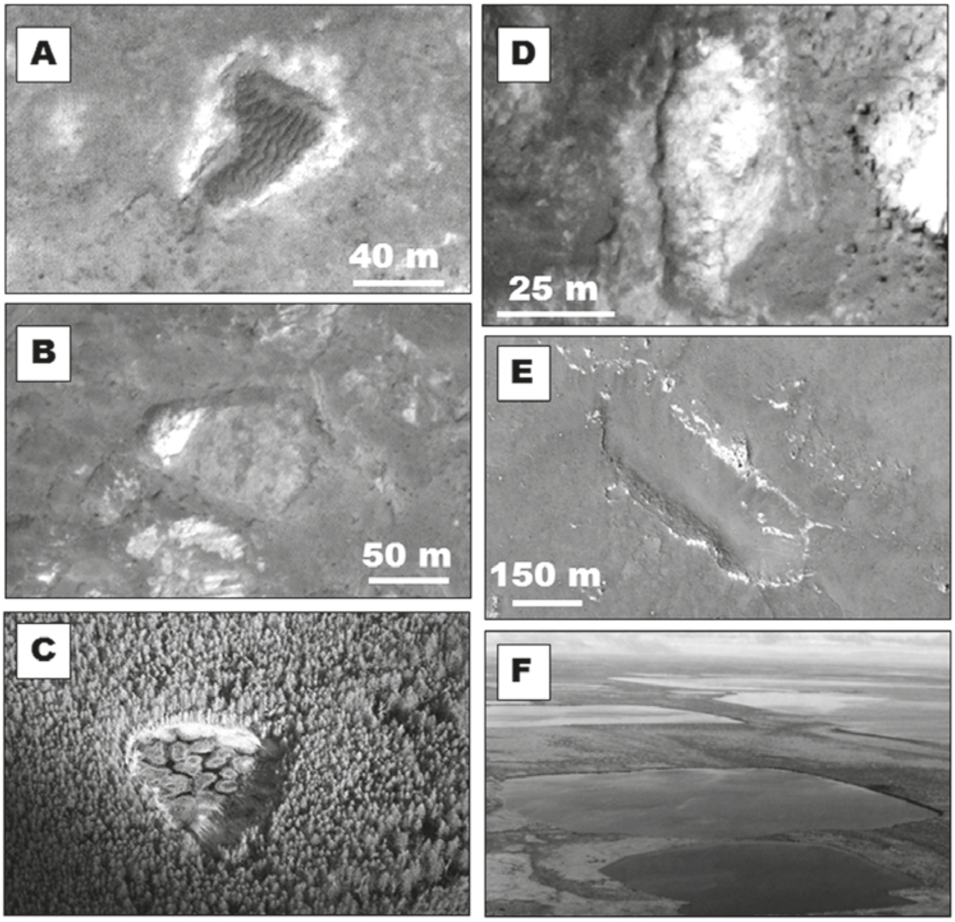

FIG. 3 - A) Polygonal depression located in the northern part of the study area (HiRISE_PSP_007101_1730) (north toward up.) B) Drop-like shaped depression located in the northern part of the study area (HiRISE PSP_007101_1730) (north toward up). C) Thermokarst lake located in the Lena Pillars Nature Park. Sakha Republic (Yakutia), Russian Federation. Image (modified) taken from the website http://whc.unesco.org/en/list/1299/gallery/. D) Elliptical depression located in the central part of the study area (HiRISE PSP_007101_1730) (north toward up). E) Elongate depression located in the eastern part of the study area (HiRISE ESP_018533_1730) (north toward up). F) Thermokarst lake located in the Old Crow Flats, northern Yukon, Canada. Image (modified) taken from the website http://pascale-royleveillee.ca/.

to lack slope processes and fan deposits at the foot and do not display stepped or terraced morphology. The floors are apparently flat and show different characteristics with regard to the accumulation of sediment (e.g. dust, sand). In fact, the floors generally lack well-developed systems of dune morphology, which can be observed in only a few depressions (fig. 3A). In some cases, the floor appears slightly shifted toward one side of the depression (fig. 2D).

Depressions range in length (long axes of the depressions defined by the outermost closed contour line) from 60 to 700 m for elongated and elliptical forms, from 20 to 500 m for more rounded forms, and from 66 to 120 m for other forms.

Widths generally range from 28 to 300 m for elliptical and elongated shapes, from 14 to 325 m for rounded shapes, and from 50 to more than 60 m for other forms. The major axes show very different orientations: N-S and ranging from NE-SW to NW-SE and NNW-SSE to NNE-SSW. These orientations appear to be unrelated to the location or shape of the depression.

Additionally, the main morphometric parameters such as the area, perimeter, and elongation index were calculated. The perimeters of the depressions, calculated on their contours, range between 50 and 1,350 m, while their areas, calculated as the measurement of the planimetric surface bordered by the perimeter, range from 300 to more than 84,000 m^2. The elongation index (Morgastern & *alii*, 2011), expressed as the ratio between the longest axis and the perpendicular width, displays values ranging from 1.789 to 2.756 for elliptical and elongated forms, from 1.222 to 1.538 for rounded forms, and from 1.095 to 1.501 for other forms.

DISCUSSION

Origin interpretation

Given the observed data and the detailed analysis of their features and of the landscape within the geological context, we interpreted these morphologies as possible thermokarst depressions.

The morphology of these landforms displays morphological convergence with the thermokarst depressions located in cold regions of the Earth such as Alaska, Siberia (fig. 3C) and northern Canada (fig. 3F), where the thawing of permafrost often involves the formation of flat-floored rimless depressions with stepped sides and sometimes ponded meltwater. In particular, they display morphometric (sizes) and morphologic (shapes, bottoms, walls) similarities with thermokarst-induced steep-sided flat-bottomed depressions that have lost their water (French, 2007;

Washburn, 1973), which are common on periglacial or glaciofluvial terrains (Costard & Kargel, 1995; Czudek & Demek, 1970).

Moreover, they also resemble the thermokarst depressions observed recently in central NL (Rodrigues et al., 2016) and by previous works in other regions of Mars such as northern Sinus Meridiani (Baioni & Sgavetti, 2013), Utopia Planitia (Morgasten & *alii*, 2007; Soare & *alii*, 2008, 2013), western Elysium Planitia (Soare & *alii*, 2007), Astapus Colles region (Soare & *alii*, 2009), and other areas (Costal & Kargel, 1995; Pacifici & *alii*, 2009; Warmer & *alii*, 2010; Baioni & *alii*, 2014).

The development of landforms related to liquid water on Mars could have been triggered by the melting of ice and/or permafrost thaw or alternatively by the structural delivery of water to the surface.

The study area lacks morphological features and topography that could suggest the presence of sapping processes due to structural control and/or hydrothermal activity, and therefore the observed depressions appear to have formed as a result of ice melting, in a manner analogous to the development of similar landforms on Earth (Brewer & *alii*, 1993; Brouchkov & *alii*, 2004; Federov & Konstantinov, 2003; French, 2007; Washburn, 1973). Ice melting and/or permafrost thaw has been assumed to be necessary for subsidence and/or collapse processes, similarly to hypothesized processes explaining thermokarst landforms and topography found also in the equatorial regions of Mars (Warner & *alii*, 2010, Baioni & *alii*, 2014) and in the periglacial regions of the Earth such as Siberia (Czudek & Demek, 1970; Morgenstern & *alii*, 2011) and Alaska (Burn & Smith, 1990; French, 2007; YoshiKawa & Hinzman, 2003; Osterkamp & *alii*, 2000).

Moreover, non-sorted and small-sized polygons that exhibit no apparent affiliation with any one geological unit can be observed. These polygons, which are particularly evident next to some depressions, on the Earth as on Mars, are diagnostic features of periglacial activity (Kerrigan & *alii*, 2012; Singleton & *alii*, 2012; Soare & *alii*, 2012; Mellon & *alii*, 2014; Haltigin & *alii*, 2014) and are often associated with thermokarst depressions (Soare & Osinski, 2009; Soare & *alii*, 2014).

The thermokarst landforms are generally well preserved and do not seem to be reworked or modified, even by wind erosion, lacking ventifacts and displaying mostly sharp and continuous margins, suggesting a young erosional age. Moreover, HiRISE images of the depressions show no superimposed impact craters.

The small differences observed in the amount of erosion of the depression margins and in the amount of dust or sediment within the depressions do not appear to be related to depression location. Nor do they appear to be related to aeolian erosion and deposition processes, which would be unlikely to vary markedly among depressions in close proximity, as was observed in the study area. Instead, we suggest that the differences may be due to variations in age among depressions. Older depressions exposed to aeolian deposition for a longer period of time might demonstrate more degraded margins and slopes and much more sediment accumulation on the floor, forming complex dune morphology systems.

The above hypothesis suggests that morphogenetic processes persisted over time and that the melting processes were not as short lived.

ALTERNATIVE FORMATION HYPOTHESES

Several hypotheses can be proposed to explain the origin of these depressions found in this trough of NL. The main possible formation mechanisms for these morphologies, which have previously been discussed in the literature, are described by the following hypotheses.

Impact craters

The features of the depressions are the best evidence to ruled out their formation as eroded or softened impact craters. In fact, the depressions display a variety of plan forms, such as lobate, elongate, drop-like and polygonal, that cannot be shaped by an impact that instead shapes depressions that are bowl-shaped and characterised by a circular plan form (De Pablo & Komatsu, 2009). They lack raised rims and ejecta, and it is unlikely that all the possible rims and ejecta deposits have been totally destroyed and/or cancelled by the erosion processes. Several authors have investigated changes in Martian crater morphology through the advanced stage of modification due to erosion processes (Forsberg-Taylor & *alii*, 2004; Watters & *alii*, 2015). When rims are removed completely due to erosion and back-wasting processes, the crater fills with a deposit having a generally parabolic or super-parabolic cross-section (Forsberg-Taylor & *alii*, 2004; Watters & *alii*, 2015), and the crater walls show a decrease of the average interior slope (Craddock & *alii*, 1997). In contrast, the depressions observed here do not display these features and instead have smaller, flat floors and steep or vertical walls. Moreover, the origin as ring-mold craters (RMC) can be ruled out by the features of the depressions. In fact, RMCs comprise a suite of craters with unusual morphologies that have as yet been identified only on lineated valley fill, lobate debris aprons, and concentric crater fill in the northern and southern mid-latitudes of Mars. RMCs are generally rimless and consist of an outer annular trough surrounding a variety of interior morphologies such as central pit, tabular plateau, bowl with central peak, bowl with tabular plateau, and double bowl (Kress & Head, 2008). Here, the depressions observed do not display any of these features.

Volcanic or tectonic processes

The analysis of the landforms suggests that their formation by volcanic processes can be ruled out, due to the absence of any volcanic morphology in this part of the chasma. Volcanic pit craters occur within collapsed magma chambers and/or lava tubes displaying the linear array of the craters (Soare & *alii*, 2007). The depressions in the study area do not follow any particular pattern of orientation.

Pit craters due to tectonic processes occur within graben systems and/or near areas that display extensional features such as fault lines (Soare & *alii*, 2007), and linear arrays of circular to elliptical depressions. The area investigated is not characterised by these features, and the depressions in the study area do not follow any orientation or circular pattern, ruling out this hypothesis.

Aeolian processes

The depressions lack a dominant orientation (the distribution of the major axis orientations shows different orientation peaks), which rules out formation by wind deflation. In particular, the orientations of the major axes of the depressions, in directions, ranging from NE-SW to NW-SE, NNW-SSE to NNE-SSW, and N-S, appear to rule out this hypothesis. Moreover, depressions shaped by wind action on the Earth, called blowouts (a bowl shaped hollow, a slight depression caused by deflation) (Neuendorf & *alii*, 2005), are very elongated along the wind flow direction, have very elliptical shapes, arcuate sides and thicker accumulations of sediments at the foot of the wall facing the wind. The depressions observed do not display any of these features, but conversely demonstrate totally different features from those normally created by wind action.

Groundwater sapping

Formation of depressions through groundwater-related processes, in which subsurface water breached the surface during occasional upwelling events, can be ruled out by the morphological features of the landforms which lack of outflow channels and are surrounded entirely by unbroken plains. In fact, the shaping of these morphologies implies very high erosion rates and the removal of a huge amount of material so as to achieve the present configuration of the depressions. A water flow to shape these depressions would need to be so powerful that it should leave a deep and wide outflow channel. Visual inspection highlights that any of the depressions have outflow channels. Moreover, the eroded material would have been deposited somewhere on the floor, and such deposits are absent.

Formation of depressions through melting processes driven by hydrothermal activity can also be ruled out by the morphology of the surrounding terrain. In fact, the geothermal melting process within the permafrost produces a substantial amount of water close to the surface that may erupted out of the ground (Ogawa & *alii*, 2003). It is expected that such an eruptive flow event would catastrophically release subsurface water accompanied by the collapse and disruption of the overlying surface, forming outflow channels and chaotic terrain (Ogawa & *alii*, 2003; El Maarry & *alii*, 2012). Here, any of these morphologies can be observed.

Karst processes

On the Earth is very difficult to identify the differences between karst and thermokarst landforms through remote sensing analysis. The karst origin can be ruled out here mainly because the rocks analysed display spectra of Al-plyllosilicates and hydrated silica which do not allow solutional processes.

THERMOKARST AND CLIMATE

The landform features observed appear to reflect ice- and/or water-related processes.

Regarding the origin of the ice, we believe that changes in Martian obliquity might be key to the construction of a plausible scenario to explain the landforms observed in the study area.

Theoretical considerations on the stability of water ice and numerical climate simulations, however, predict that areas of surface ice accumulation may have shifted repeatedly between polar, middle, tropical, and equatorial latitudes in the past in response to changes in Martian orbital and atmospheric characteristics (Forget & *alii*, 2006; Jakosky & Carr, 1985; Madeleine & *alii*, 2009; Wordsworth & *alii*, 2013). Some of these simulations predict that net ice accumulation rates might have been higher than 20 mm/y at places along the Martian equator under Amazonian physical conditions based on the present-day composition of the atmosphere (Madeleine & *alii*, 2009) and under other physical conditions that might have prevailed earlier (Wordsworth & *alii*, 2013).

The presence of ice in the planet's tropical regions and near-surface ground ice features near to and at the equator has been hypothesized or described (Burr & *alii*, 2005; De Blasio, 2011; Gourronc & *alii*, 2014; Mège & Bourgeois, 2011; Hynek, 2009; Shean, 2010), and the occurrence of permafrost processes in the equatorial regions of Mars has been documented (Warner & *alii*, 2010).

In the study area, the formation of the ice-rich permafrost was probably facilitated by the presence of sediments deposited on the chasma floor. In fact, permafrost formation would have required the presence of ice or shallow groundwater and sediments, just as occurs on the Earth (Soare & *alii*, 2007, and references therein).

Three possible explanations for the formation of permafrost and thermokarst in the study area can be proposed: (i) Recent high obliquities could have transported water-ice atmospherically from the north Martian pole with consequent accumulation of ice on the chasma ground. Subsequently, the change of climatic conditions led to thawing of the ice-rich permafrost and the formation of the thermokarst depressions; (ii) The rising of the subsurface water level, which did not reach the surface, provided the conditions for the formation of ice-rich permafrost when a change in the planet's obliquity caused reductions of temperature and atmospheric pressure. Subsequently, another change of climatic conditions led to thawing of the ice-rich permafrost and the formation of the thermokarst depressions; (iii) The melting of near-surface ground ice occurred in the surrounding landscape. An initially high temperature associated with high obliquity could have induced the melting of ground ice in the area surrounding the north-western part of the chasma, leading to the deposition of water and sediments from the chasma slope and the other higher areas of the chasma in this flat area. Surface aqueous flow, the existence of which is indicated by the presence of channels with characteristic meander pattern along the trough walls (Weiz & *alii*, 2013), provided near-surface groundwater and sediments necessary for permafrost formation. The reductions of temperature and atmospheric pressure due to a change in the planet's obliquity led to the formation of the ice-rich permafrost. Subsequently the change of climatic conditions led to the thawing of the ice-rich permafrost and the formation of the thermokarst depressions.

Thermokarst formation could be the product of evaporation/drainage or of sublimation, therein bypassing the accumulation of surface water and the formation of a lake. Commenting upon the origin of the putative periglacial landscapes on Mars, particularly the rimless depressions, most workers have suggested that sublimation and not evaporation has been the dominant process (Soare & *alii*, 2008). A recent study on the landscape evolution modelling of martian sublimation thermokarst processes (Dundas & *alii*, 2015) highlights that basic morphology consists of a shallow equator-facing slope and steeper poling-face rise. The model demonstrates that under the ice sublimation disturbance the warm equator-facing slope retreat and become shallower, while the retreat of the pole-facing scarp is much slower. Thus scallop-like landforms are an expected result of disturbante in this environment (Dundas & *alii*, 2015). Moreover, a previous study on the Martian thermokarst formation in the late Amazonian age demonstrates that the rimless depressions formed by sublimation, show a newly-dessicated regolith dotted with small surficial pockmarks and pits (Soare & *alii*, 2008).

Here, the observed depressions do not show any sublimation pits or/and pockmarks. Moreover, they do not display a marked difference in the opposite-facing slope. Thus we believe that they could be the product of evaporation/ drainage (ponded water and its slow loss by evaporation or drainage) rather than sublimation processes.

The absence of fluvial features along the adjacent plateaus appears to suggest that the source of the water within this trough must have been groundwater or snow/ice, as hypothesized in previous work (Weitz & *alii*, 2013). Moreover, according to Weitz & *alii* (2013), the presence of fluvial channels within the trough walls appears to suggest that water was provided by the melting of ice and/or snow previously concentrated in significant accumulations by winds.

CONCLUSIONS

The results of the present analysis suggest the following conclusions:

(i) On the basis of the similarities of features on Earth and Mars, and after considering other possible origins, we interpreted the investigated landforms in NL as thermokarst.

(ii) The degree of erosional features of the landforms and the absence of superposed impact craters suggest that they are relatively young, of Amazonian age (they formed hey formed upon Amazonian unit).

(iii) These landforms attributed to ice-melting processes suggest a response to climatologic change. Thus, these landforms highlight the occurrence of climatic changes that have occurred in the equatorial region of Mars, confirming the presence of ice at this latitude, probably in the Amazonian period. The melting of ice probably occurs gradually rather than abruptly.

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(Ms. received 1 August 2016; accepted 19 October 2016)