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# TWO POSSIBLE EPISODES OF KARSTIFICATION IN THE EQUATORIAL LAYERED DEPOSITS (ELDS) WITHIN KOTIDO CRATER, ARABIA TERRA (MARS)

**Abstract:** Baioni D., Luzzi E. & Marinangeli L., *Two possible episodes of karstification in the equatorial layered deposits (ELDs) within Kotido crater, Arabia Terra (Mars).* (IT ISSN 0391-9838, 2022).

This work describes the karst landforms observed in the evaporite Equatorial Layered Deposits (ELDs) located within Kotido crater in Arabia Terra, a portion of the equatorial region of Mars. We present new data and interpretations of the observed sinkholes, compared to previous studies to better understand the formation and evolution of these features. A detailed morphological and morphometric survey of the ELDs surface morphologies was carried out through an integrated analysis of the available images from the High Resolution Imaging Science Experiment (HiRISE) instrument on the Mars Reconnaissance Orbiter (MRO). More than 650 karst depressions were analyzed in detail, resulting in the detection of two main groups of depressions, displaying different features: smaller depressions are characterized by continuous scarped margins and limited sediment accumulation on the floors, while larger depressions have more degraded margins and thick sediment accumulations including well-developed dune systems. These differences between larger and smaller depressions do not appear to be related to spatial variations in aeolian erosion and deposition rates. Instead, we suggest that these differences can be explained by erosional variations due to the different ages of the depressions. Larger depressions may be older and may have been exposed to degradation and aggradation processes for a longer period of time than the smaller and presumably younger depressions. We propose that the karst landforms observed might represent the result of two possible distinct karstification episodes, related to climatic changes during the Amazonian age.

Key Words: Mars, Karst processes, Evaporite, Sinkholes, Climate change.

**Riassunto:** Baioni D., Luzzi E. & Marinangeli L., *Due possibili episodi di carsismo nei depositi stratificati equatoriali all'interno del cratere Kotido, Terra Arabia (Marte).* (IT ISSN 0391-9838, 2022).

Questo lavoro descrive le forme carsiche osservate nei depositi stratificati evaporitici equatoriali (ELD) situati all'interno del cratere Kotido nella Terra Arabia, una porzione della regione equatoriale di Marte. Presentiamo nuovi dati e interpretazioni delle depressioni osservate, rispetto a studi precedenti, per comprendere meglio la formazione e l'evoluzione di queste forme del rilievo marziano. Un'indagine morfologica e morfometrica dettagliata delle forme superficiali degli ELD è stata condotta attraverso un'analisi integrata delle immagini disponibili dello strumento *High Resolution Imaging Science Experiment* (HiRISE) sul *Mars Reconnaissance Orbiter* (MRO). Più di 650 depressioni carsiche sono state analizzate in dettaglio, con il risultato di individuare due gruppi principali di forme, che presentano caratteristiche diverse: le depressioni più piccole sono caratterizzate da margini cicatrizzati continui e da un limitato accumulo di sedimenti sul fondo, mentre le depressioni più grandi hanno margini più degradati e spessi accumuli di sedimenti, compresi sistemi di dune ben sviluppati. Queste differenze tra depressioni più grandi e più piccole non sembrano essere legate a variazioni spaziali nei tassi di erosione e deposizione eolica. Suggeriamo invece che queste differenze possano essere spiegate da variazioni erosionali dovute alla diversa età delle forme studiate. Le depressioni più grandi potrebbero essere più antiche e potrebbero essere state esposte a processi di degradazione e aggradazione per un periodo di tempo più lungo rispetto alle depressioni più piccole e presumibilmente più giovani. Proponiamo che le forme carsiche osservate possano rappresentare il risultato di due possibili episodi distinti di carsismo, legati ai cambiamenti climatici dell'epoca amazzonica.

Termini Chiave: Marte, Processi carsici, Evaporite, Doline, Cambiamento climatico.

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## INTRODUCTION

The occurrence of karst landforms and processes on Mars has been demonstrated possible by the presence of soluble evaporite rocks at the Martian surface, as reported by data from the OMEGA instrument on Mars Express (Bibring & *alii*, 2005), and the CRISM instrument on the Mars Reconnaissance Orbiter (Murchie & *alii*, 2007).

Many studies based on new high-resolution images attributed the presence of karst landforms to evaporite dissolution and processes in several Martian evaporite deposits (Baioni, 2019; Baioni & Tramontana, 2015; Grindod & Balme, 2010; Jackson & *alii*, 2011). These landforms are useful paleo-climatic and paleo-hydrological markers, since karstification processes require the presence of liquid water (Baioni, 2018; Baioni & Sgavetti, 2013; Flahault & *alii*, 2015).

The region of Arabia Terra contains a high density of impact craters that range in diameter from the lower limits of Mars Orbiter Camera resolution to over 100 km, and display variations in preservation state. Most craters are moderately to highly degraded, and some of them contain light-toned deposits, that in this region are also called informally as equatorial layered deposits (ELDs) (Okubo & *alii*, 2009; Pondrelli & *alii*, 2015), that cover their floors.

In particular, we focused our study on the ELDs of evaporite origin located within Kotido crater (KC) (Pondrelli & *alii*, 2019), a circular topographic impact basin 40 km across and about 1 km deep, located in the southern part of Arabia Terra, roughly 30 km south from Firsoff crater (fig. 1).

The presence of karst sinkholes of different shape and size, and karstification processes on an area of these ELDs located within KC have been recently demonstrated (Parenti & *alii*, 2020). The authors carried out morphologic and morphometric analysis of a total of 513 of these depressions, covering an area of 21.7 km$^2$. The results reported by Parenti & *alii*, 2020, highlighted the karst origin of the depressions, due to past subsurface dissolution of evaporites and collapse processes driven by liquid water, with consequent subsidence of the overlying sediments. Moreover, the authors describe the karst depressions as characterized by relatively fresh appearance, and dated as Amazonian (Parenti & *alii*, 2020).

The goals of this study, observing the sinkholes located in a larger area (36.0 km$^2$ where a total of 601 sinkholes have been mapped) than that previously studied by (Parenti & *alii*, 2020), are to describe the main morphological differences exhibited by some of these karst landforms, suggesting a distinct erosional age, and to discuss their possible origin related to different episodes of karstification and their paleo-climatic significance.

## STUDY AREA

Arabia Terra (fig. 1A) is located in the equatorial region of Mars, and is characterized by a gently sloping topography, which represents a gradual transition between the highlands and lowlands of Mars, in contrast with the sharp dichotomy observed in other regions.

According to Scott & Tanaka (1986), the stratigraphic succession of Arabia Terra begins with the Cratered unit of the plateau sequence (Middle Noachian Series), described by the authors as rugged, hilly, and characterized by the occurrence of channels, compressional features, fractures and erosional scarps. Moreover, the unit is densely affected by impact craters, representing the culmination of the heavy bombardment period. In the inter-crater areas the Plateau sequence is represented by the Subdued cratered unit (Upper Noachian Series), which results smoother but still widely cratered. The cratered unit has been interpreted by the authors as pyroclastic deposits, lava flows and impact breccia and as unconformably overlain by the Subdued unit, which is instead consisting of alternations of aeolian deposits and lava flows.

The Arabia Terra region contains many impact craters that range in diameter from the limits of Mars Orbiter Camera resolution to over 100 km. Throughout the region, especially within craters, depositional morphologies and erosional features occur, showing a past of intense geological processes involving liquid water. In particular, the presence of the light toned deposits (LTDs) that in the equatorial regions of Mars are informally named as Equatorial Layered Deposits (Okubo & *alii*, 2009; Pondrelli & *alii*, 2015) is a strong evidence of the role played by water during the deposition.

The ELDs, occurring all over the region (Schmidt & *alii*, 2021), have been studied and interpreted also as mud volcanoes (Pondrelli & *alii*, 2011), spring and lacustrine deposits (Ori & Baliva, 1999), linked to both subaerial and subaqueous processes (Luzzi & *alii*, 2018; Malin & Edgett, 2000) or either as the result of groundwater upwelling and consequently spring deposits (Franchi & *alii*, 2014; Oehler & Allen, 2008; Rossi & *alii*, 2008; Schmidt & *alii*, 2022). This environment and stratigraphic sequence can be suitable as landing site as well as proposed for Vernal crater (Pajola & *alii*, 2022).

A second unconformity separates the Plateau sequence units from the overlying ELDs, interpreted as Early Hesperian in age (Pondrelli & *alii*, 2015). Stratigraphically above the ELDs, a layered unit called "Hummocky material" lies unconformably, postdating the Hesperian ELDs. The Hummocky material is described as a dark-toned deposit, resistant to erosion and relatively smooth and it is interpreted as possibly pyroclastic (Pondrelli & *alii*, 2015). The succession ends with the ridged plains material, whose characteristics suggest a widespread lava flow. This unit is affected by wrinkle ridges and its age is still controversial.

Kotido crater (figs. 1A-1B) is one of the many crater basins hosting ELDs. The stratigraphic distribution of the ELDs ranges from the Noachian-Hesperian transition to the lower Hesperian (Pondrelli & *alii*, 2005), and according to spectral data they include monohydrated and/or polyhydrated sulphates (Bibring & *alii*, 2006; Gendrin & *alii*, 2005; Mangold & *alii*, 2008; Schmidt & *alii*, 2022). These sulphate-bearing sediments postdate the Noachian argillaceous units and are thought to record a major environmental change in the history of Mars (Bibring & *alii*, 2006).

Kotido crater is a circular topographic basin 40 km across and around 1 km deep, from the rim to the floor. The bedrock in which the Kotido crater was formed and that underlies the ELDs is formed by rocks of the "Middle Noachian highland unit" (mNh) (Tanaka & *alii*, 2014). The ELDs lie unconformably on the mNh unit and corresponds to the "Undivided etched unit" (HnMeu) mapped by Hynek & Di Achille (2017), within the crater and in the nearby inter-crater plains. These authors indicate that the surfaces of unit HnMeu are tabular to rugged, and intense-

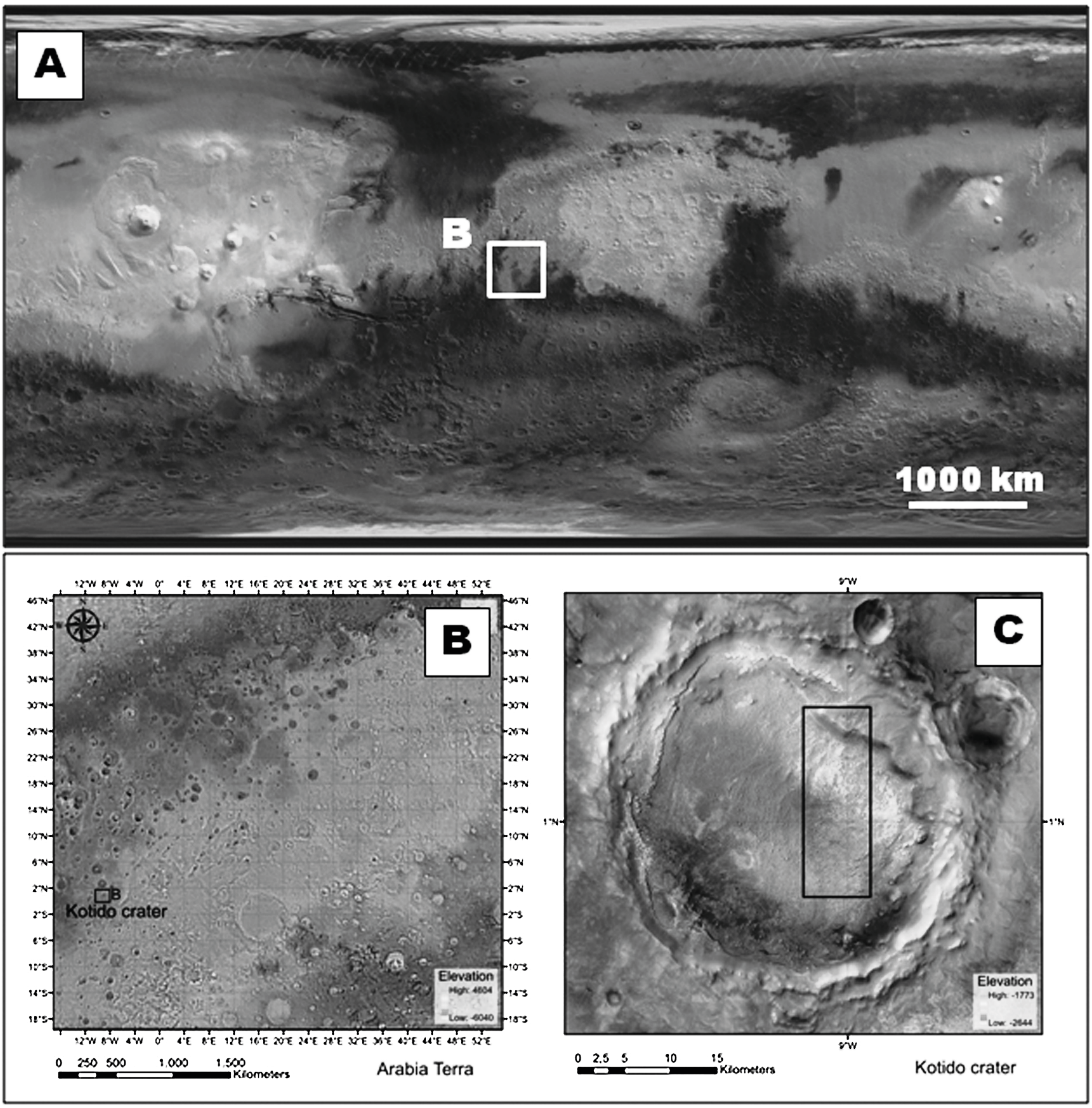


Fig. 1 - A) Image TES Albedo of Mars, with the location of the study area in Arabia Terra region (White square). Image taken from the website http://www.mars.asu.edu/data/tes_albedo/. B) Colorized terrain of Arabia Terra and location of Kotido crater (black square). C) View of Kotido crater with the study area (black box). Image MOLA-HRSC blended DEM overlaying a MOLA shaded relief.

ly affected by eolian erosion (Pondrelli & *alii*, 2019). Using the equations of Garvin & *alii* (2003) and Robbins & *alii* (2013), Hynek & Di Achille (2017) reconstructed the original geometry of the crater, inferring a rough estimate for the thickness of its sedimentary fill of 1 km. Previous authors (Pondrelli & *alii*, 2019) mapped the ELDs of Kotido crater at 1:20,000 scale, where the deposits show significant variability and good exposure conditions with limited dust cover. The authors analyzed their characteristics (i.e., morphology, texture, composition) and architectural features in order to infer the depositional environment and processes.

The ELDs exposed in Kotido crater consist of interbedded light- and dark-toned deposits, locally with interspersed intermediate-tone mounds (Pondrelli & *alii*, 2019). The light-toned sediments are composed of well-stratified layers or packages of meter-scale thickness forming undulated surfaces with polygons around 5 m across. The dark-toned layers are made of more erodible material with smoother texture, which tend to occur in topographically lower areas. The attitude of the ELDs of Kotido crater shows spatial variations. In the central sector of the crater they mainly lie horizontally or show gentle dips, whereas in the marginal areas are affected by gentle folds.

A recent study (Pondrelli & *alii*, 2019) reported the following morphological features in the layered deposits of Kotido crater: (1) Mounds in lateral continuity with the layered deposits, displaying a rounded depositional geometry, occasionally with an apical pit, and commonly forming alignments. (2) Straight to sinuous scarps, mesas, buttes and cuestas controlled by the more resistant horizontal or dipping light-toned beds, acting as caprocks. (3) Elongated yardangs with a prevalent NE trend generated by aeolian erosion. (4) Kilometre-scale linear layered ridges made up of resistant material and locally in spatial association with the mounds. These structurally controlled features are interpreted as fissure ridges formed by the upwelling of material through fractures or faults. According to Pondrelli & *alii*, 2019, these lineaments show a roughly radial or circular distribution, suggesting that they are influenced by fracturing associated with the formation of the impact crater. (5) Numerous closed depressions that riddle the ELDs, which are the focus of this investigation. The same authors suggest that the ELDs of Kotido crater were deposited in a playa-lake environment with spring mounds and fissure ridges fed by salt-rich pressurized groundwater (Pondrelli & *alii*, 2019). Sedimentation was characterized by alternating periods of evaporitic (light-toned layers) and fine-grained detrital sedimentation (dark-toned layers). They propose that the gentle dips and antiforms observed in the strata could be related to deposition over an inherited topography (i.e. sediments draping a paleorelief) or post-sedimentary deformation. The ELDs in the mapped sector of Kotido crater are unconformably overlain by dark-toned dune fields, mainly concentrated in topographic lows, and slope deposits with distinctive rockfalls. The latter are typically associated with steep-slopes controlled by resistant light-toned deposits (caprock), including the scarped margins of the closed depressions and residual reliefs. The studied ELDs are fragmented into polygons on average about 5 meters in diameter (Pondrelli & *alii*, 2019), that have been interpreted to be also produced by post-depositional weathering (Chan & *alii*, 2008).

A very recent study in the east-central sector of Kotido crater highlighted the karstic origin of the closed depressions located in the ELDs (Parenti & *alii*, 2020). This investigation concluded that the closed depressions are collapse sinkholes which developed in the ELDs within Kotido craters, likely related to subsurface dissolution of evaporites and related collapse processes. These sinkholes have been interpreted as relict landforms related to dissolution of evaporites with the development of underground voids and the collapse of cavity roofs, highlighting significant underground circulation of liquid water, presumably derived from the melting of snow and/or ice (Parenti & *alii*, 2020). Our investigation is focused on the morphological features of the karstic sinkholes locate in the ELDs within Kotido crater in a larger area (fig. 1C) than those analyzed previously (Parenti & *alii*, 2020).

## DATA AND METHODS

The morphological features in the study area were investigated through an integrated visual analysis of data from the MRO High-Resolution Imaging Science Experiment (HiRISE) (Mc Even et al., 2010) and the Context Camera (CTX) (Malin & *alii*, 2007). The CTX images analyzed (F05_037663_1794_XI_00S009W; B18_016776_1818_XN_01N009W) have a space resolution ranging between 5.48 m and 5.50 m per pixel, while the HiRISE images analyzed (ESP_016921_1810; ESP_016776_1610) have a space resolution ranging between 50.0 cm and 55.1 cm per pixel (objects 165 cm across are resolved).

A Digital Elevation Models (DEM) of the study area was built from HiRISE stereo pairs images through the photostereogrammetry software ASP (NASA AMES Stereo Pipeline v. 2.4.0) (Moratto et al., 2010). The DEM was bundle-adjusted to Mars Orbiter Laser Altimeter (MOLA) data (Smith et al., 2001), and it was aligned to HRSC data (Neukum & Jaumann, 2004). The DEM has a spatial resolution of about 0.58 m/pixel, and the analysis were carried on using 2D (ArcGIS) and 3D (ArcScene) ESRI GIS systems. HiRISE images, including enhanced RGB, IRB and derived DEM provide enough detail to observe even small morphological characteristics of the studied depressions.

## KARST DEPRESSIONS MORPHOLOGICAL ANALYSIS

Two distinct kinds of karst depressions displaying different features from the morphological point of view can be observed throughout the study area. These karst depressions are characterized by a variety of shapes and sizes that apparently display different kinds and degrees of erosional age.

As the focus of this study, these two kinds of depressions are named and referred below as "younger karst depressions" (YKD) and "older karst depressions" (OKD) and are described in detail below.

### *Younger karst depressions (YKD)*

This kind of sinkholes represents about the 92% (552 on a total 601) of the all sinkholes observed in the study area. The depressions display various shapes, including rounded (fig. 2C), subcircular (fig. 2F) polygonal (figs. 2A-2D), drop-like (fig. 2B), and elliptical (fig. 2E).

Sinkholes range in length (L) (measured as the long axes of the depressions defined by the outermost closed contour line) from 8 m for smaller depressions up to 345 m for compound basins formed by the coalescence of several depressions.The major axes show a broad NE prevalent orientations, spanning mainly from ENE-WSW to NE-SW and to E-W. These orientations appear to be unrelated to the location or shape of the depression.

The sinkholes mainly display well-defined, continuous and sharp margins, generally controlled by resistant light-toned layers (figs. 2A-2F). Their sides exhibit both symmetrical (figs. 2A-2D-2E) and asymmetrical (figs. 2B-2C-2F) slopes, with very steep to almost vertical walls. The sides

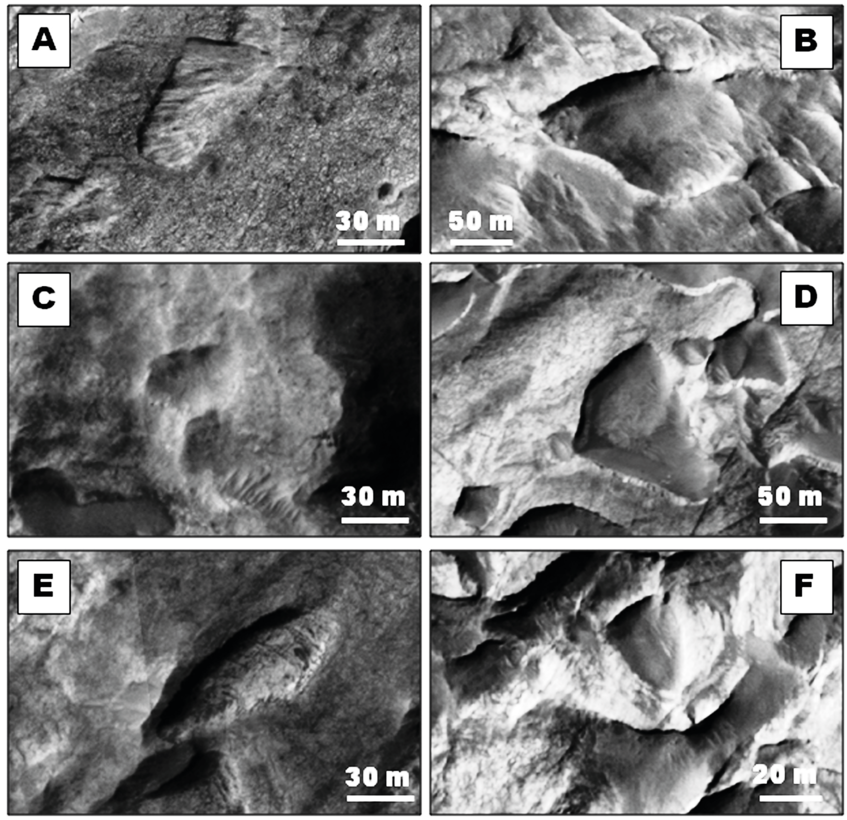


FIG. 2 - Younger karst depressions (YKD) in Kotido crater: A) Polygonal sinkhole displaying sharp margins, flat floor with no sediment accumulation (image MRO HiRISE ESP_016921_1810 north toward up). B) Drop-like shaped sinkhole displaying sharp margins, flat floor with very little sediment accumulation (image MRO HiRISE ESP_016921_1810 north toward up). C) Rounded sinkhole displaying sharp margins, flat floor with no sediment accumulation (image MRO HiRISE ESP_016921_1810 north toward up). D) Polygonal sinkhole displaying sharp margins, flat floor with very little sediment accumulation (image MRO HiRISE ESP_016921_1810 north toward up). E) Elliptical sinkhole displaying sharp margins, flat floor with no sediment accumulation (image MRO HiRISE ESP_016921_1810 north toward up). F) Subcircular sinkhole displaying sharp margins, flat floor with very little sediment accumulation (image MRO HiRISE ESP_016921_1810 north toward up).

appear to lack deep gravitational slope processes and fan deposits at the foot and /or stepped or terraced morphology. Debris were observed only on the floor of a few depressions.

The floors are apparently flat and have only small different characteristics in the accumulation of dust and/or sediment between these kind of depressions. In fact, they show very little (figs. 2B-2D-2F) or no sediment accumulation (figs. 2A-2C-2E) where often the layers on the bottom of the depressions can be observed.

These sinkholes seem well preserved and apparently lack deep signs of weathering, erosion, slumping or ventifacts. Moreover, HiRISE images of the well-exposed depressions show no superposed impact craters.

### *Older karst depressions (OKD)*

This kind of sinkholes represents about the 8% (48 on a total 601) of the sinkholes observed in the study area. The depressions mainly display elliptical (figs. 3B-3E-3F), elongate (figs. 3A-3D-3G), or irregular shapes (fig. 3C).

Sinkholes range in length (L) from 40 to 345 m., with the major axes ranging mainly from E-W to NE-SW and to NW-SE. These orientations appear to be unrelated to the location or shape of the depression.

The OKDs display more degraded and poorly defined margins that often are not sharp and are interrupted by signs erosion or slumping (figs. 3A-3C-3D-3F). Their sides exhibit mainly asymmetrical slopes, with steep walls, in some case terraced morphology (fig. 3F), and they show slope processes due to erosion and deposits accumulation (figs. 3A-3E-3F) or fan deposits (figs. 3B-3D) of bright material at the foot.

The floors are completely buried by dark sediments showing well-developed systems of dunes, which locally overlap the edges of the depressions. Here, different kinds of dunes overlapping each other are distinguishable, suggesting that each type of dunes formed in a different time (figs. 3A-3F1). Furthermore, the direction of the main older dunes is slightly different from the younger ones (figs. 3F, 3F1), and this could suggest a different wind direction over time. The shape of the floors and their bottom cannot be observed because they are covered by the big amount of sediments as described above.

HiRISE images of the well-exposed depressions show no superposed impact craters.

## DISCUSSION AND CONCLUSION

The studied landforms, according with previous works (Parenti & *alii*, 2020), can be interpreted as karst sinkholes. In fact, they lack features which suggest other possible origin such as, evidence of wind action, erosional features associated with the evolution of impact craters, or thermokarst processes. In particular, they were not formed by wind deflation, mainly because they lack a dominant orientation (Parenti & *alii*, 2020) as it happens in the depressions shaped by wind action on the Earth, called blowouts (Neuendorf & *alii*, 2005). Moreover, they do not support

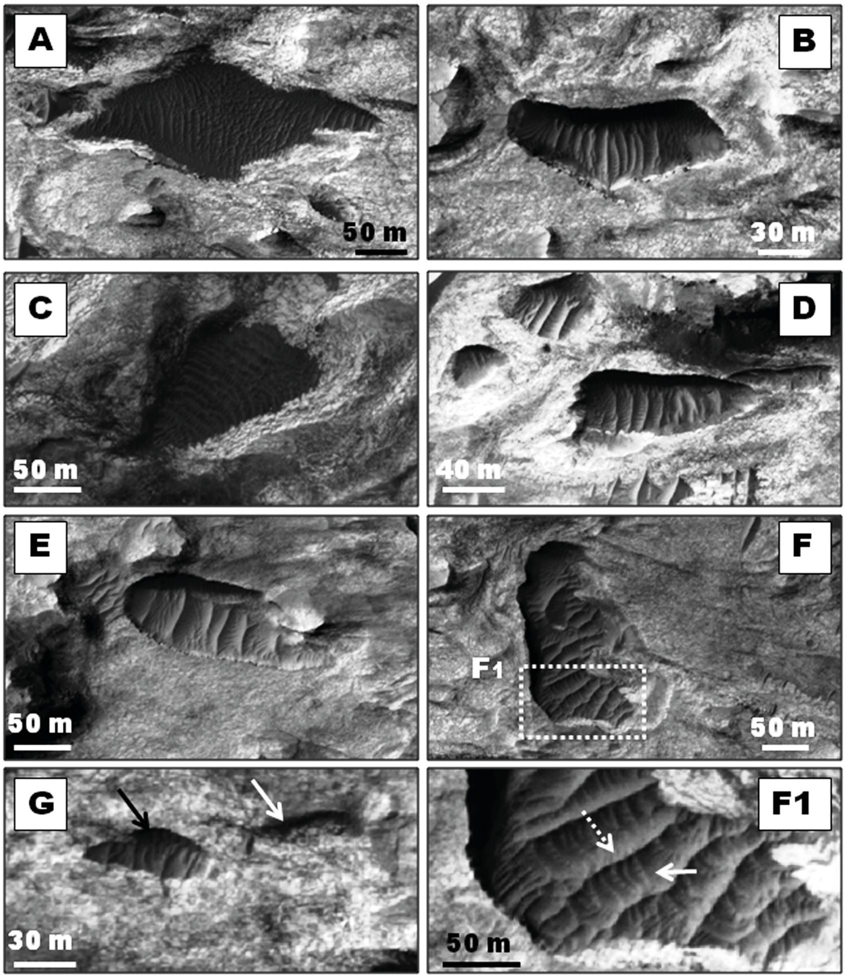


FIG 3 - Older karst depressions (OKD) in Kotido crater. A) Elongated sinkhole displaying poorly defined and irregular margins, floor completely buried by dark sediments showing well-developed systems of dune morphology and bright slope deposit at the foot of western side (image MRO HiRISE ESP_016921_1810 north toward up). B) Elliptical sinkhole displaying a floor completely buried by dark sediments showing well-developed systems of dune morphology and bright slope deposit at the foot of southern side (image MRO HiRISE ESP_016921_1810 north toward up). C) Irregular shaped sinkhole displaying smooth and irregular margins, and floor completely buried by dark sediments showing well-developed systems of dune morphology (image MRO HiRISE ESP_016921_1810 north toward up). D) Elongated sinkhole (in the center) displaying poorly defined and irregular margins (western and southern), floor completely buried by dark sediments showing well-developed systems of dune morphology and bright slope and fan gray deposit at the foot of southern side (image MRO HiRISE ESP_016921_1810 north toward up). E) Elliptical sinkhole displaying floor completely buried by dark sediments showing well-developed systems of dune morphology and bright slope deposit at the foot of south-eastern side (image MRO HiRISE ESP_016921_1810 north toward up). F) Elliptical sinkhole displaying degraded and poorly defined margins with terraced morphology (southern and eastern) and floor completely buried by dark sediments showing well-developed systems of dune morphology (image MRO HiRISE ESP_016921_1810 north toward up). F1) Particular of the dune morphology locate in the floor of the sinkhole, where different kind of dunes overlapping each other can be observed (image MRO HiRISE ESP_016921_1810 north toward up). G) Elliptical sinkholes displaying YKD features (right - white arrow) and OKD features (left – black arrow) located in close proximity adjacent to one another (image MRO HiRISE ESP_016921_1810 north toward up).

their formation as eroded or softened impact craters, as indicated by two lines of evidence. Firstly, the depressions display various plan forms that cannot be shaped by an impact, which would instead create bowl-shaped depressions characterised by a circular plan form (Barlow & Bradley, 1990). Secondly, all of the observed depressions lack raised rims and ejecta. It is unlikely that all possible rims and ejecta deposits were totally destroyed or cancelled by erosion processes. The thermokarst origin can be ruled out in this study due to the absence of other morphologies on the floor of the depressions, suggesting ice sublimation such as unsorted polygons. Moreover, they display morphological convergence with terrestrial sinkholes that commonly develop in all kinds evaporite terrains in several regions on Earth (Cucchi & Zini, 2003; Ferrarese & *alii*, 2002; Gutierrez & *alii*, 2008). Additionally, they strongly resemble the evaporite sinkholes described in other regions of Mars (Baioni & *alii* 2011; Baioni, 2013; Baioni & Tramontana, 2015; Flahaut & *alii* 2015; Grindrod & Balme 2010).

The analysis of karst depressions in the study area revealed significant differences among the YKD and OKD.

The YKD (figs. 2A-2F) appear well preserved and apparently lack deep reworking or modification by aeolian erosion. In particular, the absence of landforms with evidence of aeolian erosion, such as degraded depression margins or ventifacts, and in particular, the little or the absence of sediment accumulation on the floor forming complex dune morphology can be observed. These characteristics highlight the freshness of these landforms and might suggest a young erosional age.

The OKD (figs. 3A-F) display features such as degraded margins, slope processes, fan deposits at the foot of the depressions sides and, in particular, thick accumulations of sediments on the floor, which display well developed complex dune morphology systems. Conversely, these characteristics highlight the effects of erosive processes over the time and might suggest an older erosional age.

As in similar features on Earth, these differences between YKDand OKD may be caused mainly by five factors, such as, different topographic conditions (e.g. surface morphology, slope), different amounts of water that affected the surface, different responses to solutional processes due to the diversity of rock composition, response to exposure to different degree of erosive processes over a long time, and as a result of their different age.

The differences between YKD and OKD observed in the depression features such as size, presence or absence, and amount of dust and/or sediments on the bottom, and margin/slope characteristics, do not seem to be related to the location of the depressions. In fact, in some cases it is possible to observe these two different kinds of depressions adjacent one to another, within areas with practically uniform topographic features (fig. 3G).

Likewise, it is unlikely that these differences might be due to different amounts of melt water that affected the surface within such small areas, especially for the period of time required for the development of karst landforms, as well as they cannot be due to differences in material responses to solutional processes. In fact, mineralogical data do not highlight any significant differences within the study area and even if some very small variation in rock mineralogical composition might be not recorded from CRISM and OMEGA data, it is unlikely that such variations can berelated to the morphological differences between depressions located side by side, as observed in some areas (fig. 3G).

Moreover, the morphological differences between YKD and OKD cannot be related to a difference in the degree of aeolian erosion and deposition over time because these processes are unlikely to vary markedly in the same topographic area among depressions in close proximity, as observed in the study area.

For the reasons above we suggest that the differences may be due to variations in age among depressions. The OKD may be older and exposed to morphological processes for a longer period of time than the YKD, which are presumably younger.

In fact, ancient depressions exposed to aeolian deposition for a long period might demonstrate both degraded margins and slopes, and much more sediment accumulation on the floor, forming complex dune morphology systems, while young depressions should display both the presence of slope processes and the absence of sediment accumulation on the floor, as it can be observed in the study area.

The very marked morphological differences between YKD and OKD, probably related to their erosional age, as described above, as well as the different amount of the number of depressions observed between YKD and OKD, might suggest that they belong to two different episodes of karstification, rather than a single episode where solution processes and water penetration into bedrock persisted over time. If this is the case, karstification processes were not short lived, as it has been hypothesized for karst landforms developed in similar evaporite deposits located in other regions of Mars. In fact, for karst depressions observed in similar geological contexts, such as the LTDs within Cagli crater (Baioni, 2019) and Tyrrena Terra craters (Baioni & Tramontana, 2016), it has been proposed that their variations in morphological features are likely due to a single, but not short lived, episode of karstification. These landforms do not display significant differences, in particular regarding the sediment accumulation and dune system features as those observed in the study area, which appear unlikely to have been shaped by the same geological episode.

The karst depressions appear to reflect ice- and/or water-related processes. The landform features appear to be the work of water-related processes. The development of landforms related to liquid water on Mars could have been triggered by the melting of snow, ice or icy permafrost or alternatively by the structural delivery of water to the surface. The study area lacks morphological features and topography that would suggest the presence of sapping processes due to structural control. Therefore, the melting of snow, ice or icy permafrost could have driven the processes of dissolution and collapse on the evaporite rock. Therefore, the melting of ice and/or snow have driven the processes of solution and collapse on the evaporite rock just as it happens on the Earth, where dissolution may occur also on ice-covered terrain. Ice and/or snow melting provide the water necessary for dissolution and collapse processes as inferred to explain the karst landforms and topography found both in other regions of Mars (Baioni & *alii* 2011; Baioni, 2013; Baioni & Tramontana, 2015; Baioni, 2018; Flahaut & *alii* 2015; Grindrod & Balme 2010; Jackson & *alii*, 2011).

Episodic changes in Martian obliquity may explain the origin of ground ice and/or snow that melted and provide the liquid water to shape these karst landforms. Theoretical considerations about the stability of water ice and numerical simulations of climate predicted that areas of surface ice or snow accumulation may have shifted repeatedly between polar, middle, tropical and equatorial latitudes in response to changes in Martian orbital and atmospheric characteristics in the past (Forget & *alii*, 2006; Madeleine & *alii*, 2009; Wordsworth & *alii*, 2013). According to some simulations, the net ice accumulation rates might have exceeded 20 mm/year in locations along the Martian equator. Such shifts may have been necessary to achieve the Amazonian physical conditions, given the current composition of the atmosphere (Madeleine & *alii*, 2009), and other physical conditions in the past (Wordsworth & *alii*, 2013). A very recent study suggests that the potential effects of these Martian orbital variations on recent ice ages led to the proposal from orbital data that a geologically recent ice age occurred (from roughly 2.1 to 0.4 Myr) and that after roughly 0.4 Myr, Mars entered an interglacial period (Liu & *alii*, 2023). Moreover, recent studies have hypothesised and described the presence of ice in the planet's tropical regions and near-surface, as well as the presence of ground ice features near or at the equator (Burr et *alii*, 2005; De Blasio, 2011; Gourronc & *alii*, 2014; Shean, 2010) and the presence of permafrost processes (Warner & *alii*, 2010; Baioni & *alii*, 2017).

Thus, the karst landforms as markers and as response of climatic change, here might suggest that two possible climatic change occurred, confirming two possible episodes characterized by the presence of liquid water at this latitude.

Regarding the age of the landforms observed, they must be younger than the evaporite deposits of Hesperian age on which they were shaped. They are generally well preserved and lacked very deep reworking or modification by aeolian erosion.

Evaporites are much less resistant to erosive processes than carbonates and they do not survive long in outcrops especially beyond arid areas (Klimchouuk, 2012). Thus, the wind action should erode and the depressions more easily and quickly compared to carbonates. The features of the YKD and OKD described above suggest that they have not exposed to wind action for very long time and therefore they are young from the erosional point of view. TheThe relatively youthful age of the karst landforms is also supported by the absence of impact craters. Erosional effect that might have led to an underestimation of the true age of the landforms are not substantial. In fact, even at the highest resolution, HiRISE images of the well-exposed depressions show no superposed impact craters, which further suggests a young erosional age. Moreover, comparing this landform with those found in similar martian evaporite rocks investigated in previous studies, they exhibit an younger erosional age than the karst landforms observed in Tithonium Chasma and dated of early Amazonian age (Baioni & *alii*, 2009), while they apparently exhibit an older erosional age of the karst landforms observed within Iani Chaos (Baioni & Tramontana, 2015) and Noctis Labyrinthus (Baioni, 2018) which are dated of late Amazonian age. Taken together, these observations suggest that the observed karst landforms might be very young, probably of middle-Late Amazonian age, according with previous works (Parenti & *alii*, 2020).

The analysis performed in this study suggests the following conclusions:

(i) The differences observed in the morphological features of the landforms suggests the presence of two distinct kinds of karst sinkholes that display different erosional and/or depositional characteristics, such as the presence or absence, and amount of dust and/or sediment on their bottom, together with margin and slope characteristics, which can be distinguished clearly in the sinkholes within the study area.

(ii) The investigation carried out suggests that these differences among sinkholes could be the result of a significantly different erosional age, rather than the result of other factors such as relative karst susceptibility among units due to solutional properties (e.g. lithologic and/or mineralogic composition) or topographic characteristics. The older sinkholes appear to have been affected by erosional processes for a much longer time than the younger.

(iii) We believe that the formation of the investigated landforms could be consistent with the occurrence of two different episodes of karstification, thus suggesting the occurrence of two climatic changes during which water was available in the equatorial region of Mars in the Amazonian age.

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