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Possible pingos and a periglacial landscape in northwest Utopia Planitia

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Abstract

Hydrostatic (closed-system) pingos are small, elongate to circular, ice-cored mounds that are perennial features of some periglacial landscapes. The growth and development of hydrostatic pingos is contingent upon the presence of surface water, freezing processes and of deep, continuous, ice-cemented permafrost. Other cold-climate landforms such as small-sized, polygonal patterned ground also may occur in the areas where pingos are found. On Mars, landscapes comprising small, elongate to circular mounds and other possible periglacial features have been identified in various areas, including Utopia Planitia, where water is thought to have played an important role in landscape evolution. Despite the importance of the martian mounds as possible markers of water, most accounts of them in the planetary science literature have been brief and/or based upon Viking imagery. We use a high-resolution Mars Orbiter Camera image (EO300299) and superposed Mars Orbiter Laser Altimeter data tracks to describe and characterise a crater-floor landscape in northwest Utopia Planitia (64.8° N/292.7° W). The landscape comprises an assemblage of landforms that is consistent with the past presence of water and of periglacial processes. This geomorphological assemblage may have formed as recently as the last episode of high obliquity. A similar assemblage of landforms is found in the Tuktoyaktuk peninsula of northern Canada and other terrestrial cold-climate landscapes. We point to the similarity of the two assemblages and suggest that the small, roughly circular mounds on the floor of the impact crater in northwest Utopia Planitia are hydrostatic pingos. Like the hydrostatic pingos of the Tuktoyaktuk peninsula, the origin of the crater-floor mounds could be tied to the loss of ponded, local water, permafrost aggradation and the evolution of a sub-surface ice core.

Keywords: Mars, surface; Geological processes; Ices

1. Introduction

Hydrostatic (closed-system) pingos are small, elongate to circular, ice-cored mounds that are perennial features of some periglacial landscapes. The growth and development of hydrostatic pingos is contingent upon the presence of surface water, freezing processes and of deep, continuous, ice-cemented permafrost (French, 1993; Mackay, 1979, 1998; Müller, 1962). Other cold-climate landforms such as small-sized polygonal patterned ground also may occur in the areas where pingos are found (Mackay, 1979, 1998).

On Mars, landscapes that include small, elongate to circular mounds hypothesised to be pingos, as well as other possible periglacial features have been identified in three areas: (1) the vast northern plains (Kargel and Costard, 1993; Parker and Banerdt, 1999; Seibert and Kargel, 2001) encompassing Acadilia (Lucchitta, 1981), Chryse (Theilig and Greeley, 1979), Elysium (De Hon, 1997; Rice et al., 2002), and Utopia Planitiae (Tanaka et al., 2000; Seibert and Kargel, 2001; Thomson and Head, 2001); (2) Vastitas Borealis (Greeley and Guest, 1987); and (3) the Gusev crater (Cabrol et al., 1997, 2000; Grin and Cabrol, 1998). Water is thought to have played an important role in the landscape evolution of each area.

Despite the importance of the martian mounds as possible geomorphological markers of water, most accounts of them

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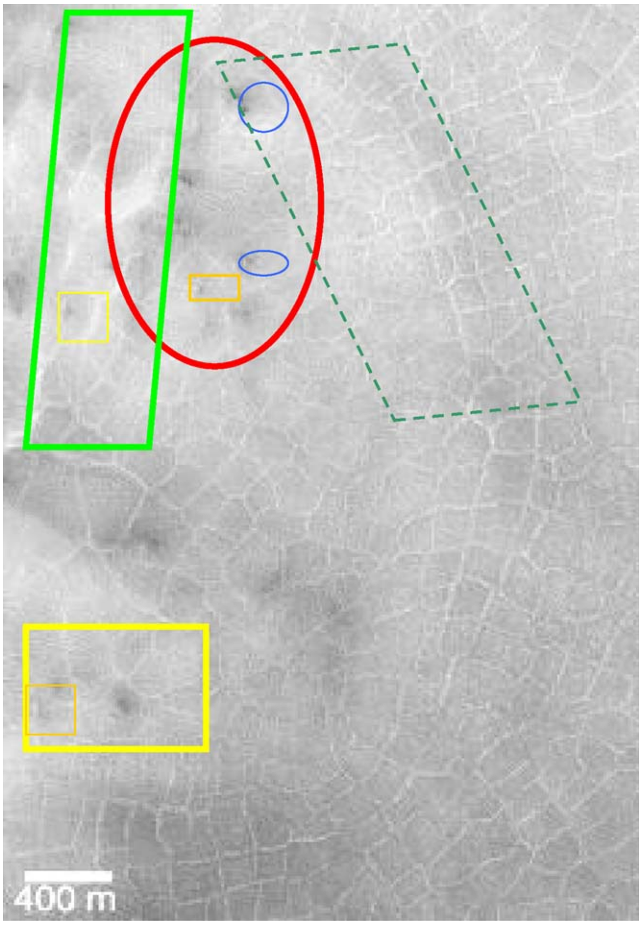


Fig. 1. MOC image EO300299, centred near 64.8° N, 292.7° W, northwest Utopia Planitia. Resolution is 5.05 m/pixel and the sun illuminates the landscape from the southwest. Large oval encloses mound Group A. Large box encloses mound Group B. Parallelogram encloses a set of thin dendritic-like features and a thicker adjoining trunk. Serrated parallelogram encloses a channel-like, curvilinear feature that loses elevation to the south. Small boxes enclose mounds crossed by crack; Small ovals enclose summit depression or collapse feature. Image is 3.2 km across.

in the planetary science literature have been brief (De Hon, 1997; Greeley and Guest, 1987; Seibert and Kargel, 2001; Lucchitta, 1981, 1993; Parker and Banerdt, 1999; Rice et al., 2002; Theilig and Greeley, 1979) and/or based upon Viking imagery (Cabrol et al., 1997, 2000; Grin and Cabrol, 1998).

Using a high-resolution (5.5 m/pixel) Mars Orbiter Camera (MOC) image EO300299 (Fig. 1) and individual data tracks generated by the Mars Orbiter Laser Altimeter (MOLA) (Fig. 2) that are superposed on EO300299, we describe a set of small, roughly circular mounds and an associated crater-floor landscape in northwest Utopia Planitia (64.8° N/292.7° W). We argue that the formation and presence of this landscape assemblage is consistent with the past work of water and of periglacial processes (Soare and Peloquin, 2003). This assemblage may have formed as recently as the last episode of high obliquity. A similar landscape assemblage is found in the Tuktoyaktuk peninsula of northern Canada and in other terrestrial cold-climate

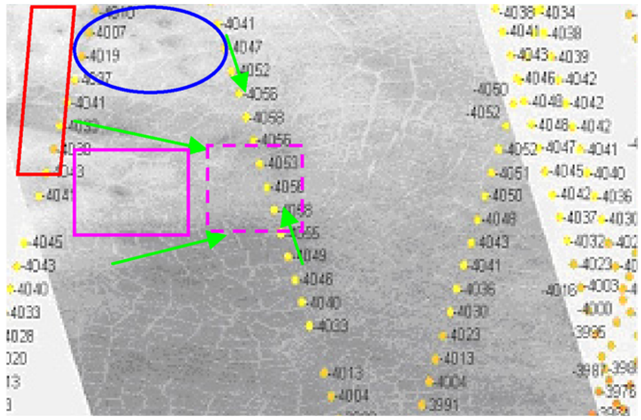


Fig. 2. MOLA altimetric data superposed on MOC image EO300299. Arrow points to elevation loss in the direction of a two small, circular features, possibly dust covered impact craters (serrated rectangle). Parallelogram encloses an area in which there could be a confluence (immediately to the west of the crater floor imaged by EO300399) between the dendritic features and the basin lying to the south. Oval encloses a plateau or terrace upon which the Group A mounds rest. Rectangle encloses a basin in which the Group B mounds rest.

landscapes (French, 1993; Mackay, 1979; Müller, 1962; Washburn, 1973). We point to the similarity of the two assemblages and suggest that the small crater-floor mounds in northwest Utopia Planitia are hydrostatic pingos. Like the hydrostatic pingos of the Tuktoyaktuk peninsula, the origin of the crater-floor mounds may be tied to the loss of local water, permafrost aggradation and the evolution of a subsurface ice core.

2. Description of the Utopian crater-floor landscape

The subject of our investigation is a landscape located on the floor of an impact crater in northwest Utopia Planitia. The crater is ∼17 km in diameter (Viking Orbiter image M165N295) (Fig. 4). An area of uplift near the centre of the crater is indicated by the MOLA data tracks. The area of uplift also is partially visible in the Viking image noted above and in MOC image EO300300. Central uplift in a crater of this size is not unexpected as the transition diameter on Mars between craters with simple and complex morphologies, represented by areas of central uplift, is ∼7 km (Melosh, 1985).

The crater-floor landscape comprises a number of intriguing landforms. Small, roughly circular mounds that are ∼25–50 m in diameter (Groups A and B) (Fig. 1) bracket the latitudinal median of the crater. They are concentrated in an area ∼10 km^2 that lies ∼2–3 km east of the crater centre. A few of the mounds are crossed or cracked (Fig. 1). Summit depressions or collapse features also are visible on some mounds (Fig. 1). The MOLA tracks show that the mounds of Group A are arrayed longitudinally on a slightly elevated terrace or plateau (Fig. 2). This terrace could be topographically related to the area of uplift at the centre of the crater.

Evaluation of this hypothesis awaits the production of higher resolution images of the central crater area.

A set of thin, dendritic features lies immediately to the west of the terrace (Fig. 1). The dendritic features are connected to a thick main trunk (Fig. 1). A few mounds are clustered to the northwest of Group A on the opposite side of the dendritic features (Fig. 1). The absence of MOLA tracks in the area of the western mounds makes it difficult to ascertain whether these features are located on a plateau or a basin. A curvilinear, channel-like feature lies to the northeast and to the east of the Group A terrace (Fig. 1). A band of polygons— ∼800 m in diameter—overlies the curvilinear feature and is orthogonal to the terrace. The channel-like feature loses elevation southwardly, as shown by the MOLA data, in the direction of one or possibly two circular features that are ∼0.8 and ∼1.0 km in diameter (Fig. 2). These features may be old, dust-covered impact craters.

To the south of the Group A terrace, the MOLA tracks indicate that the mounds of Group B sit in a small, elliptical basin. The basin grades to the east and intersects the curvilinear feature that has graded from the north in the area of the two possible impact craters (Fig. 2). The gradual loss of elevation to the east of the Group A and B mounds (Fig. 2) is consistent with the presence of an area of central uplift to the west of the mounds. Small-sized, polygonal patterned ground that is ∼40–300 m in diameter is ubiquitous on the crater-floor and underlies each of the features identified above (Fig. 1). In a number of instances, polygon cracks intersect mound cracks (Fig. 1).

3. Possible terrestrial analogues

On the basis of their size, morphology and mutual association, we hypothesise that the mounds on the Utopian crater floor are pingos and that the polygonal patterned ground on the crater floor is comprised of thermal contraction polygons that could be/have been underlain by ice wedges. We provide a description of terrestrial pingos and polygonal patterned ground as an analogue for the Utopian landforms.

3.1. Hydrostatic and hydraulic pingos

There are two main types of terrestrial pingos: hydrostatic (closed-system) or hydraulic (open-system). Pingos range in height from ∼3–70 m and in basal diameter from ∼30–600 m (Gurney, 1998; Washburn, 1973). Hydrostatic pingos form when soil moisture migrates into an increasingly small near-surface pocket of non-frozen soil as a result of permafrost aggradation; by contrast, the formation of hydraulic pingos is driven by the movement of groundwater under high artesian, topographic or elevational pressure (French, 1993; Mackay, 1979; Müller, 1962; Washburn, 1973). The highest spatial concentration of hydrostatic pingos in the world is in the Tuktoyaktuk peninsula of northern Canada (Mackay, 1998). There may be as many as 1380 pingos in the area (Müller, 1962). Many of these pingos are nested in fields of polygonal patterned ground.

The Tuktoyaktuk pingos are underlain by a large fraction of deltaic sand (0.1–0.05 mm) and a much smaller fraction of silt (<0.05 mm) (Mackay, 1979; Müller, 1962). The coarseness of the soil facilitates the migration of intra- or subpermafrost water to the area of pingo genesis. Ninety-eight percent of these pingos reside in lake basins that are adjacent to the Beaufort Sea and have lost their water through drainage channels (Fig. 3) (Mackay, 1962, 1979, 1998). The drainage of these lakes has been triggered by one of three factors: (1) coastal recession (MacKay, 1979, 1998; Washburn, 1973); (2) ice wedge erosion at lake outlets as a result of coastal wave action (Mackay, 1979, 1998), or (3) the headward erosion of rivers or lakes, perhaps at a time of lower sea-level (Mackay, 1998).

The evolution of a hydrostatic pingo within a drained lake comprises two main phases: growth and decay. Often, the growth of a hydrostatic pingo is initiated when a lake is drained and the unfrozen albeit water-saturated sediment beneath the lake floor is exposed directly to freezing temperatures for the first time (Mackay, 1966). The downward aggradation of permafrost ensues. Pore water is expelled from the saturated soil as the freezing front advances and the water becomes trapped in an increasingly small space. The pressure of this trapped pore water rises substantially (Mackay, 1966, 1979; Müller, 1962). As the freezing process continues, a core of ice begins to form above the trapped pore water. Under intense hydrostatic pressure the ice begins to deform the overburden, creating a small mound.

Compared to distal areas of higher elevation in the basin, the deepest part of the former lake basin is the last region to undergo permafrost aggradation (Mackay, 1962, 1999). This is because pockets of vestigial water collect in residual ponds on the lake floor. These residual ponds buffer the underlying sediments from freezing until the pond water itself evaporates or is drained away. Permafrost is at its minimum thickness in the area directly beneath the residual ponds. Thin permafrost is more susceptible to deformation by the flow of groundwater under pressure and by an incipient core of ice than is thick permafrost (Mackay, 1962, 1979). The growth of hydrostatic pingos tends to occur in these areas of thin permafrost (Mackay, 1962, 1987, 1998, 1999).

When a pingo grows, summit cracks may appear. Summit cracks are apparent on both the Ibyuk and Split pingos (Figs. 3 and 5a). Summit cracks are produced by the dilation of the pingo overburden (Mackay, 1987, 1998). As the cracks widen, the overburden is stretched and becomes increasingly thin (Mackay, 1998). The thinness of the overburden may expose the underlying pingo ice to thaw or melt conditions. Thermokarst may ensue (Fig. 5b). This would be the first stage of a process leading to the eventual collapse of the pingo (Fig. 6) (Mackay, 1998). Pingo growth and development also induce circumferential stretching and tension. This tension is relieved by the formation of radial dilation cracks. Radial dilation cracks propagate from the top to the

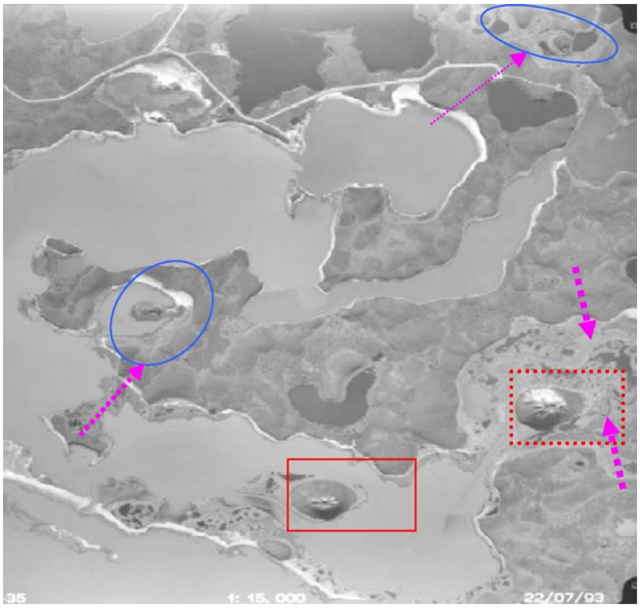


Fig. 3. Coastal pingos in the Tuktoyaktuk peninsula, northern Canada (Air Photo A27917-35-1993, National Air Photo Library, Ottawa), southwest of the town of Tuktoyaktuk. Solid-line rectangle encloses Split Pingo, ∼300 m in diameter and ∼35 m in height. Serrated rectangle encloses Ibyuk Pingo, ∼300 m in diameter and ∼49 m in height, the second highest pingo in the world. Ovals encloses small pingos whose formation and growth, similarly to Split and Ibyuk pingos, are related to lake drainage. Arrow points to polygonal patterned ground underlain by ice wedges. Image is ∼3.4 km across.

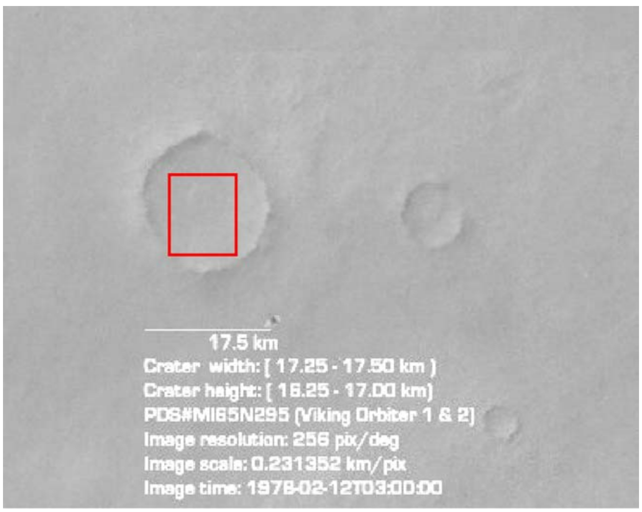
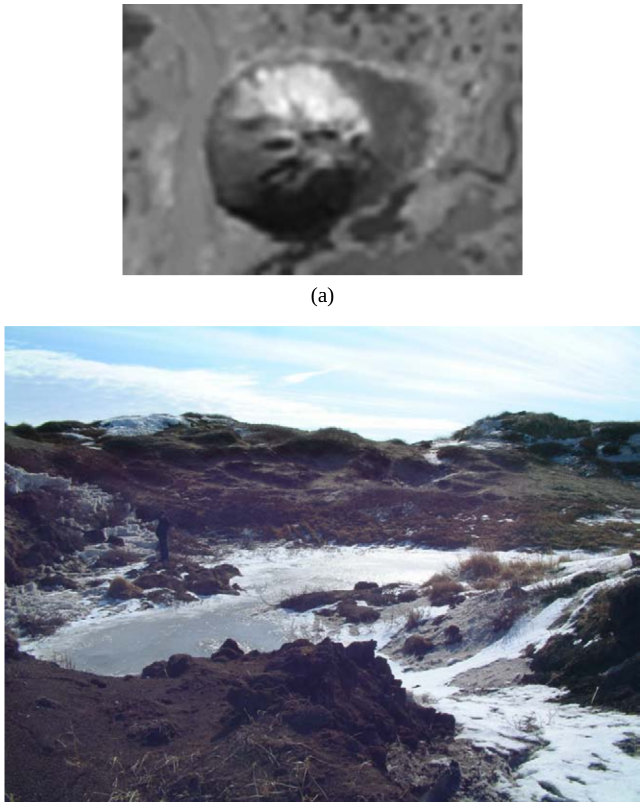


Fig. 4. Viking Orbiter Image M165N295, northwest Utopia Planitia. Resolution is 231 m/pixel. Background view of the impact crater (on the left) highlighted by MOC image EO300299. An area of central uplift is partially visible near the crater centre. Image is ∼86 km across.



(a)

(b)

Fig. 5. (a) Enlargement of summit cracks and crater, Ibyuk Pingo, Tuktoyaktuk peninsula (Air Photo A27917-35-1993, National Air Photo Library, Ottawa). Image is ∼450 m across (b) Frozen thermokarst, Ibyuk pingo summit, Tuktoyaktuk peninsula, spring 2004. Image is ∼40 m across.

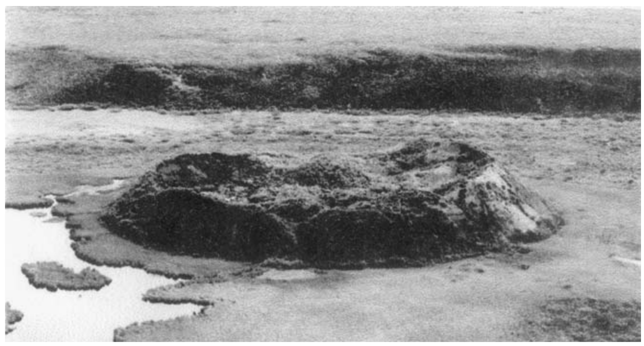


Fig. 6. A collapsed pingo in the midst of a drained lake, Tuktoyaktuk peninsula; the mound might have reached ∼15–20 m in height before collapsing (Mackay, 1998).

bottom of the pingo; on occasion, they may intersect with thermal contraction cracks in the lake flats that are adjacent to the pingo (Fig. 7) (Mackay, 1987, 1998).

The genesis and growth of hydraulic pingos are a function of two factors: (1) the downslope flow of intra- and sub-permafrost flow of groundwater, which creates a hydraulic gradient (Mackay, 1998); and (2) the downslope presence of thin or discontinuous permafrost and of very coarse sediment (Cruickshank and Calhoun, 1965; French, 1993; Lasca, 1969; O'Brien, 1971). Coarse sediment facilitates the upward migration of artesian water through the permafrost and the subsequent formation of an ice core as the distance to the surface lessens. Consequently, hydraulic pingos tend to be found on lower valley-side slopes, valley bottom alluvium, alluvial fans, braided channels and outwash material (Cruickshank and Calhoun, 1965; French, 1993;

Fig. 7. Dilation cracks converging with thermal contraction cracks on the perimeter of mid-sized, lake drainage pingo, Tuktoyaktuk peninsula (Mackay, 1998). Pingo is ∼200 m across.

Mackay, 1998; O'Brien, 1971). Dilation cracks and collapse features are commonplace amongst hydraulic pingos as well (Bennike, 1998).

3.2. *Thermal contraction polygons*

In periglacial environments where liquid water is present, there are two types of polygonal patterned ground—freeze-thaw (sorted) and thermal contraction (non-sorted). With regard to the first type of patterned ground, freeze-thaw cycles separate coarse grains, cobbles and stones from fine grained material in the active layer of the sediment profile (Washburn, 1973). Separation generates polygons in which fine material is bordered by coarse material (Washburn, 1973). Most freeze-thaw polygons are $\leqslant \sim$10 m in diameter (Washburn, 1973). Thermal contraction polygons tend to be larger than freeze-thaw polygons.

The formation of thermal contraction cracks and polygons begins when temperature-induced tensile stress exceeds tensile strength in frozen ground. Thermal contraction cracks are the product of a severe and rapid decline of sub-zero temperatures in ground that is already frozen (Lachenbruch, 1962; Plug and Werner, 2002). Crack spacing is a function of horizontal stress relief, as determined by the distance from the crack to points of 5% stress relief on the ground normal to the crack itself (Lachenbruch, 1962). According to this theory, 5% stress relief should be achieved by a 3 m crack at a horizontal distance of 12 m, by a 6 m crack at a horizontal distance of 18.8 m and by a 9.1 m crack at a horizontal distance of 21.5 m (Lachenbruch, 1962). This represents a vertical-crack depth to horizontal distance ratio of ∼((4.0–2.5) to 1). The crack depth to horizontal distance ratio becomes smaller with depth because frozen ground has a low thermal conductivity. This means that the penetration depth of surface temperatures is relatively shallow (Maloof et al., 2002; Pechmann, 1980; Plug and Werner, 2002).

The cracks or troughs that bound thermal contraction polygons may be underlain by ice, sand or a combination of the two fills (Lachenbruch, 1962; Washburn, 1973). Melt-water that is seasonally available percolates down through the active layer and becomes the source of crack- or trough-fill in wet, periglacial environments (Lachenbruch, 1962). Other sources of crack- or trough-fill may be the sub-surface thawing of ground ice or condensation from atmospheric vapour (Lachenbruch, 1962; Mellon, 1997; Washburn, 1973). In extremely cold and dry environments such as the Antarctic and even eastern Greenland, the infiltrate may be sand (Bennike, 1998; Lachenbruch, 1962; Marchant et al., 2002; Sletten et al., 2003; Washburn, 1973).

When a water-filled crack freezes, a small vertical vein of ice forms at the interface between the active layer and the permafrost underlying it; subsequent cracking, initiated at the top of the wedge, propagates upward through the active layer and downward through the permafrost (Lachenbruch, 1962). Repeated cycles of cracking and infiltration transform the ice vein into a vertical ice-wedge (Lachenbruch, 1962); the process that leads from crack infiltration by sand to sand wedge development is quite similar (Sletten et al., 2003).

As early as the first winter following the loss of basin water, isolated thermal-contraction cracks underlain by ice may begin to appear in the floors of drained Arctic lakes (Mackay, 1999). Crack consolidation and the formation of discrete but unconnected ice-wedge polygons could take place within ten years of lake drainage (Mackay, 1999). The formation of metre-wide ice-wedges and larger-sized polygon networks may take thousands of years (Plug and Werner, 2002). The presence of orthogonal cracks, either normal to or parallel with the contour of a lake or a shoreline, is indicative of slow drainage (Lachenbruch, 1962; Kuzmin et al., 2002).

The polygons of the Tuktoyaktuk peninsula, most of which are or have been underlain by ice (Fig. 3), are ∼10–20 m in diameter. Ice-wedge polygons that are ∼30–60 m in diameter have been identified in the Fosheim Peninsula, Ellesmere Island, Canada (Lewkowicz and Duguay, 1999). Ice-wedge polygons that are ∼60–80 m in diameter are found in the flood plains of the Yamal peninsula in Siberia, only to be surpassed in size by sea-terrace polygons in the region that are ∼100 m in diameter (Kuzmin et al., 2002).

While crack depth measurements for the large Russian polygons are unavailable, ice-wedges that are ∼52 m in depth have been reported in the coastal region of the Laptev Sea, Russia (Romanovskii et al., 2000). If the coastal ice-wedges of Russia are an indirect benchmark of possible polygon size, then the crack depth to horizontal distance ratio noted above suggests that terrestrial thermal contraction polygons that are ∼130 m in diameter would not be implausible.

4. The crater-floor landscape identified by EO300299

4.1. Mounds

The shape and size of the crater floor mounds is consistent with the shape and size of hydrostatic pingos on Earth (Gurney, 1998; Washburn, 1973). Moreover, the convergence of mound-based cracks with crater-floor cracks seen in EO300299 is typical of the convergence between the dilational cracking of a pingo and the thermally-induced ground cracks that occurs in terrestrial periglacial landscapes such as the Tuktoyaktuk peninsula (Fig. 7) (Bennike, 1998; Mackay, 1998).

Possible collapse features and/or summit depressions are visible amongst a few of the mounds on the crater floor. Along with the convergence of mound-based cracks and crater-floor cracks, these characteristics are associated quite strongly with pingos and pingo evolution on Earth. These characteristics are not shared with rootless cones (Lanagan et al., 2001), dust-covered erratics, falling rim debris, small impact craters or impact ejecta on Mars.

As noted above, the crater mounds bracket the latitudinal median of the crater, are concentrated in a region ∼10 km^2 that is located ∼2–3 km east of the crater centre and are nested in an area of relatively low elevation. Generally, the MOLA data tracks (Fig. 2) indicate that both groups of crater-floor mounds reside in an area of low elevation, although the Group A mounds are slightly more elevated than are the Group B mounds.

Were water to have been present in the crater basin and then gradually lost through evaporation, sublimation or drainage, the areas of lowest elevation in the crater, i.e., the crater floor, are where the vestiges of residual water would have collected. Protected by this vestigial water, the low-lying areas of the crater floor would have been the last to undergo permafrost aggradation if freezing conditions had ensued. Eventually, with the loss of residual water, the regolith beneath the formerly ponded areas also would have frozen. The depth of this newly frozen ground, however, would have been shallower than that of the surrounding regolith that had frozen earlier. Shallow or thin permafrost is more susceptible than thick permafrost to deformation by pore-water pressure and the growth of incipient ice cores. In the Tuktoyaktuk peninsula and other periglacial regions on Earth, a chronology of events leading from lake drainage through permafrost aggradation often initiates the formation of hydrostatic pingos.

4.2. Polygonal patterned ground and other features

Large- and small-sized patterns of polygonal ground are ubiquitous in Utopia Planitia (Seibert and Kargel, 2001) as they are in other mid- to high-latitude regions of Mars (Lucchitta, 1981; Kuzmin et al., 2002; Pechmann, 1980; Seibert and Kargel, 2001; Yoshikawa, 2002). Generally, the martian polygons are characterised as large when their trough to trough diameters are $\gtrsim$250 m; many large polygons are kilometres in diameter; some polygons are as large as ≈20 km in diameter (Kanner et al., 2003; Lucchitta, 1981; Pechmann, 1980; Rossbacher and Judson, 1981; Seibert and Kargel, 2001; Wenrich and Christensen, 1993; Yoshikawa, 2002).

The study of periglacial landscapes on Earth suggests that the stress of contraction exceeds the tensile strength of frozen ground at distances measured in metres not kilometres (Lachenbruch, 1962). Even if one accounts for the differences between the gravitational forces of Earth and of Mars in calculating the relative rates of surface stress and strain on both planets, planetary scientists think that the large martian polygons are too big to have been formed by thermal contraction (Heisinger and Head, 2000; Pechmann, 1980; Rossbacher and Judson, 1981; Seibert and Kargel, 2001). Some of the processes that have been suggested to explain the formation of large polygons on Mars include the cooling of lava flows (Morris and Underwood, 1978) tectonic rebound following the removal of the water/ice load in areas such as the Utopia Basin (Carr and Head, 2003; Heisinger and Head, 2000; Pechmann, 1980) and dessication of water-saturated sediments (Morris and Underwood, 1978).

Martian polygons are characterised as small if their trough to trough diameters are < ∼250 m (Kanner et al., 2003; Kuzmin et al., 2002; Mellon, 1997; Pechmann, 1980; Seibert and Kargel, 2001). Small-sized patterns of polygonal terrain have been identified in areas of low elevation in the high to mid-latitudes of both martian hemispheres (Mellon, 1997; Seibert and Kargel, 2001). At these poleward latitudes, the partial pressure of water vapour and maximum annual temperatures are consistent with the possible presence of near-surface ground ice or ice-cemented permafrost (Feldman et al., 2002; Mellon et al., 1997; Seibert and Kargel, 2001). The largest concentration of small-scale polygons is in and around the Utopia basin (Seibert and Kargel, 2001). Most of the polygons in EO300299 are < ∼250 m in diameter; many of them are ∼100–200 m in diameter; (Fig. 1). Polygons < ∼100 m in diameter may be present on the crater floor but this evaluation is limited by the coarse resolution of EO300299.

To what extent are polygons of this size consistent with thermal contraction theory? Recently, it has been suggested that the depth to which a fracture forms in permafrost is contingent upon the rheological properties of the ground more than it is on the penetration depth of surface temperatures (Maloof et al., 2002). Deep cracks will propagate more easily in very cold and very brittle ground than in warmer ground that is less brittle. On the assumption that the martian regolith is very cold, with temperatures below 60 K in some places, and consequently, very brittle, it has been argued that cracks as deep as ∼100 m could form (Mangold, in preparation). If the diameter of small-scale polygons is proportional to crack depth, then a crack depth of ∼100 m in the very cold regolith of Mars could initiate the formation of polygons that are ∼200–300 m in diameter.

The size of the Utopia crater-floor polygons is consistent with that of terrestrial polygons formed by thermal contraction. If water had been present on the crater floor, crack infiltration and ice-wedge formation could have occurred. In addition, while the general orientation of the martian polygons in EO300299 is random (Fig. 1), the polygons immediately to the east of the Group A mounds are orthogonal to the Group A terrace, are at a lower elevation and lie within a curvilinear feature that could be a channel. We suggest that the channel might have been a collection point for vestigial water as crater water was being lost through evaporation, sublimation or drainage. As noted above, when lakes or rivers in terrestrial periglacial regions drain slowly, thermal contraction cracks form orthogonally, either normal to or parallel with the contour of the lake basin or shoreline.

The morphology of the dendrite/trunk assemblage to the west of the Group A terrace is similar to that of an ordered, terrestrial, fluvial system. Drainage of this system into the graded basin upon which lie the mounds of Group B also is consistent with terrestrial fluvial analogues. We suggest that water could have collected locally between the two groups of mounds in the northwest quadrant of EO300299 and then flowed into the Group B basin that grades to the east. This is consistent with the MOLA data tracks and with the crater peak hypothesis that explains the general loss of elevation away from the centre of the crater in an eastwardly direction.

The processes required by the formation of drained-lake hydrostatic pingos—freezing and pore water expulsion—differ from the processes leading to the cracking of frozen ground and the formation of ice-wedge polygons—thermal contraction induced by sudden, severe drops of sub-zero temperature, the in-filling of cracks by liquid water and the subsequent freezing of this water. But both processes are contingent upon the availability of liquid water and of freezing temperatures. In terrestrial periglacial regions like the Tuktoyaktuk peninsula, it is not unusual to find hydrostatic pingos and fields of polygonal patterned ground underlain by ice-wedges lying side by side (Fig. 3). Sometimes, the evolution of the two landforms is concurrent (Mackay, 1999). On Richard's Island, not far from the Tuktoyaktuk peninsula, the formation of ground cracks, ice wedges and of small pingos has been reported within ten years of lake drainage (Mackay, 1999).

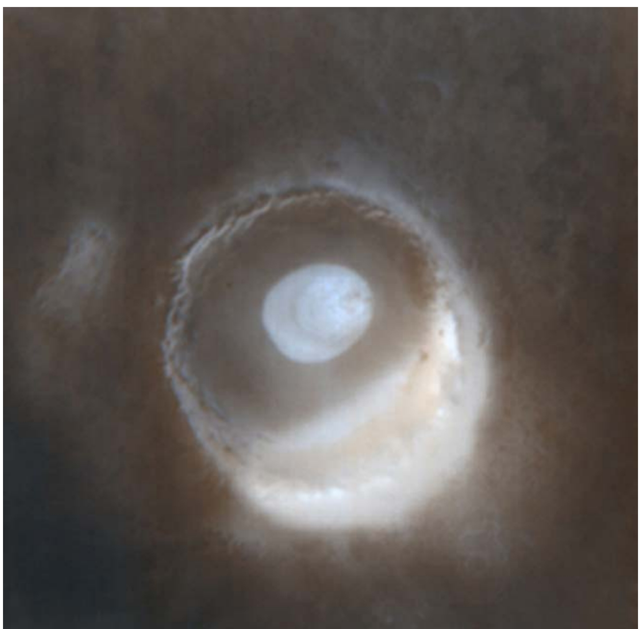


Fig. 8. MOC image M2000356; frosted northern crater centred near 71° N, 257° W, late spring. Crater is ∼48 km across.

5. Possible sources of crater-basin water

There are two possible sources of water in the crater, both of them mobilised by high obliquity. A recent hypothesis relates the transportation of water vapour from high polar latitudes to middle latitudes when obliquity exceeds 30° (Head et al., 2003; Mustard et al., 2001). Upon reaching the middle latitudes the water vapour nucleates on dust particles in the air or on the ground; subsequently, the water-nucleated particles coalesce and cover the regolith like an ice-rich blanket (Head et al., 2003). The ice-rich blanket could be similar in appearance to the blanket of seasonal frost that accumulates in high to mid-latitude impact craters on Mars today as the result of atmospheric transportation and deposition (Fig. 8).

The higher temperatures and atmospheric pressure that accompanied the last episode of high obliquity (Head et al., 2003; Mustard et al., 2001) could have induced the melting of this atmospherically transported ice, the formation of ponded lakes on the floor of impact craters in the northern plains and the saturation by water of the regolith underlying the crater lakes. As Mars moved away from obliquity, temperature and atmospheric pressure would have fallen. The decline of temperature and of atmospheric pressure might have initiated a series of pingo-forming events: (1) dissipation and subsequent evaporation or sublimation of ponded water; (2) permafrost aggradation and pore-water expulsion within the porous crater-floor, its porosity having been produced by a combination of impact, aeolian and possible fluvio-lacustrine-marine processes (Feldman et al., 2002); (3) formation of an ice-core below the area in which vestigial water collected on the crater floor; and (4) deformation of the crater-floor surface by the ice core. On the other hand, the volume of water-ice emplaced in a relatively small impact crater by atmospheric transportation at high obliquity could be insufficient to initiate a series of hydrological and periglacial events that lead to pingo formation.

A second possible source of water in the crater, in the surrounding landscape and in the northwest quadrant of the Utopia basin is old, near-surface ground ice that has melted. This ground ice could have formed in the late Hesperian to early Amazonian sediments laid down by the massive discharges of the circum-Chryse channels (Carr and Head, 2003; Costard and Kargel, 1995). Generally, the presence of fluidised ejecta surrounding impact craters on Mars is thought to be an indication of near-surface ground ice (Costard and Kargel, 1995; Barlow and Perez, 2003). Neither the Viking Orbiter image M165N295 nor EO300300 are of sufficiently fine resolution to clearly identify fluidised ejecta surrounding the EO299300 crater. However, of the thirty-three Mars Odyssey Thermal Emission Imaging System (THEMIS) context images centred within a $\sim 5°$ longitudinal and latitudinal radius of the EO300299 crater, nearly all of them identify impact craters surrounded by fluidised ejecta. This finding is consistent with the recent data generated by the Mars Odyssey Neutron Spectrometer, which suggests that near-surface regolith poleward of 60° latitude is rich in hydrogen, possibly water-ice (Feldman et al., 2002; Boynton et al., 2002; Mitrofanov et al., 2002). As with the first hypothesis, the second hypothesis suggests that high obliquity is the key to constructing a plausible scenario of pingo formation. Initially, the higher temperatures associated with high obliquity could have induced the melting of ground ice in the Utopia crater basin. The combination of higher temperatures and atmospheric pressure, in turn, would enable the melted ground ice to stabilise and pond. Thereafter, the lowering of temperature and of atmospheric pressure associated with the loss of obliquity could engender the same course of pingo-forming events described by the first hypothesis.

A third hypothesis integrates hypotheses one and two.

6. The age of the crater-floor features

We hypothesise that the crater-floor landscape identified by EO300299 is relatively young, perhaps dating back to the last episode of obliquity $\sim 100{,}000$ years ago. The hypothesis is based upon four assumptions. First, the impact crater lies within an area of the northern plains that may have undergone re-surfacing as recently as the early Amazonian period (Tanaka et al., 2003). The formation of the crater postdates this resurfacing and the crater rampart shows relatively few signs of erosion or deformation. Second, the dendritic features, main trunk and fields of polygonal patterned ground on the crater floor are neither highly eroded nor are they overwhelmed with dust and debris. Similarly, the mound crosses appear to be relatively free of dust and debris. Third, if the crater-floor mounds are hydrostatic pingos then the general absence of collapse features in their midst suggests that their ice-cores may still be extant. The ice-cores of older hydrostatic pingos on Mars are more likely to sublimate than are the ice-cores of younger hydrostatic pingos. Although hydraulic pingos may have their ice cores replaced by sediments (Davis, 2001), hydrostatic pingos appear to maintain their positive relief only if an ice core is present. Fourth, the formation of the crater-floor landscape, as an assemblage of landforms and landform attributes, is consistent with the warmer temperatures and higher atmospheric pressure that may have prevailed at the time of the most recent episode of high obliquity.

7. Summary

The size and shape of the Utopia crater-floor mounds are consistent with the size and shape of hydrostatic, drained-lake pingos such as those found in the Tuktoyaktuk peninsula. The crater mounds are located in an area of low elevation in a crater-floor basin. This location is consistent with an origin and with growth tied to the past presence of ponded water, water drainage and of hydrostatic processes. The areas of least elevation are where ninety-eight percent of the drained-lake pingos in the Tuktoyaktuk peninsula are found (Mackay, 1979). In addition, the crater-floor mounds are closely associated with basin, curvilinear and dendritic-like features that we interpret as having been formed by water.

Some of the crater-floor mounds are crossed; some may be depressed or collapsed. Crossed pingos are common in the landscape of the Tuktoyaktuk peninsula, as are pingos with summit depressions and collapse features. The size of the polygon cracks on the crater floor is consistent with thermal contraction theory and may be indicative of ice wedging. The polygons that share the landscape with the hydrostatic pingos in the Tuktoyaktuk peninsula are underlain by ice wedges and are the product of thermal contraction.

We have shown that the assemblage of landforms—mounds and polygonal patterned ground—in the Utopia impact crater is consistent with the assemblage of landforms - hydrostatic pingos and thermal contraction polygons—of the Tuktoyaktuk peninsula. The assemblage of landforms also is consistent with the presence of near-surface ground ice in the mid- to high- latitudes—identified by the Gamma Ray Spectrometer and by the THEMIS context images noted above. Examination of other mid- to high-latitude craters may reveal similar geomorphological assemblages.

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References

Barlow, N.G., Perez, C.B., 2003. Martian impact crater ejecta morphologies as indicators of the distribution of subsurface volatiles. J. Geophys. Res. 108 (E8).

Bennike, O., 1998. Pingos at Nioghalvfjerdsfjorden, eastern North Greenland. Geol. Greenland Surv. Bull. 180, 159–162.

Boynton, W.V., 24 colleagues, 2002. Distribution of hydrogen in the near surface of Mars: evidence for subsurface ice deposits. Science 296, 81–85.

Cabrol, N.A., Grin, E.A., Pollard, W.H., 1997. Perennial frost mounds in Gusev crater (Mars). Lunar Planet. Sci. 28. Abstract 1027.

Cabrol, N.A., Grin, E.A., Pollard, W.H., 2000. Possible frost mounds in an ancient martian lake bed. Icarus 145, 91–107.

Carr, M.H., Head, J.W., 2003. Oceans on Mars: an assessment of the observational evidence and possible fate. J. Geophys. Res. 108 (E5).

Costard, F.M., Kargel, J.S., 1995. Outwash plains and thermokarst on Mars. Icarus 114, 93–112.

Cruickshank, J.G., Calhoun, E.A., 1965. Observations on pingos and other landforms in Schuchertdal, northeast Greenland. Geogr. Ann. 471, 224–236.

Davis, N., 2001. Permafrost: A Guide to Frozen Ground in Transition. Univ. of Alaska Press, Fairbanks, Alaska.

De Hon, R.A., 1997. The relationship of subdued grooved terrain, mesas and knobs in northeast Elysium Planitia. Lunar Planet. Sci. 28. Abstract 1446.

Feldman, W.C., 12 colleagues, 2002. Global distribution of neutrons from Mars: results from Mars Odyssey. Science 297 (5578), 75–78.

French, H.M., 1993. Cold-climate processes and landforms. In: French, H.M., Slaymaker, O. (Eds.), Canada's Cold Environments. McGill Queens Univ. Press, Montreal, pp. 271–290.

Greeley, R., Guest, J.E. 1987. Geological map of the eastern equatorial region of Mars. USGS Misc. Invest. Series Map I-11802-B, 1:15,000,000. Geologic Series. U.S. Geological Survey, Denver, Colorado.

Grin, E.A., Cabrol, N.A., 1998. Limnologic analysis of Gusev crater paleolake, Mars. Icarus 130, 461–474.

Gurney, S.D., 1998. Aspects of the genesis and geomorphology of pingos: perennial permafrost mounds. Prog. Phys. Geog. 22.3, 307–324.

Head, J.W., Mustard, J.F., Kreslavsky, M.A., Milliken, R.E., Marchant, D.R., 2003. Recent ice ages on Mars. Science 426, 797–802.

Heisinger, H., Head, J.W., 2000. Characteristics and origin of polygonal terrain in southern Utopia Planitia, Mars: results from Mars Orbiter Laser Altimeter and Mars Orbiter Camera data. J. Geophys. Res. 105 (E5), 11999–12022.

Kanner, L.C., Bell, M.S., Allen, C.C., 2003. Prospecting for martian ice from orbit. In: 3rd Mars Polar Science Conference. Abstract 8113.

Kargel, J.S., Costard, F.M., 1993. Possible occurrence and origin of massive ice in Utopia Planitia. In: Ice and Water in the Northern Plains, MSATT Workshop on the Martian Northern Plains. Lunar Planet. Sci.

Kuzmin, R.O., Ershow, E.D., Komarow, L.A., Kozlov, A.H., Isaev, V.S., 2002. The comparative morphometric analysis of polygonal terrain on Mars and the Earth high latitude areas. Lunar Planet. Sci. 33. Abstract 2030.

Lachenbruch, A.H., 1962. Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost. Geol. Soc. Am. Special Paper 70, 69 p.

Lanagan, P.D., McEwen, A.S., Keszthelyi, L.P., Thordarson, T., 2001. Rootless cones on Mars indicating the presence of shallow equatorial ground ice in recent times. Geophys. Res. Lett. 28 (12), 2365–2367.

Lasca, N.P., 1969. The surficial geology of Skeldal, Mesters Vig, northeast Greenland. Meddelelser om Grønland 176 (3), 2–54.

Lewkowicz, A.G., Duguay, C.R., 1999. Detection of permafrost features using SPOT Panchromatic Imagery, Fosheim Peninsula, Ellesmere Island, N.W.T. Can. J. Remote Sensing 25, 34–44.

Lucchitta, B.K., 1981. Mars and Earth: comparison of cold climate features. Icarus 45, 264–303.

Lucchitta, B.K., 1993. Ice in the northern plains, relic of a frozen ocean. In: MSATT Workshop on the Martian Northern Plains. Lunar Planet. Sci., Tech. Rep. 93-04, 9–10.

Mackay, J.R., 1962. The pingos of the Pleistocene Mackenzie Delta area. Geogr. Bull. 18, 21–63.

Mackay, J.R., 1966. Pingos in Canada. In: Permafrost International Conference, Proceedings. National Research Council, Publication 1287. National Academy of Science, Ottawa, Canada, pp. 71–76.

Mackay, J.R., 1979. Pingos of the Tuktoyaktuk Peninsula area, Northwest Territories. Geogr. Phys. Quatern. 33 (1), 3–61.

Mackay, J.R., 1987. Some mechanical aspects of pingo growth and failure, western Arctic coast, Canada. Can. J. Earth Sci. 24 (6), 1108–1119.

Mackay, J.R., 1998. Pingo growth and collapse, Tuktoyaktuk Peninsula area, western Arctic coast, Canada: a long-term field study. Geogr. Phys. Quatern. 52 (3), 271–323.

Mackay, J.R., 1999. Periglacial features developed on the exposed lake bottoms of seven lakes that drained rapidly after 1950, Tuktoyaktuk Peninsula area, western Arctic coast, Canada. Permafrost Periglac. 10, 39–63.

Maloof, A.C., Kellogg, J.A., Anders, A.M., 2002. Neoproterozoic sand wedges: crack formation in frozen soils under diurnal forcing during a snowball Earth. Earth Planet. Sci. Lett. 204, 1–15.

Marchant, D.R., Lewis, A.R., Phillips, W.M., Moore, E.J., Souchez, R.A., Denton, G.H., Sugden, D.E., Potter Jr., N., Landis, G.P., 2002. Formation of patterned ground and sublimation till over Miocene glacial ice in Beacon Valley, southern Victoria Land, Antarctica. Geol. Soc. Am. Bull. 114 (6), 718–730.

Mellon, M.T., 1997. Small-scale polygonal features on Mars: seasonal thermal contraction cracks in permafrost. J. Geophys. Res. 102 (E11), 25617–25628.

Mellon, M.T., Jakosky, B.M., Postawko, S.E., 1997. The persistence of equatorial ground ice on Mars. J. Geophys. Res. 102 (E11), 19357–19369.

Melosh, H.J., 1985. Impact Cratering: A Geologic Process. Oxford Univ. Press, Oxford.

Mitrofanov, I., 11 colleagues, 2002. Maps of subsurface hydrogen from the High Energy Neutron Detector, Mars Odyssey. Science 5578 (297), 78–81.

Morris, E.C., Underwood, J.R., 1978. NASA Tech. Mem. 79729, 97–99.

Müller, F., 1962. Observations on pingos. Meddelelser om Grønland 153 (3), 1–117. Translated by D.A. Sinclair, National Research Council of Canada.

Mustard, J.F., Cooper, C.D., Rifkin, M.F., 2001. Evidence for recent climate change on Mars from the identification of youthful near-surface ground ice. Nature 412, 411–414.

O'Brien, R., 1971. Observations on pingos and permafrost hydrology in Schuchert Dal, northeast Greenland. Meddelelser om Grønland 195 (1), 1–19.

Pechmann, J.C., 1980. The origin of polygonal troughs on the northern plains of Mars. Icarus 42, 185–210.

Parker, T.J., Banerdt, W.B., 1999. Observational tests of the Mars ocean hypothesis: selected MOC and MOLA results. In: 5th International Conference on Mars. Lunar and Planetary Science Institute, Houston. Abstract 6114.

Plug, L.J., Werner, B.T., 2002. Nonlinear dynamics of ice-wedge networks and resulting sensitivity to severe cooling events. Nature 417, 929–932.

Rice, J.W., Parker, T.J., Russel, A.J., Knudsen, O., 2002. Morphology of fresh outflow channel deposits on Mars. Lunar Planet. Sci. 33. Abstract 2026.

Romanovskii, N.N., Hubberten, W.H., Gavrilov, A.V., Tumskoy, V.E., Tipenko, G.S., Grigoriev, M.N., Siegert, C., 2000. Thermokarst and land–ocean interactions, Laptev Sea Region, Russia. Permafrost Periglac. 11, 137–152.

Rossbacher, L.S., Judson, S., 1981. Ground ice on Mars: inventory, distribution and resulting landforms. Icarus 45, 39–59.

Seibert, N.M., Kargel, J.S., 2001. Small-scale martian polygonal terrain: implications for liquid surface water. Geophys. Res. Lett. 28 (5), 899–902.

Sletten, R.S., Hallett, B., Fletcher, R.C., 2003. Resurfacing time of terrestrial surfaces by the formation and maturation of polygonal patterned ground. J. Geophys. Res. 108 (E4), 8044.

Soare, R.J., Peloquin, C., 2003. A crater-based periglacial landscape in northwest Utopia Planitia. EOS Trans. AGU, Fall Meet. Suppl. 84, 46.

Tanaka, K.L., Skilling, I., Skinner, J., 2000. Mega-lahars of Elysium, Mars. In: Volcano/Ice Interaction on Earth and Mars Conference, University of Iceland, Reykjavik, Iceland. Abstract, p. 54.

Tanaka, K.L., Skinner Jr., J.A., Hare, T.M., Joyal, T., Wenker, A., 2003. Resurfacing history of the northern plains of Mars based on geologic mapping of Mars Global Surveyor data. J. Geophys. Res. 108 (E4).

Theilig, E., Greeley, R., 1979. Plains and channels in the Lunae Planum-Chryse Planitia region of Mars. J. Geophys. Res. 84 (814), 7994–8010.

Thomson, B.J., Head, J.W., 2001. Utopia basin, Mars: characterisation of topography and morphology and assessment of the origin and evolution of basin internal structure. J. Geophys. Res. 106, 1–22.

Washburn, A.L., 1973. Geocryology: A Survey of Periglacial Processes and Environments. Wiley, New York.

Wenrich, M.L., Christensen, P.R., 1993. A formational model for the polygonal terrains of Mars: taking a 'crack' at the genesis of the martian polygons. In: MSATT Workshop on the Martian Northern Plains. Lunar Planet. Sci., Tech. Rep. 93-04, 17–18.

Yoshikawa, K., 2002. Origin of the polygons and underground structures in western Utopia. Lunar Planet. Sci. 33. Abstract 1159.