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Notes

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ABSTRACT

On Earth, permafrost thawing is linked to climate warming. Similarly, on Mars, permafrost degradation, described from mid-latitude and equatorial settings, is likely linked to global or regional climate change. Putative thermokarst depressions identified on Mars are widely considered to be the result of sublimation, evaporation, or thawing of an ice-rich substrate. The possibility that the depressions formed by melting of permafrost to create alas-like lakes has been recently proposed, but is controversial, owing to the lack of primary evidence for liquid filling the depressions. Here we use high-resolution Mars Reconnaissance Orbiter Context Camera images and derived topographic data to characterize possible thermokarst terrain in Ares Vallis. The terrain comprises subcircular to irregular, flat-floored rimless topographic depressions that occur at varying elevations. We report the discovery of narrow channels connecting thermokarst-like depressions that provide evidence for the previous presence of ponded liquid water. Crater counts on these surfaces indicate resurfacing that is likely related to flood deposition of water-saturated sediments in Ares Vallis during the Hesperian (ca. 3.6–3.0 Ga). We infer that thermokarst lakes formed after flooding by thawing of ice within the sediments during transient warm periods in the Hesperian, a time previously considered to be too cold to permit ice thaw.

INTRODUCTION

The surface of Mars contains multiple lines of evidence that liquid water has flowed and/or ponded at various times in its earliest history until the Noachian-Hesperian boundary (ca. 3.7 Ga) (Fassett and Head, 2008). During the Hesperian–Amazonian (3.7 Ga to the present) the climate is considered to have been a cold, hyperarid desert with conditions generally below the triple point of water (Carr, 2007). Under current climate conditions, water is stable only as ice within the upper few meters of the surface at latitudes >60° (Costard and Kargel, 1995; Mellon et al., 1997; Mellon and Phillips, 2001). Evidence for Amazonian age near-surface water ice is present within the mid-latitude and equatorial regions of Mars and is defined by the occurrence of possible periglacial features such as alas-like depressions, pingos, rock glaciers, and polygonally fractured terrain (Carr, 2007).

Of these relict ice features, thermokarst-like rimless depressions have recently warranted attention due to the disputed role of liquid water in their formation. These depressions have previously only been described on Amazonian-age mantled terrains at Utopia Planitia, Elysium Planitia, Malea Planum, Mangala Valles, Hellas basin, and the Cerberus Plains (Costard and Kargel, 1995; Mustard et al., 2001; Seibert and Kargel, 2001; Burr et al., 2005; Levy and Head, 2005; Page and Murray, 2006; Morgenstern et al., 2007; Costard et al., 2008; Soare et al., 2008; Lefort et al., 2009). They are defined by a circular or lobate map-view morphology, often have flat and polygonally fractured floors, are sometimes rimmed by multiple sets of interior terraces, and sometimes contain small, circular mounds that resemble terrestrial pingos (French, 2007; Soare et al., 2008). Currently, the depressions are regarded as either water-ice sublimation pits (Morgenstern et al., 2007; Lefort et al., 2009) or depressions formed from the evaporation of liquid water (thermokarst basins, or alases) (Costard and Kargel, 1995; Soare et al., 2008). The first hypothesis invokes sublimation of near-surface ice and collapse of the substrate. The second hypothesis requires climate warming beyond the triple point of water and melting of ice-rich sediments to form small ponded lakes. Previous studies that favored the melting hypothesis have lacked unequivocal evidence of morphologies that are unique to formation by liquids.

Here we analyze high-resolution Mars Reconnaissance Orbiter Context Camera (CTX) images (6 m $pixel^{-1}$), derived CTX digital terrain models (DTMs) with 18 m grid spacing (Kim and Muller, 2009) (see the GSA Data Repository[1]), and Mars Orbiter Laser Altimeter (MOLA) topography data to describe thermokarst-like features from the Ares Vallis outflow channel. We describe previously unidentified morphologic indicators of permafrost thaw and overland fluid exchange between thermokarst-like depressions that suggest a brief period of surface water stability. Furthermore, we present relative age relationships and high-resolution crater statistics that constrain the time of formation to the Hesperian period.

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[1]GSA Data Repository item 2010012, CTX Digital Terrain Model (DTM) construction methods, assessment of DTM height accuracy, crater count methods, and Figures DR1–DR8, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

GEOLOGIC SETTING

Ares Vallis is one of the largest outflow channels on Mars. In its proximal reach there are two north-south–oriented channels, identified here as the eastern and western branches, that emerge from Iani Chaos (Baker, 1982; Komatsu and Baker, 1997; Pacifici et al., 2009) (Fig. DR1). Within crater Y, centered at 2.5°N, 344°E, the eastern branch of Ares Vallis bisects an ~250-m-thick crater-fill unit (Fig. 1) that exhibits numerous irregular depressions (Pacifici et al., 2009) (Figs. 1 and 2; Fig. DR2). This unit embays the walls of the impact crater, indicating that it was deposited after formation of the crater.

POSSIBLE THERMOKARST LANDFORMS: OBSERVATIONS AND INTERPRETATION

The depressions within crater Y are rimless, noncircular, sometimes lobate, and have a maximum width of ~7.5 km. The floors of the depressions are relatively flat. The depth of each feature, measured from MOLA- and CTX-derived topography data, varies from 20 m to 250 m with a mean depth of ~130 m (Fig. 2; Fig. DR2b). Polygonal patterned ground, the result of thermal contraction of an ice-rich substrate, is common to thermokarst terrains on Earth and Mars (Kuzmin et al., 2002; French, 2007; Soare et al., 2008; Levy et al., 2009). CTX images display local evidence in crater Y for polygonal fractures exposed through gaps in a thin (1–10 m) surface mantle (Fig. DR3). These polygons are superimposed by the local crater population, are 95–180 m in diameter, and are similar at the largest scale to ice-wedge polygons on the flood plains of the Yamal Peninsula in Siberia (60–80 m) (Kuzmin et al., 2002). In addition, conical mounds are present within a few depressions, being absent on the upper surface of the deposit (Fig. DR3). These features are ~400 m in diameter and may be analogous to

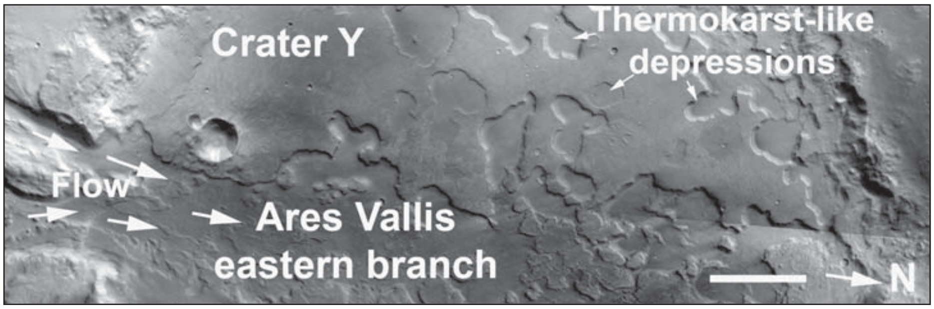

Figure 1. Mars Reconnaissance Orbiter Context Camera mosaic of thermokarst terrain within crater Y in proximal Ares Vallis. Surface is marked by several flat-floored depressions that may represent ancient alas-like lakes. Thermokarst terrain is bisected by eastern branch of Ares Vallis. Scale bar is 10 km.

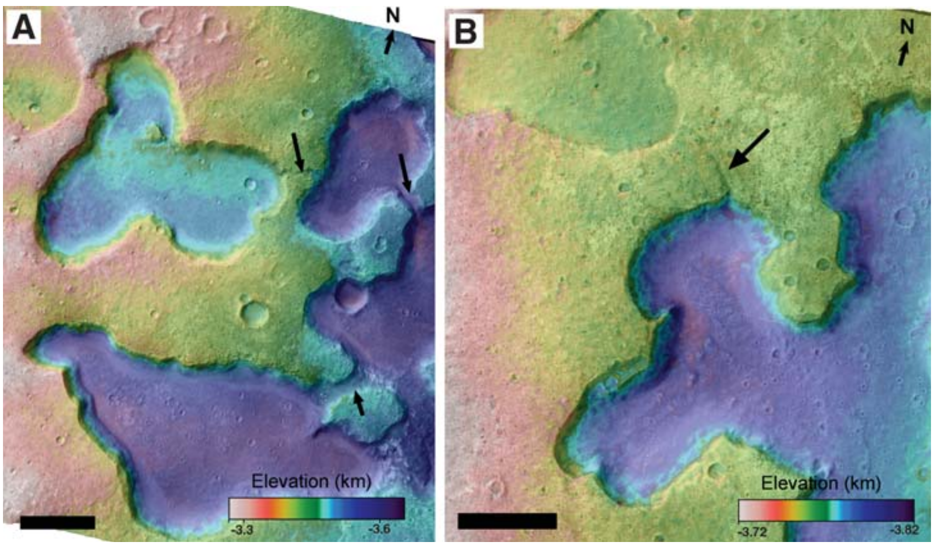

Figure 2. Mars Reconnaissance Orbiter Context Camera digital terrain models (DTM; 18 m) of thermokarst-like depressions within crater Y in Ares Vallis. Images are DTMs overlain by transparent orthoimagery. Topography data illustrate that channels form networks connecting depressions of different base elevation. Scale bars are 2 km.

terrestrial perennial ice-cored mounds (pingos), commonly associated with thermokarst depressions (Gurney, 1998; Soare et al., 2008). Alternatively, these mounds may represent remnants of pedestal craters that did not completely degrade during thermokarst formation. The spatial occurrence and morphology of this suite of landforms are indicative of permafrost degradation processes on Earth and Mars.

Here we present the discovery of linear to sinuous channel-like features that connect the depressions on the floor of crater Y (Figs. 2 and 3). The channel-like features range in length from 1.2 to 4.3 km and in width from 70 to 100 m and have a general west-east strike. Figure 3A identifies a 1.2-km-long, 70-m-wide sinuous feature centered at 2.63°N, 343.82°E that connects two depressions with a difference in base elevation of ~90 m. Figure 3B illustrates a 1.8-km-long, 100-m-wide linear channel-like form located at 2.27°N, 343.83°E that connects depressions with a difference in base elevation of ~210 m. The channel-like feature displayed in Figure 3C is centered at 2.78°N, 343.79°E. Like all depression-connecting channel forms identified here, this 2.8-km-long, 80-m-wide feature connects two depressions of significantly different base elevations (~230 m). A 4.3-km-long, 70-m-wide sinuous feature located at 2.29°N, 343.72°E connects depressions with a difference in base elevation of ~60 m (Fig. 3D).

We interpret these features as channels that connected former fluid-filled depressions, based on their sinuous morphology and similarity to terrestrial alas-lake connecting sinuous channels. Alas lake-connecting channels on the north coast of Alaska, identified in Figure 3F, are 0.5–5 km long, 50–180 m wide, and connect lakes that range in diameter from 100 m to 6 km. To date, evidence for fluid movement between thermokarst depressions on Mars is lacking. This has led many authors to reject the alas-lake hypothesis in favor of ice sublimation and/or collapse mechanisms (Burr et al., 2005; Morgenstern et al., 2007; Lefort et al., 2009). The only hypothesis that is consistent with the observed morphologies in this analysis is that the depressions were fluid filled in the past, and that there was fluid exchange between them. These observations are inconsistent with a solely sublimation origin, and suggest permafrost thaw.

Supporting the hypothesis for fluid flow, the topography data indicate that all channel-like features in the west portion of crater Y connect depressions with progressively lower base elevations, and show a west-east orientation that suggests flow toward the crater Y bisecting erosion channel (Fig. 2). In addition, channels are only found between depressions that are in close proximity (within ~4.5 km). Figure 2A identifies a connected network of channels that tap three depressions. These networks may have drained eastward in response to base-level changes resulting from breaching of lakes during erosion of the crater Y bisecting outflow channel (Fig. 1). Drainage of the breached channel-proximal lakes likely initiated progressive eastward-directed tapping of nonbreached lakes.

A second set of depressions that are inferred to be thermokarst in origin is found within putative flood deposits on the floor of the main western channel of Ares Vallis, centered at 13°N, 332°E (Figs. DR1 and DR5) (Costard and Baker, 2001; Pacifici et al., 2009). In this distal reach of Ares Vallis, the outflow channel broadens where the thermokarst terrain is exposed. Here we identify similar depression-connecting sinuous channels that may also indicate a thermokarst-lake origin (Fig. 3E). The depressions in this region are similar in dimension and map-view morphology to the features in crater Y. Polygonal terrain is identified on the floors of the features and may either represent fractures within the basal sequence of the deposit, or fractures from an older unit now superimposed by the thermokarst terrain (Fig. DR3). Inferred thermokarst depressions are also present within layered materials along the west bank of medial Ares Vallis (6.93°N, 338.76°E). Figure 3G identifies a sinuous channel-like feature that connects a thermokarst-like depression to the main channel of Ares Vallis. The identification of relict thermokarst lakes in the proximal, medial, and distal portions of the outflow system suggests that permafrost thaw and thermokarst-lake formation could have been a regional process.

CHRONOLOGY OF THERMOKARST-LAKE FORMATION

Table 1 summarizes crater statistics acquired from CTX images for crater diameters (D) >100 m on the thermokarst terrains and associated flood erosion surfaces (see the Data Repository). For the thermokarst terrain in crater Y,

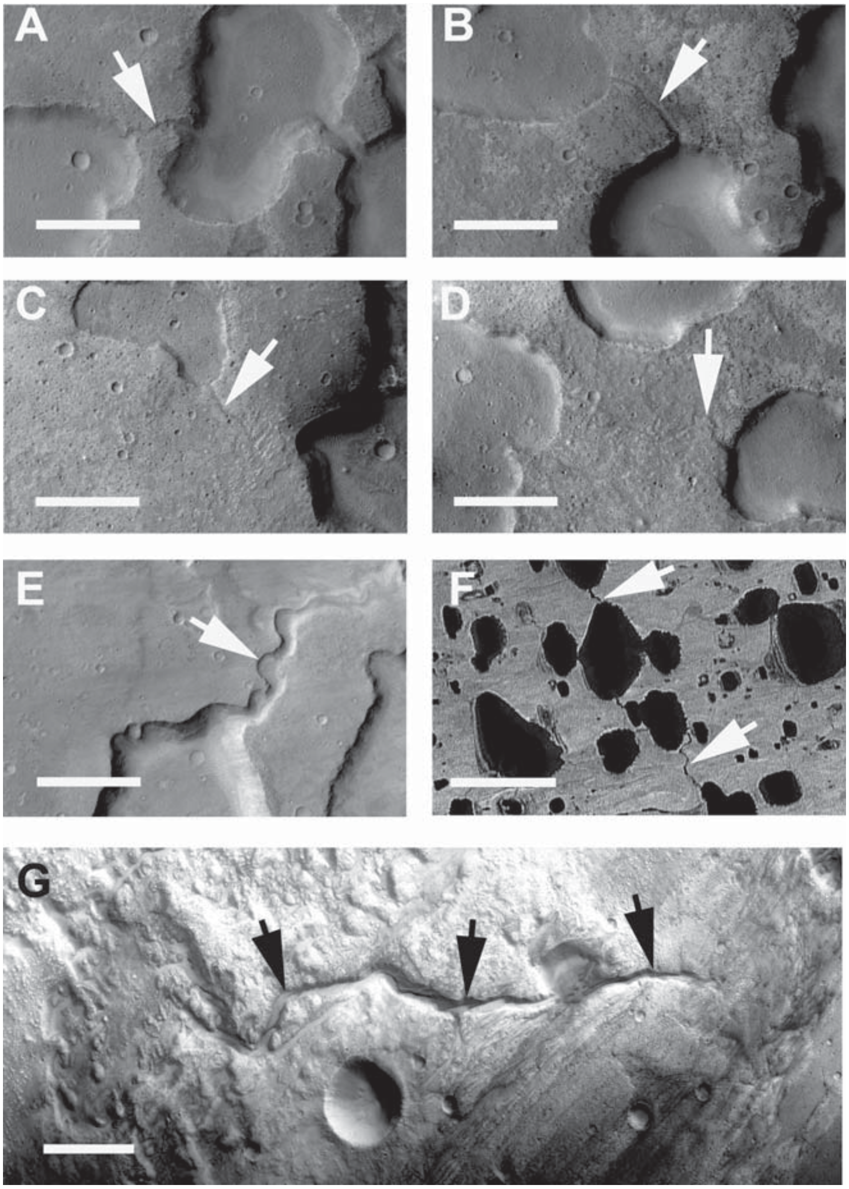

Figure 3. A–D: Mars Reconnaissance Orbiter Context Camera (CTX) images of depression connecting channels on thermokarst surface of crater Y in Ares Vallis. Scale bars represent 2 km. E: CTX image of depression-connecting channel in distal Ares Vallis. Scale bar is 2 km. F: Alas lakes with lake-connecting channels in northern Alaska. Image provided by Google Earth (http://earth.google.com). Scale bar is 5 km. G: Large sinuous channel leaving irregular depression along west bank of Ares Vallis. Scale bar is 4 km.

a model fit (Hartmann and Neukum, 2001) to postdepositional impact craters (D = 700 m–1.6 km), superimposed on the thermokarst surface, indicates a surface age of ca. 3.30 Ga (Fig. DR7). Craters <700 m ± 150 m in diameter show poor preservation in the Ares Vallis region due to dust burial and rim modification by wind. For the erosional surface of the channel that bisects crater Y (Ares Vallis eastern branch), a model age of ca. 3.62 Ga was determined from postflood, unmodified impact craters. The observed crosscutting relationship of the crater Y bisecting channel with the thermokarst-like depressions indicates that the depressions formed before this particular fluvial erosional event (Fig. 1). However, the crater model ages provided here suggest a younger age for the thermokarst terrain relative to the flood channel. This apparent inconsistency can be explained if degradation of ice continued throughout the final crater Y incision event, preventing surface hardening and crater retention until 3.30 Ga. Importantly, the stratigraphic relationships indicate that ice-rich sediment must have been present within crater Y before formation of the crater Y bisecting channel. This suggests that deposition of water-saturated sediment occurred before 3.62 Ga. Deposition was likely caused by earlier, more voluminous floods in the eastern branch of Ares Vallis that were responsible for carving the ~1-km-deep, ~20-km-wide overspill channels that enter and exit crater Y.

Within distal Ares Vallis, for craters with D > 2 km, a predeposition surface age of ca. 3.77 Ga is indicated. The large crater (D > 2 km) population in distal Ares Vallis is represented by highly subdued impact craters that were likely exhumed from an older Noachian surface during Hesperian weathering and flood erosion (Fig. DR6). These large craters were subsequently partially buried by the deposits that exhibit thermokarst depressions. At D < 2 km, a model age for impact craters superimposed on the thermokarst terrain is ca. 2.94 Ga. For comparison, crater statistics from the proximal bedrock erosion surface of the western branch of Ares Vallis indicate a postflood surface age

TABLE 1. CRATER STATISTICS FOR THE THERMOKARST AND EROSION SURFACES OF ARES VALLIS, MARS

Surface	Area (km^2)	Counts	N (D = 0.1)	N (D = 0.5)	N (D = 1)	Preflood (Ga)	Postflood (Ga)	Postflood period
Thermokarst crater Y	2051	980	4.78×10^5	7.31×10^3	1.95×10^3	N/A	3.30 +0.17/–0.98	LH*, EA†
Thermokarst distal Ares Vallis	12,913	7604	5.89×10^5	1.73×10^4	3.30×10^3	3.77 +0.05/–0.10	2.94 +0.13/–0.17	LH*, EA†
East branch erosion channel	2243	1795	8.00×10^5	1.25×10^4	3.57×10^3	N/A	3.62 +0.08/–0.18	LN*, EH†
West branch erosion channel	5735	3078	5.37×10^5	9.94×10^3	1.66×10^3	N/A	2.86 +0.39/–0.76	LH*, EA†
Total	22,942	13,457						

Note: Cumulative number, N, of impact craters per 10^6 km^2 is given for diameter D = 0.1 km, 0.5 km, and 1 km. Absolute ages are estimated following model chronology functions (Hartmann and Neukum, 2001) and production functions (Ivanov, 2001).
*Hartmann age system.
†Neukum age system.

of ca. 2.86 Ga. The occurrence of ice-rich sediment and formation of thermokarst-like depressions in this region of Ares Vallis are therefore possibly the results of late Hesperian outflow activity, deposition of water-saturated sediment, freezing, and subsequent thawing to form thermokarst lakes.

DISCUSSION

From morphologic analysis of the thermokarst-like depressions and the crater statistics, we suggest the following: (1) Ground ice was present in specific regions of Ares Vallis, resulting from deposition and freezing of water-saturated sediment during Hesperian outflow activity. The occurrence of smooth deposits exhibiting thermokarst-like features within topographic lows (impact craters and broader portions of channels) suggests that ground ice was present and most likely derived from freezing of wet, flood-derived sediments (Fig. DR1). (2) Ground ice was subsequently melted to form isolated pockets of ponded water. (3) Water evaporated and drained from the lakes into adjacent topographic depressions. In the case of crater Y, erosive floods in the eastern branch of Ares Vallis may have facilitated sudden draining by lowering of the local base level. For this reason, the depressions show little evidence for terracing that would be consistent with gradual drainage or evaporation.

The identification of channels connecting the depressions in Ares Vallis provides strong evidence for the presence of liquid water, supporting the alas-lake hypothesis. Alas lakes on Earth form as a result of permafrost thaw in regions where the volume of ground ice exceeds sediment pore space (French, 2007). Climate fluctuations resulting from intense volcanism (Harrison and Grimm, 2005), large impact events (Segura et al., 2002), and the formation of temporary atmospheres following major outflows (Baker et al., 1991; Santiago et al., 2005) may be the primary triggering factors for permafrost thaw during the Hesperian. In addition, similar obliquity-controlled climate fluctuations to those predicted for the Amazonian may have operated during this period to create transient warm conditions (Head et al., 2003; Forget et al., 2006). However, orbital and climate models that predict these relatively recent climate shifts cannot predict events in the Hesperian. The relict lake depressions in Ares Vallis provide strong evidence for transient warm conditions during the Hesperian period (ca. 3.6–3.0 Ga). Importantly, the extension of warm and wet surface conditions on Mars from the early Noachian (4.5 Ga) into the late Hesperian (3.0 Ga) may have facilitated long-term evolution of microbial life in isolated pockets of stable near-surface and subsurface water.

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REFERENCES CITED

Baker, V.R., 1982, The channels of Mars: Austin, University of Texas Press, 198 p.

Baker, V.R., Strom, R.G., Gulick, V.C., Kargel, J.S., and Komatsu, G., 1991, Ancient oceans, ice sheets and the hydrological cycle on Mars: Nature, v. 352, p. 589–594, doi: 10.1038/352589a0.

Burr, D.A., Soare, R.J., Tseung, J., and Emery, J.P., 2005, Young (late Amazonian), near-surface, ground ice features near the equator, Athabasca Valles, Mars: Icarus, v. 178, p. 56–73, doi: 10.1016/j.icarus.2005.04.012.

Carr, M.H., 2007, The surface of Mars: Cambridge, Cambridge University Press, 322 p.

Costard, F., and Baker, V.R., 2001, Thermokarst landforms and processes in Ares Vallis, Mars: Geomorphology, v. 37, p. 289–301, doi: 10.1016/S0169-555X(00)00088-X.

Costard, F.M., and Kargel, J.S., 1995, Outwash plains and thermokarst on Mars: Icarus, v. 114, p. 93–112, doi: 10.1006/icar.1995.1046.

Costard, F., Forget, F., Madeleine, J.B., and Kargel, J., 2008, The origin and formation of scalloped terrain in Utopia Planitia: Insight from a general circulation model: Lunar and Planetary Science Conference XXXIX, abs. 1234.

Fassett, C.I., and Head, J.W., 2008, The timing of martian valley network activity: Constraints from buffered crater counting: Icarus, v. 195, p. 61–89, doi: 10.1016/j.icarus.2007.12.009.

Forget, F., Haberle, R.M., Montmessin, F., Levrard, B., and Heads, J.W., 2006, Formation of glaciers on Mars by atmospheric precipitation at high obliquity: Science, v. 311, p. 368–371, doi: 10.1126/science.1120335.

French, H.M., 2007, The periglacial environment (third edition): London, John Wiley & Sons, 458 p.

Gurney, S.D., 1998, Aspects of the genesis and geomorphology of pingos: Perennial permafrost mounds: Progress in Physical Geography, v. 22, p. 307–324.

Harrison, K.P., and Grimm, R.E., 2005, Groundwater-controlled valley networks and the decline of surface runoff on early Mars: Journal of Geophysical Research, v. 110, E12S16, doi: 10.1029/2005je002455.

Hartmann, W.K., and Neukum, G., 2001, Cratering chronology and the evolution of Mars: Space Science Reviews, v. 96, p. 165–194, doi: 10.1023/A:1011945222010.

Head, J.W., Mustard, J.F., Kreslavsky, M.A., Milliken, R.E., and Marchant, D.R., 2003, Recent ice ages on Mars: Nature, v. 426, p. 797–802, doi: 10.1038/nature02114.

Ivanov, B., 2001, Moon cratering rate ratio estimates: Space Science Reviews, v. 96, p. 87–104, doi: 10.1023/A:1011941121102.

Kim, J.-R., and Muller, J.-P., 2009, Multi-resolution topographic data extraction from Martian stereo imagery: Planetary and Space Science, doi: 10.1016/j.pss.2009.09.024 (in press).

Komatsu, G., and Baker, V.R., 1997, Paleohydrology and flood geomorphology of Ares Vallis: Journal of Geophysical Research, v. 102, p. 4151–4160, doi: 10.1029/96JE02564.

Kuzmin, R.O., Ershow, E.D., Komarow, L.A., Kozlov, A.H., and Isaev, V.S., 2002, The comparative morphometric analysis of polygonal terrain on Mars and the Earth high latitude areas: Lunar and Planetary Science Conference XXXIII, abs. 2030.

Lefort, A., Russell, P.S., Thomas, N., McEwen, A.S., Dundas, C.M., and Kirk, R.L., 2009, HiRISE observations of periglacial landforms in Utopia Planitia: Journal of Geophysical Research, v. 114, E04005, doi: 10.1029/2008JE003264.

Levy, J.S., and Head, J.W., 2005, Evidence for remnants of ancient ice rich deposits: Mangala Valles outflow channel, Mars: Terra Nova, v. 17, p. 503–509, doi: 10.1111/j.1365-3121.2005.00642.x.

Levy, J., Head, J., and Marchant, D., 2009, Thermal contraction crack polygons on Mars: Classification, distribution, and climate implications from HiRISE observations: Journal of Geophysical Research, v. 114, E01007 doi: 10.1029/2008je003273.

Mellon, M.T., and Phillips, R.J., 2001, Recent gullies on Mars and the source of liquid water: Journal of Geophysical Research, v. 106, p. 23,165–23,179, doi: 10.1029/2000JE001424.

Mellon, M.T., Jakosky, B.M., and Postawko, S.E., 1997, The persistence of equatorial ground ice on Mars: Journal of Geophysical Research, v. 102, p. 19,357–19,369, doi: 10.1029/97JE01346.

Morgenstern, A., Hauber, E., Reiss, D., van Gasselt, S., Grosse, G., and Schirrmeister, L., 2007, Deposition and degradation of a volatile-rich layer in Utopia Planitia and implications for climate history on Mars: Journal of Geophysical Research, v. 112, E06010, doi: 10.1029/2006je002869.

Mustard, J.F., Cooper, C.D., and Rifkin, M.K., 2001, Evidence for recent climate change on Mars from the identification of youthful near-surface ground ice: Nature, v. 412, p. 411–414, doi: 10.1038/35086515.

Pacifici, A., Komatsu, G., and Pondrelli, M., 2009, Geological evolution of Ares Vallis on Mars: Formation by multiple events of catastrophic flooding, glacial and periglacial processes: Icarus, v. 202, p. 60–77, doi: 10.1016/j.icarus.2009.02.029.

Page, D.P., and Murray, J.B., 2006, Stratigraphical and morphological evidence for pingo genesis in the Cerberus plains: Icarus, v. 183, p. 46–54, doi: 10.1016/j.icarus.2006.01.017.

Santiago, D.L., Colaprete, A., Haberle, R.M., Sloan, L.C., and Asphaug, E.I., 2005, Outflow channels influencing Martian climate; global circulation model simulations with emplaced water: Lunar and Planetary Science Conference XXXVI, abs. 1787.

Segura, T.L., Toon, O.B., Colaprete, A., and Zahnle, K., 2002, Environmental effects of large impacts on Mars: Science, v. 298, p. 1977–1980, doi: 10.1126/science.1073586.

Seibert, N.M., and Kargel, J.S., 2001, Small-scale Martian polygonal terrain: Implications for liquid surface water: Geophysical Research Letters, v. 28, p. 899–902, doi: 10.1029/2000GL012093.

Soare, R.J., Osinki, G.R., and Roehm, C.L., 2008, Thermokarst lakes and ponds on Mars in the very recent (late Amazonian) past: Earth and Planetary Science Letters, v. 272, p. 382–393, doi: 10.1016/j.epsl.2008.05.010.

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