GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L04202, doi:10.1029/2007GL032813, 2008

Identification of sublimation-type thermal contraction crack polygons at the proposed NASA Phoenix landing site: Implications for substrate properties and climate-driven morphological evolution

Joseph S. Levy,[1] James W. Head,[1] David R. Marchant,[2] and Douglas E. Kowalewski[2]

Received 3 December 2007; revised 18 January 2008; accepted 29 January 2008; published 27 February 2008.

[1] We identify a surface within the NASA Phoenix landing site Area D characterized by boulder-topped, polygonally-patterned mounds comparable in radius and cross-sectional morphology to terrestrial sublimation polygons found in Antarctica. Both Martian and Antarctic polygons display topographic asymmetry, with shallow equator-facing slopes and steep pole-facing slopes, interpreted to indicate insolation-dependent, differential sublimation of buried ice. On the basis of morphological similarities, we classify the Phoenix Box 1 polygons as sublimation polygons. Terrestrial sublimation polygons form where ice volumes exceeding available pore space occur in the shallow subsurface and where near-surface conditions are too cold and dry to permit the development of saturated active layers: conditions comparable to those recently modeled for Mars in the Phoenix landing site Area D, Box 1. The identification of sublimation polygons on Mars would provide direct evidence for shallow, ground ice exceeding pore-ice volumes and shed light on the emplacement mechanism of this ice. **Citation:** Levy, J. S., J. W. Head, D. R. Marchant, and D. E. Kowalewski (2008), Identification of sublimation-type thermal contraction crack polygons at the proposed NASA Phoenix landing site: Implications for substrate properties and climate-driven morphological evolution, *Geophys. Res. Lett.*, *35*, L04202, doi:10.1029/2007GL032813.

1. Introduction

[2] Polygonally patterned ground has been identified on Mars since the Viking era [*Lucchitta*, 1981], and has long been interpreted as a signal of the presence of subsurface ice deposits [*Malin and Edgett*, 2001; *Mangold et al.*, 2004]. The origin of ice in the shallow Martian subsurface, whether by cyclical vapor diffusion or primary deposition, remains an area of active inquiry [*Mustard et al.*, 2001; *Head et al.*, 2003; *Schorghofer and Aharonson*, 2005; *Kostama et al.*, 2006; *Schorghofer*, 2007]. Recent modeling suggests that high-latitude terrains on Mars may support buried ice sheets, produced by direct atmospheric ice deposition within the past 5 My [*Head et al.*, 2003], overlain by a sublimation lag deposit ranging in thickness from 10s to 100s of cm [*Schorghofer*, 2007]. These results are consistent with coarse-resolution (100s of km per pixel) neutron-spectrometer results correlating high-latitude patterned ground with subsurface water ice, which were interpreted to indicate ice deposition by vapor diffusion [*Boynton et al.*, 2002; *Feldman et al.*, 2002; *Mangold et al.*, 2004], as well as a suite of geomorphological observations linking young terrains to recently deposited, ice-rich units [*Mustard et al.*, 2001; *Head et al.*, 2003; *Kostama et al.*, 2006].

[3] The thermal contraction mechanism for polygon generation on Mars under current climate conditions was demonstrated by *Mellon* [1997] for terrains polewards of ~30° latitude. A comprehensive survey of polygonally patterned ground at MOC resolution was conducted by *Mangold* [2005], which indicated a correlation of polygon morphology with latitude, suggesting climate control on polygon development. On the basis of MOC-resolution similarity with terrestrial ice-wedge polygons, *Mangold* [2005] invoked thermal contraction cracking and freeze-thaw processes as the origin of Martian polygons, occurring during a period of high obliquity within the past 10 My [see *Kreslavsky et al.*, 2008].

[4] Estimating the burial depth of ice on Mars is critical for ice-analyzing spacecraft payloads, such as that carried by the NASA Phoenix mission [*Boynton et al.*, 2002; *Smith et al.*, 2007; *Arvidson et al.*, 2007].Given the inaccessibility of the Martian subsurface, a full understanding of climate controls (presence or absence of an active layer) and rheology influences (subsurface distribution of ice and rock) on polygon morphology on Mars has relied on the identification of surface morphological indicators of shallow subsurface processes [*Mellon*, 1997; *Mangold*, 2005; *Tamppari et al.*, 2007]. Here, we combine stereo-topography with high-resolution imaging of Antarctica and Mars to identify 1) morphological characteristics of polygonally patterned ground indicative of a thin cover of insulating debris over massive ice, and 2) polygon modification by sublimation processes under current Mars climate conditions.

2. Background: Sublimation Polygons

[5] Sublimation polygons [*Marchant et al.*, 2002] are a subtype of thermal contraction-crack polygon. Thermal contraction cracking in the substrate arises from failure of cohesive ground materials subjected to rapid thermal cooling [*Lachenbruch*, 1962]. Following crack development, the morphologic evolution of thermal contraction crack polygons is to a large extent dependent on subsurface rheological properties (including ice content), and surface environmental factors, including the presence or absence of saturated active layers [*Pewe*, 1959, 1963; *Lachenbruch*, 1961; *Maloof et al.*, 2002; *Marchant and Head*, 2007]. In wet climates, in which a typical active layer is present, ice-

[1]Department of Geological Sciences, Brown University, Providence, Rhode Island, USA.

[2]Department of Earth Science, Boston University, Boston, Massachusetts, USA.

0094-8276/08/2007GL032813$05.00

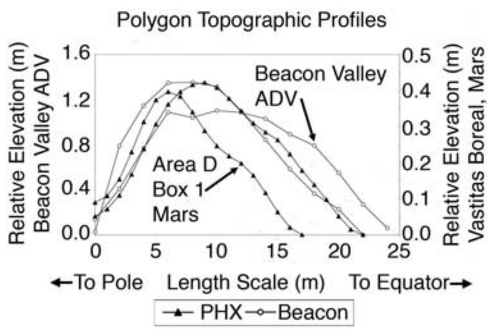

Figure 1. Topographic profiles of thermal contraction crack polygons in Beacon Valley, Antarctica, and in Box 1 (Vastitas Borealis, Mars). Both sets of profiles show steepened pole-facing slopes (north-facing on Mars, south-facing in Beacon Valley), and shallow, inflected equator-facing slopes. Polygons are of nearly identical diameter. Relative elevation indicates topographic relief above the deepest point of the polygon troughs. HiRISE topography is plotted on a vertically exaggerated scale to demonstrate morphological similarity between polygon profiles. Terrestrial topographic data courtesy of a joint NSF/NASA/USGS effort, with basic post processing from the Byrd Polar Research Center, as reported by *Schenk et al*. [2004]; Mars topography courtesy USGS and the HiRISE Team.

wedge polygons commonly develop [*Washburn*, 1973]; in cold and dry climates, in which soil conditions are too dry to develop traditional wet active layers, sand-wedge polygons may form. Sublimation polygons are a special type of sand-wedge polygon that form where excess ice (ice exceeding available pore ice) occurs in the shallow subsurface [*Marchant et al.*, 2002; *Levy et al.*, 2006; *Marchant and Head*, 2007]. The strong dependence of polygon type on climate and subsurface ice conditions means that polygon types can be used as an equilibrium landform to chart the spatial and temporal variation in local environmental conditions [*Black*, 1952; *Marchant and Head*, 2007].

[6] The sublimation polygons of central Beacon Valley, Antarctica (77.855°S, 160.580°E; illustrated in supplementary materials[1]), one of the Antarctic Dry Valleys (ADV), form where sublimation till <1 m thick rests directly on massive buried glacier ice containing ~3% debris by volume [*Marchant et al.*, 2002]. Climatically, Beacon Valley is a hyper-arid, cold desert, with a mean annual temperature of ~−21.5°C and <10 mm water-equivalent precipitation per year [*Doran et al.*, 1995; *Marchant and Head*, 2007]. These conditions do not permit the development of a typical active layer in central Beacon Valley.

[7] Polygon morphology is strongly dependent on the rate and spatial variability of underlying ice sublimation. Textural changes in overlying sublimation till yield marked variations in the rate and location of underlying ice sublimation [*Marchant et al.*, 2002; *Kowalewski et al.*, 2006; *Levy et al.*, 2006]. Reductions in till thickness and tortuosity occurring at thermal contraction cracks [e.g., *Marchant et al.*, 2002] locally increase the sublimation rate of buried ice along the cracks, resulting in preferential loss of ice at polygon margins. Buried ice at polygon interiors is relatively protected by undisturbed till [*Schaefer et al.*, 2000]. The spatial variation in ice sublimation yields elevated polygon interiors surrounded by marginal polygon troughs [*Marchant et al.*, 2002; *Kowalewski et al.*, 2006].

[8] The polygons of central Beacon Valley occur at two distinct scales: a large-scale variety, including amorphous "megagons" with an average diameter of ~100 m, and more typical, small-scale sublimation polygons that crosscut megagons; the latter show a mean long-axis diameter of ~23 m (range: 9–35 m), mean short-axis diameter of ~11 m (range: 6–15 m), mean trough depth of ~1.4 m (range: 1.2–3.0 m), mean trough angle of ~29° (range: 10–34°), and mean depth to buried ice of ~49 cm (range: 25–80 cm), that is generally deeper in polygon interiors and shallower at margins (*Marchant et al.*, 2002). Multiple generations of the small-scale polygons are observed in stratigraphic sections as relict sand wedges, and individual sublimation polygons can be crosscut by young, developing wedges [*Marchant et al.*, 2002; *Levy et al.*, 2006]. Polygons are morphologically similar at the "megagon," polygon, and developing wedge scales.

[9] Inspection of Beacon Valley sublimation polygons reveals aspect dependence on surface slope: pole-facing (south-facing) slopes are steeper than equator-facing (north-facing) slopes (Figure 1). Insolation is a strong driver of sublimation rates in Beacon Valley, and at high latitudes, equator-facing slopes receive more insolation than pole-facing slopes. Accordingly, this asymmetry is interpreted to be the result of enhanced sublimation of buried ice on equator-facing slopes, and correspondingly, of reduced sublimation of ice on pole-facing slopes [*Hecht*, 2002; *Kreslavsky and Head*, 2003; *Kowalewski et al.*, 2007]. This inference is confirmed by excavations demonstrating shallower depths to ice on pole-facing slopes, and deeper depths to ice on equator-facing slopes [*Levy et al.*, 2006]. Aspect-dependent asymmetry is not observed in sand-wedge polygons, which form in ice-cemented sediments with ice volumes less-than or equal-to available pore space. This is because loss of pore ice in grain-supported materials results in negligible volumetric change (schematically illustrated in supplementary materials).

[10] Analysis of the eastern portion of central Beacon Valley was undertaken using high-resolution laser altimetry data (2 m per pixel) (T. Schenk, DEM generation from the Antarctic LiDAR data: Site report, 2004, http://usarc.usgs.gov/lidar/lidar_pdfs/Site_reports_v5.pdf) and high-resolution (sub-meter scale) air-photographs (courtesy USARC). These data sets have comparable spatial resolution to HiRISE image and stereo topography data for Mars [*Kirk et al.*, 2007]. Topographic profiles of ten sublimation polygons in Beacon Valley are consistent with direct field observations: mean polygon diameter is ~22 m (σ = 5.7 m), mean polygon trough depth is ~1.0 m (σ = 0.37 m), mean pole-facing slope angle is ~8.6° (σ = 1.9°), and mean equator-facing slope angle is ~5.0° (σ = 1.5°).

3. Polygonally Patterned Ground in Vastitas Borealis, Mars

[11] High-resolution stereo imaging a of portion of Vastitas Borealis, Mars, has been conducted by the HiRISE team

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL032813.

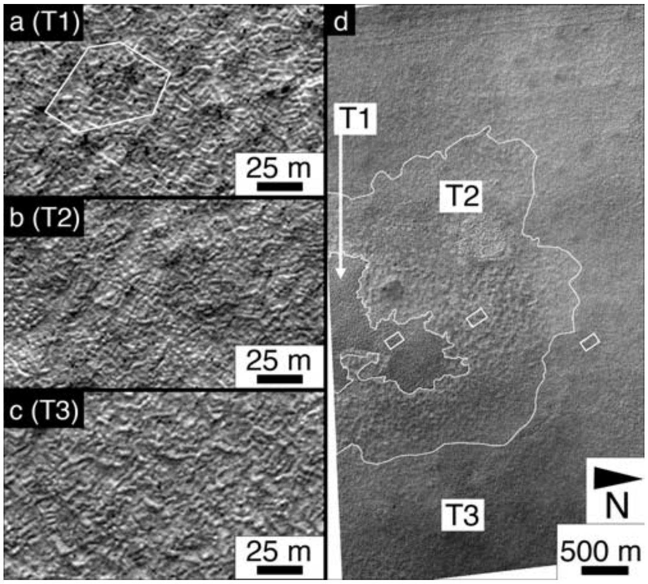

Figure 2. Central portion of HiRISE image PSP_001959_2485. (a) Type 1 terrain consisting of well-defined polygons and boulder-topped mounds. An example patterned mound has been outlined in white. (b) Type 2 terrain, consisting of polygons and subdued mounds. (c) Type 3 terrain consisting of poorly defined polygons, poorly oriented cracks, and little topographic relief. (d) Distribution of terrain types in the Area D, Box 1 potential Phoenix lander site. Image data courtesy USGS and the HiRISE Team.

as part of landing site selection for the NASA Phoenix mission [*Kirk*, 2007; *Smith et al.*, 2007]. Based on neutron spectrometer data and surface thermal properties, the Area D region of Vastitas Borealis is expected to have massive subsurface ice [*Boynton et al.*, 2002; *Feldman et al.*, 2002; *Titus and Prettyman*, 2007] beneath a dry layer of ~5 cm [*Mitrofanov et al.*, 2007] to ~20 cm [*Smith et al.*, 2007] thickness. The Box 1, Area D, region is centered on 68.165°N, 232.678°E: a polygonally patterned unit of Amazonian age [*Smith et al.*, 2007] (Figure 2). Image data (30 cm per pixel) and stereo topographic data (1 m per pixel) were used to characterize and map three terrain types in the region (Figure 2). Type 1 terrain has a sharply defined network of polygonal troughs. Type 1 terrain has topographic mounds which are crosscut by multiple polygons, and which are commonly centered on groupings of meter-scale boulders. Type 2 terrain has polygonal patterning which is less well organized than in Type 1 terrain, has a mounded texture, but lacks boulder groups. Type 3 terrain has a poorly defined network of cracks, has little topographic relief, and no boulders.

[12] Topographic transects were made across the three terrain types in Box 1 (Figure 1) using USGS HiRISE stereo-photoclinometric digital topography models (DTMs) [*Kirk et al.*, 2007]. Terrain types 2 and 3 had little variation in topography at the tens of meters scale. A suite of 20 topographic profiles across polygonally patterned mounds in Type 1 terrain indicate a mean diameter of ~22 m (σ = 5.8 m), a mean inter-mound trough depth of ~0.5 m (σ = 0.13 m), a mean pole-facing slope angle of ~3.5° (σ = 1.0°), and a mean equator-facing slope of ~1.9° (σ = 0.66°). Further, pole-facing slopes were found to be continuously steep, while equator-facing slopes were found to be inflected, a possible indication of slumping. Analogous, gravity-driven slumps occur in terrestrial sublimation polygons in the absence of saturated sediment or meltwater at the buried ice surface [*Marchant et al.*, 2002].

[13] The aspect-dependent asymmetry of Type 1 polygonally patterned mounds is interpreted to be a result of differential sublimation rates of subsurface ice in response to increased insolation on equator-facing slopes and decreased insolation on pole-facing slopes. The cross-cutting of Type 1 mounds by small (<1 m wide), polygon-forming, thermal contraction cracks is interpreted as a process analogous to the cross-cutting of terrestrial sublimation polygons by younger thermal contraction cracks [*Marchant et al.*, 2002; *Levy et al.*, 2006]. Aspect-dependent topographic asymmetry, in areas without wet active layers, requires the presence of excess ice in the shallow subsurface.

[14] The greater topographic relief of Type 1 terrain versus Types 2 and 3 is interpreted to be the result of enhanced ice content beneath Type 1 terrain, resulting from insulation of buried icy soil by a thickened sublimation till in Type 1 terrain [*Sugden et al.*, 1995; *Marchant et al.*, 2002; *Kowalewski et al.*, 2006]. The poorly developed polygon network in Type 3, showing no topographic asymmetry, is interpreted to be a result of reduced subsurface ice content [*Washburn*, 1973], possibly indicating the formation of sand-wedge-like polygons in a substrate dominated by pore ice, rather than by excess ice. The morphological gradient between terrain Types 1 and 3 suggests that Type 2 terrain may be intermediate in present-day ice-content.

4. Conclusions and Implications

[15] Type 1 polygonally patterned ground at the Phoenix Area D, Box 1 site, shows well-formed, boulder-topped, polygonally-patterned mounds, with nearly identical diameters, comparable topographic relief, and comparable aspect-dependent slope asymmetries to sublimation polygons in Beacon Valley, Antarctica. On the basis of these morphological analyses we interpret polygons in Type 1 terrain to have formed by processes similar to terrestrial sublimation polygons, which form in the absence of a wet active layer and incise massive ice, with ice volume exceeding available pore space. These observations are consistent with the presence of ice-rich, ice-sheet-like units overlain by a sublimation lag deposit, as predicted by *Mustard et al.* [2001] and *Head et al.* [2003]. This genetic classification of a group of Martian polygons demonstrates that a direct linkage between polygon morphological parameters, polygon substrate composition, and climate conditions is possible. Our analysis suggests that subsurface ice content decreases as a function of decreasing terrain roughness in the Box 1 region, and that buried ice may be more accessible on the steepened, pole-facing slopes of Martian polygons, where the insolation environment allows ice to exist closer to the surface. Further, this analysis provides independent confirmation of thermal predictions of shallow subsurface ice in the Area D, Box 1 region [*Bandfield*,

2007]. Morphological analysis of polygonally patterned ground terrain types occurring at the hundreds of meters scale allows a spatial refinement to predictions of subsurface ice-content above the hundreds of km resolution of neutron spectrometer data [*Boynton et al.*, 2002; *Feldman et al.*, 2002]. Lander missions such as NASA Phoenix will help to further refine the understanding of the subsurface distribution of ice in the Martian northern plains at scales of cm to tens of cm. Such missions will also collect data, such as stable isotopes, which can directly test ice-deposition and polygon-formation mechanism hypotheses.

[16] **Acknowledgments.** This work was made possible with support from NSF grant ANT-0338291, and NASA MFRP grant NNX06AE32G to both David Marchant and James Head, and by NASA MDAP grants NNG04GJ99G and NNG05GQ46G to James Head. Thanks to A. McEwen and the HiRISE team for Mars image data, and to Jerry Mullins, Dan Sechrist, and Bob Allen of the United States Antarctic Resource Center (USARC) for historical air photographs. LiDAR topography kindly made possible through a joint effort from the NSF, NASA, and the USGS, with basic post processing from the Byrd Polar Research Center.

References

Arvidson, R. E., et al. (2007), Overview of Mars exploration program 2007 Phoenix mission landing site selection, paper presented at 7th International Conference on Mars, Lunar and Planet. Inst., Pasadena, Calif., 9–13 Jul.

Bandfield, J. L. (2007), High-resolution subsurface water-ice distributions on Mars, *Nature*, *447*, 64–67.

Black, R. F. (1952), Polygonal patterns and ground conditions from aerial photographs, *Photogramm. Eng.*, *17*, 123–134.

Boynton, W. V., et al. (2002), Distribution of hydrogen in the near-surface of Mars: Evidence for sub-surface ice deposits, *Science*, *297*, 81–85.

Doran, P. T., G. L. Dana, J. T. Hastings, and R. A. Wharton Jr. (1995), McMurdo Dry Valleys Long-Term Ecological Research (LTER): LTER automatic weather network (LAWN), *Antarct. J. U. S.*, *30*, 276–280.

Feldman, W. C., et al. (2002), Global distribution of neutrons from Mars: Results from Mars Odyssey, *Science*, *297*, 75–78.

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

Hecht, M. H. (2002), Metastability of water on Mars, *Icarus*, *156*, 373–386.

Kirk, R. L. (2007), Phoenix landing site topomapping update, paper presented at 5th Phoenix Landing Site Workshop, Lunar and Planet. Inst., Pasadena, Calif., 23 Jan.

Kirk, R. L., E. Howington-Kraus, M. R. Rosiek, D. Cook, J. Anderson, K. Becker, B. A. Archinal, L. Keszthelyi, R. King, A. S. McEwen, and the HiRISE team (2007), Ultrahigh resolution topographic mapping of Mars with HiRISE stereo images: Methods and first results, paper presented at 7th International Conference on Mars, Lunar and Planet. Inst., Pasadena, Calif., 9–13 Jul.

Kostama, V.-P., M. A. Kreslavsky, and J. W. Head (2006), Recent high-latitude icy mantle in the northern plains of Mars: Characteristics and ages of emplacement, *Geophys. Res. Lett.*, *33*, L11201, doi:10.1029/2006GL025946.

Kowalewski, D. E., D. R. Marchant, J. W. Head, and J. S. Levy (2007), Modeling vapor diffusion in sublimation tills of the Antarctic Dry Valleys: Implications for the preservation of near-surface ice on Mars, *Lunar Planet. Science Conf.*, *38th*, abstract 2143.

Kowalewski, D. E., D. R. Marchant, J. S. Levy, and J. W. Head (2006), Quantifying summertime sublimation rates for buried glacier ice in Beacon Valley, Antarctica, *Antarct. Sci.*, *18*, 421–428.

Kreslavsky, M. A., and J. W. Head (2003), North–south topographic slope asymmetry on Mars: Evidence for insolation-related erosion at high obliquity, *Geophys. Res. Lett.*, *30*(15), 1815, doi:10.1029/2003GL017795.

Kreslavsky, M. A., J. W. Head, and D. R. Marchant (2008), Periods of active permafrost layer formation during the geological history of Mars: Implications for circum-polar and mid-latitude surface processes, *Planet. Space Sci.*, *56*(2), 289–302.

Lachenbruch, A. H. (1961), Depth and spacing of tension cracks, *J. Geophys. Res.*, *66*, 4273–4292.

Lachenbruch, A. H. (1962), Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost, *Geol. Soc. Am. Spec. Pap.*, *70*, 1–69.

Levy, J. S., D. R. Marchant, and J. W. Head (2006), Distribution and origin of patterned ground on Mullins Valley debris-covered glacier, Antarctica: The roles of ice flow and sublimation, *Antarct. Sci.*, *18*, 385–397.

Lucchitta, B. K. (1981), Mars and Earth: Comparison of cold-climate features, *Icarus*, *45*, 264–303.

Malin, M. C., and K. S. Edgett (2001), Mars Global Surveyor Mars Orbiter Camera: Interplanetary cruise through primary mission, *J. Geophys. Res.*, *106*, 23,429–23,570.

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

Mangold, N. (2005), High latitude patterned grounds on Mars: Classification, distribution and climatic control, *Icarus*, *174*, 336–359.

Mangold, N., S. Maurice, W. C. Feldman, F. Costard, and F. Forget (2004), Spatial relationships between patterned ground and ground ice detected by the Neutron Spectrometer on Mars, *J. Geophys. Res.*, *109*, E08001, doi:10.1029/2004JE002235.

Marchant, D. R., and J. W. Head (2007), Antarctic Dry Valleys: Microclimate zonation, variable geomorphic processes, and implications for assessing climate change on Mars, *Icarus*, *192*, 187–222.

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

Mellon, M. T. (1997), Small-scale polygonal features on Mars: Seasonal thermal contraction cracks in permafrost, *J. Geophys. Res.*, *102*, 25,617–25,628.

Mitrofanov, I. G., M. T. Zuber, M. L. Litvak, N. E. Demidov, A. B. Sanin, and W. V. Boynton (2007), Burial depth of water ice in Mars permafrost subsurface, *Lunar Planet. Sci. Conf.*, *38th*, abstract 3108.

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

Pewe, T. L. (1959), Sand-wedge polygons (tessellations) in the McMurdo Sound region, Antarctica—A progress report, *Am. J. Sci.*, *257*, 545–552.

Pewe, T. L. (1963), Ice-wedges in Alaska-classification, distribution, and climatic significance, paper presented at 2nd International Conference on Permafrost, Int. Permafrost Assoc., Yakutsk, Russia, 13–28 Jul.

Pewe, T. L. (1974), Geomorphic processes in polar deserts, in *Polar Deserts and Modern Man*, edited by T. L. Smiley and J. H. Zumberge, pp. 33–52, Univ. of Ariz. Press, Tucson.

Schaefer, J. M., H. Baur, G. H. Denton, S. Ivy-Ochs, D. R. Marchant, C. Schluchter, and R. Wieler (2000), The oldest ice on Earth in Beacon Valley, Antarctica: New evidence from surface exposure dating, *Earth Planet. Sci. Lett.*, *179*, 91–99.

Schorghofer, N. (2007), Dynamics of ice ages on Mars, *Nature*, *449*, 192–194.

Schorghofer, N., and O. Aharonson (2005), Stability and exchange of subsurface ice on Mars, *J. Geophys. Res.*, *110*, E05003, doi:10.1029/2004JE002350.

Smith, P. H., L. K. Tamppari, R. E. Arvidson, and W. V. Boynton (2007), Phoenix landing site selection update, *Lunar Planet. Sci. Conf.*, *38th*, abstract 1176.

Sugden, D. E., D. R. Marchant, N. Potter Jr., R. A. Souchez, G. H. Denton, C. C. Swisher III, and J. Tison (1995), Preservation of Miocene glacier ice in East Antarctica, *Nature*, *376*, 412–415.

Tamppari, L. K., et al. (2007), Atmospheric characteristics expected at the Phoenix Landing season and location, paper presented at the 7th International Conference on Mars, Lunar and Planet. Inst., Pasadena, Calif., 9–13 Jul.

Titus, T. N., and T. H. Prettyman (2007), Thermal inertia characterization of the proposed Phoenix landing sites, *Lunar Planet. Sci. Conf.*, *38th*, abstract 2088.

Washburn, A. L. (1973), *Periglacial Processes and Environments*, 320 pp., St. Martin's Press, New York, 320 pp.

J. W. Head and J. S. Levy, Department of Geological Sciences, Brown University, 324 Brook Street, Box 1846, Providence, RI 02912, USA. (joseph_levy@brown.edu)

D. E. Kowalewski and D. R. Marchant, Department of Earth Science, Boston University, 675 Commonwealth Avenue, Boston, MA 02215, USA.