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Cold and dry processes in the Martian Arctic: Geomorphic observations at the Phoenix landing site and comparisons with terrestrial cold desert landforms

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[1] We analyze Surface Stereo Imager observations of rocks, sediments, and permafrost-related landforms in the vicinity of the Phoenix lander, comparing the imaged features to analogous examples of physical weathering and periglacial processes observed in the Antarctic Dry Valleys. Observations at the Phoenix landing site of pitted rocks, "puzzle rocks" undergoing in-situ breakdown, perched clasts, and thermal contraction crack polygon morphologies strikingly similar to terrestrial sublimation polygons, all strongly suggest that stable (non-churning) permafrost processes dominate the Phoenix landing site. Morphological evidence suggests that cold-desert processes, in the absence of wet active-layer cryoturbation, and largely driven by sublimation of buried ice (either pore ice, excess ice, or both) are shaping the landscape. **Citation:** Levy, J. S., J. W. Head, and D. R. Marchant (2009), Cold and dry processes in the Martian Arctic: Geomorphic observations at the Phoenix landing site and comparisons with terrestrial cold desert landforms, *Geophys. Res. Lett.*, *36*, L21203, doi:10.1029/2009GL040634.

1. Introduction

[2] The Phoenix mission has provided a unique in-situ investigation of permafrost processes operating at northern polar latitudes (68.21°N) [*Smith et al.*, 2009]. Critical results from the mission include 1) the detection of relatively clean icy substrates containing a few percent dust and of ice-cemented soil, overlain by several centimeters of dry sediments [*Smith et al.*, 2009]; 2) complex carbonate, chloride, perchlorate, and pH soil chemistry comparable to that observed in terrestrial cold and arid terrains [*Boynton et al.*, 2009; *Hecht et al.*, 2009; *Kounaves et al.*, 2009; *Smith et al.*, 2009]; and 3) cold, arid, and windy weather conditions consistent with the generation and preservation of a range of cold-desert landforms [*Smith et al.*, 2009; *Whiteway et al.*, 2009]. These important findings lead to additional questions, particularly, 1) what is the history of H_20 (liquid or solid) at the landing site and 2) how stable or churned is the landing-site surface at various spatial scales?

[3] Data from Phoenix can be used to examine whether liquid water or brines have played a major role in modifying the landscape: e.g., has the formation of a wet active layer (seasonally warmer than the freezing point of pure water or brines [*Kreslavsky et al.*, 2008]) mixed the sediment through cryoturbation and frost heave [*Stoker et al.*, 2008; *Smith et al.*, 2009]; has "dry cryoturbation" modified the surface and subsurface through viscous diapirism and rock sorting [*Heet et al.*, 2009; *Mellon et al.*, 2009a, 2009b]; or has the permafrost remained cold and dry with only vertical ablation (no churning) as subsurface ice sublimates [*Arvidson et al.*, 2008; *Levy et al.*, 2008]?

[4] Here we build upon the recent Phoenix results [*Boynton et al.*, 2009; *Hecht et al.*, 2009; *Mellon et al.*, 2009a, 2009b; *Smith et al.*, 2009; *Whiteway et al.*, 2009] and present a range of additional observations of the Phoenix landing site from the surface stereo imager (SSI) [*Lemmon et al.*, 2008] that provide insight into geomorphic processes at the landing site. We compare landforms observed at the Phoenix landing site to terrestrial analogs across microclimate zones in the Antarctic Dry Valleys (ADV) [*Marchant et al.*, 2002; *Marchant and Head*, 2007]; including the stable upland zone, in which soil conditions are too dry and cold to permit a seasonally thawed active layer, and a coastal thaw zone, in which spatially extensive cryoturbation is associated with a widespread, seasonal active layer. The region has long been known to serve as an excellent terrestrial analog to Mars [*Anderson et al.*, 1972; *Marchant and Head*, 2007], in part because it contains a wide range of permafrost landforms, including those formed in cold-and-wet conditions (e.g., costal thaw zone) and cold and hyper-arid conditions (stable upland zone).

2. Permafrost Landforms Observed at Phoenix and Terrestrial Analogs

[5] The Martian landscape observed at the Phoenix landing site (68.21°N, 234.25°E) has examples of many landforms typical of terrestrial polar deserts (Figure 1a and auxiliary material) [*Heet et al.*, 2009; *Mellon et al.*, 2009a, 2009b].[4] As shown below, landforms including pitted cobbles, "puzzle rocks", perched cobbles, and thermal contraction-crack polygons, are most analogous with the suite of cold-desert features found in the coldest and driest region of the ADV (the stable upland zone), and appear inconsistent with those that form in regions with seasonally thawed active layers (e.g., the coastal thaw zone).

[6] Pitted cobbles and boulders are common at the Phoenix landing site and have been interpreted as vesicular

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boulders [*Arvidson and Mellon*, 2008] (Figure 1b). Alternatively, rock pits may indicate a surficial process such as salt-weathering; in the stable upland zone of the ADV, mm-to-cm scale weathering pits form by undercutting and mineral prying associated with crystallization and hydration of salts on exposed rocks on timescales of 1–4 Ma [*Conca and Astor*, 1987; *Allen and Conca*, 1991; *Matsuoka*, 1995; *Staiger et al.*, 2006; *Marchant and Head*, 2007, Figure 8] (Figure 1c). Due to subtle changes in aspect, shielding, wind speed and direction, as well as the influence of neighboring rocks, salt-weathering in the stable upland zone is highly localized, producing dramatic pits on one clast, while leaving surfaces on neighboring rocks largely unmodified (Figure 1b). The abundance of salt species identified at the Phoenix landing site [*Kounaves et al.*, 2009] is consistent with the range of salts typical of Antarctic salt-weathering

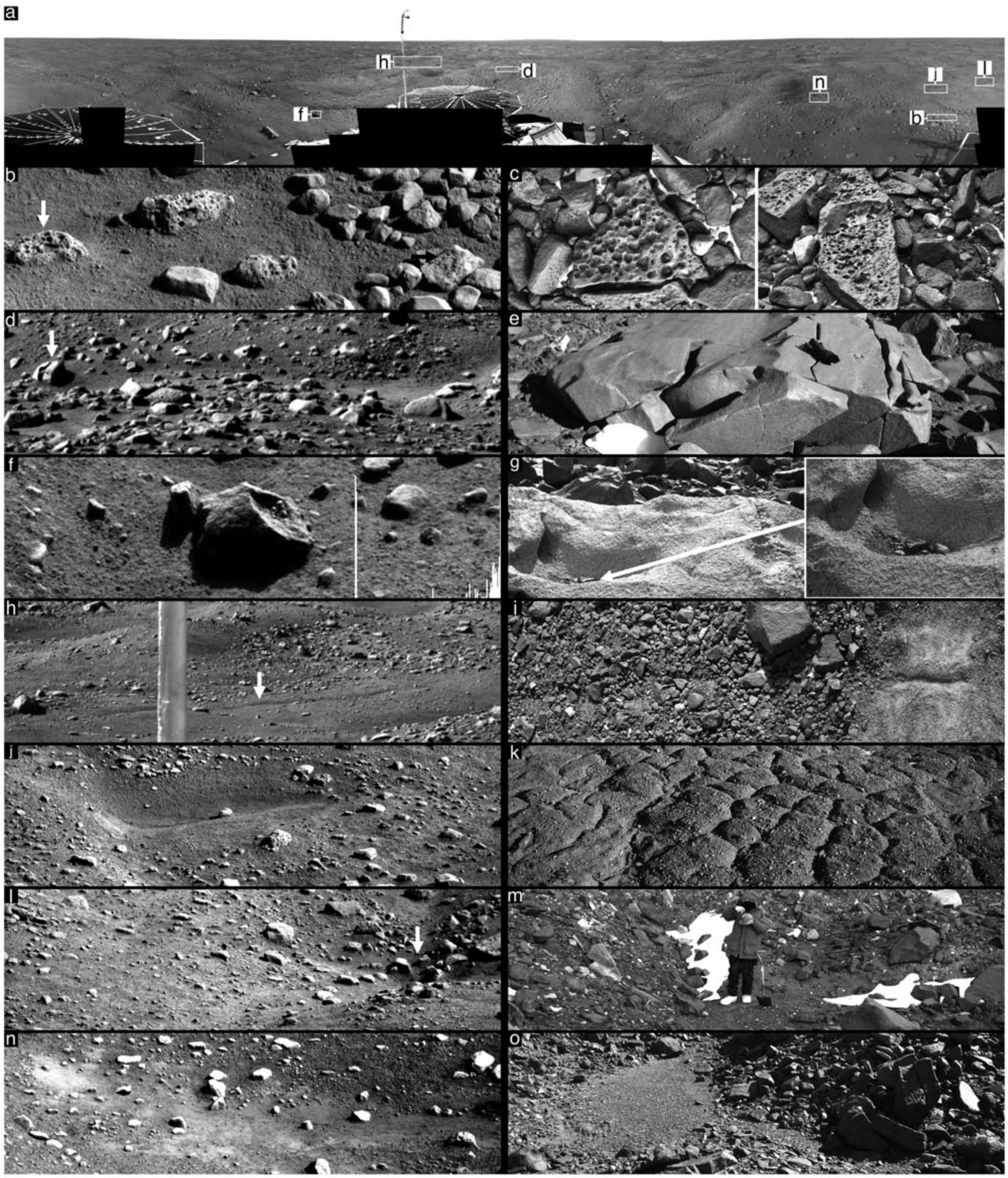

Figure 1

environments [*Bao and Marchant*, 2006; *Bao et al.*, 2008]. As in the Antarctic stable upland zone, salt weathering on Mars may result from the combined action of snow/frost deposition and sublimation [*Head and Kreslavsky*, 2006; *Marchant and Head*, 2007; *Whiteway et al.*, 2009] or the persistence of slowly-evaporating brines [*Chevrier et al.*, 2009] on clast surfaces.

[7] "Puzzle rocks" (disintegrated boulders that remain loosely articulated) [*Marchant and Head*, 2007, Figure 10] are present at the Phoenix landing site (Figure 1d). Antarctic "puzzle rocks" (Figure 1e) in the stable upland zone form from jointed clasts undergoing physical breakdown on landscapes that are not sufficiently churned by cryoturbation to disaggregate the broken-apart segments [*Staiger et al.*, 2006].

[8] Other features observed at the Phoenix landing site that may indicate stable surface conditions include the presence of perched pebbles—mm-to-cm scale clasts present in depressions on larger rocks (Figure 1f). Continuous movement of rocks, by wet or dry permafrost churning, would disrupt these delicate sediment piles. Some perched sediments may be too large to have been emplaced by explosive erosion during landing [*Mehta et al.*, 2008]. Similar sediment accumulations are observed on stable Antarctic boulders (Figure 1g). Terrestrial examples of perched sediments (sand to boulder size) may result from sublimation-lag development and aeolian deflation [*Sugden et al.*, 1995; *Marchant et al.*, 2002] or from extreme saltation events [*Greeley et al.*, 1980].

[9] The abundance of thermal contraction crack polygons observed at the Phoenix landing site [*Levy et al.*, 2008; *Mellon et al.*, 2008b; *Heet et al.*, 2009; *Mellon et al.*, 2009a, 2009b; *Smith et al.*, 2009] provides additional evidence regarding landsurface stability. As anticipated by *Mellon et al.* [2008a], thermal contraction crack polygons are observed at Phoenix [*Smith et al.*, 2009]. Of the many varieties of thermal contraction crack polygons that could form on Mars, e.g., ice-wedge, sand-wedge, and sublimation polygons, the morphological characteristics (below), along with the evidence presented above for dry near-surface conditions, favor the formation and evolution of sand-wedge and sublimation polygons [*Marchant et al.*, 2002; *Levy et al.*, 2009a, 2009b]. Sublimation polygons are a special class of sand-wedge polygon that forms in regions with excess subsurface ice (e.g., ice exceeding available pore space) buried under dry sediments [*Marchant et al.*, 2002]. At the Phoenix site, linear depressions, or furrows, are common on the surface, and suggest open, or recently-open, thermal contraction cracks (Figure 1h; see also Figure 1i) [*Mellon et al.*, 2009b]. The rounded, sloping shoulders of Phoenix polygons (Figure 1j) [*Mellon et al.*, 2009b] are closely analogous to the rounded shoulder and domical microtopography of sublimation polygons in the stable upland zone within Beacon Valley, Antarctica [*Marchant et al.*, 2002; *Marchant and Head*, 2007; *Levy et al.*, 2008]; the latter form as sublimation of buried, excess ice is locally enhanced at polygon margins. The lack of raised shoulders along polygon margins observed at the Phoenix landing site (Figure 1j) suggests that the volume of ice loss at polygon margins exceeds the sediment volume introduced by crack infill—a situation typical of most terrestrial sublimation polygons [*Marchant et al.*, 2002]. For terrestrial sublimation polygons, boulders occasionally slump from the polygon interior into polygon troughs [*Marchant et al.*, 2002], providing a slight increase in rock abundance in troughs as compared to interiors [e.g., *Heet et al.*, 2009]—a process distinct from soil overturn (cryoturbation) caused by wedge-growth-induced diapirism (see below) [*Heet et al.*, 2009; *Mellon et al.*, 2009b].

[10] Raised shoulders found alongside other varieties of contraction-crack polygons may arise from compressive forces in association with significant and sustained crack infill; infilling of cracks could either occur by refreezing of liquid water, as is the case for ice-wedge polygons, e.g., in the Antarctic coastal thaw zone [*Berg and Black*, 1966], or by the addition of aeolian debris into vertical cracks, as is typical of sand-wedge polygons of the Antarctic stable upland zone [*Pewe*, 1959; *Berg and Black*, 1966]. Given the morphology of polygons and associated landforms observed at the Phoenix landing site, crack infill from liquid water is not expected, and sand-wedge formation seems limited given the lack of upturned polygon margins. The increased depth of polygon troughs observed at junctions between Phoenix landing site polygons (Figure 1j) is instead typical of terrestrial sublimation polygons, driven by disturbances to the overlying, protective debris resulting in greater sublimation of subjacent buried ice (Figure 1k) [*Marchant et al.*, 2002; *Marchant and Head*, 2007; *Kowalewski*, 2008]. Deepened polygon margins and trough junctions may act as sediment traps at the Phoenix landing site (Figure 1n), suggesting incomplete winnowing of surface sediments into polygon troughs and a lack of complete surface homogenization by cryoturbation (Figure 1o).

Figure 1. (a) Panoramic view of the Phoenix landing site showing image locations. Photo credit NASA/JPL-Caltech/University of Arizona/Texas A&M University. (b) Pitted cobbles at the Phoenix landing site. (c) (left and right) Pitted dolerite cobbles in Farnell Valley, Antarctica. Pitted cobbles are ~10 cm in width. (d) Candidate puzzle rocks at the Phoenix landing site. (e) Puzzle rock in Beacon Valley. Boulder is ~1 m wide. (f) Candidate perched sediments at Phoenix landing site. (g) Sediments trapped in a boulder hollow in Beacon Valley. 80 cm field of view. (h) Candidate active polygon furrow at Phoenix landing site. (i) Polygon surface furrow and underlying glacier ice fracture in Friedman Valley, Antarctica. 80 cm field of view. (j) Candidate rounded polygon shoulders at Phoenix landing site. (k) Round-shouldered sublimation polygons in Beacon Valley, Antarctica. 100 m field of view. (l) Candidate deepened polygon trough junction at Phoenix landing site. (m) Over-deepened junction of three sublimation polygon troughs. Person for scale. (n) Light-toned sediment accumulations at Phoenix landing site. (o) Sand pit at inactive polygon trough junction in Beacon Valley. 4 m field of view. Phoenix landing site images b–n are excerpted from SSI images SS104EFF905439344_165C0L2M1-b, SS112EFF906150479_165C0L2M1-b, SS092EFF904382147_165C0R2M1-b, SS104EFF905437632_165C0L2M1-b, SS101EFF905172029_165C0L2M1-b, SS080EFF903311661_165C0L2M1-b, and SS051EFF900731785_15C28R2M1-b, respectively.

[11] Taken together, these observations are consistent with sublimation polygon formation, with microtopography generated by subsurface ice loss rather than by sediment/ice infill that could lead to doming, diapirism, and shoulder upturning [e.g., *Sletten et al.*, 2003; *Mellon et al.*, 2009b]. Alternatively, if the permafrost column at the Phoenix landing site is dominated by pore-ice [*Mellon et al.*, 2009a], then the polygons could represent sediment-starved sand-wedge polygons [*Mellon et al.*, 2009b]. However, the morphological observations presented here are most consistent with a landing site subsurface containing abundant, buried, excess ice [*Head et al.*, 2003; *Byrne et al.*, 2009], strongly implying sublimation polygon formation [*Levy et al.*, 2009a, 2009b].

3. Differences Between the Phoenix Landing Site and the Antarctic Dry Valleys

[12] Despite the similarities between landforms observed at the Phoenix landing site and those in Beacon Valley, ADV [*Marchant and Head*, 2007], two notable geomorphic elements typical of Beacon Valley are not observed at Phoenix: salt accumulations beneath rocks and soil weathering horizons. Snow containing salt condensation nuclei [*Bao et al.*, 2008] can melt in Beacon Valley when it falls on, or is blown onto, low-albedo dolerite cobbles warmed by peak summer insolation, resulting in the trickling of water to the base of the rock and concentration of salts at the ground surface as the brine refreezes and sublimates (direct sublimation of snow, in the absence of melting, may also be capable of producing soil salts and can generate minor salt weathering features) [*Marchant and Head*, 2007]. Peak-summer infiltrated snowmelt in Beacon Valley results in soil rubification associated with minor oxidation of iron-bearing minerals within the uppermost 5 to 15 cm of soil profiles [*Marchant et al.*, 2002]. Phoenix analysis of sediment beneath analogous cobbles on Mars did not reveal the presence of increased salt concentrations [*Sizemore et al.*, 2009]. Likewise, excavations into Phoenix landing-site soils reveal no changes in soil color or chemistry with depth, implying a uniform weathering state for Phoenix sediments [*Smith et al.*, 2009], suggesting a lack of recently flowing, wicking, or percolating brines at the Phoenix landing site.

4. Discussion

[13] Strong morphological similarities exist between landforms observed at the Phoenix landing site and those observed in the stable upland zone, ADV [*Marchant and Denton*, 1996; *Marchant et al.*, 2002; *Marchant and Head*, 2007]. The Phoenix assemblage of landforms includes pitted boulders, puzzle rocks, perched cobbles, and sublimation polygons [*Marchant et al.*, 2002; *Levy et al.*, 2008], an assemblage also found in the coldest and driest regions of the ADV, but atypical of the coastal thaw zone. This diagnostic assemblage of landforms may be indicative of equilibrium climate conditions driving geomorphic processes [*Marchant and Head*, 2007]. For comparison, the mean annual temperature in Beacon Valley (stable upland zone) is ~251 K, with a mean water vapor pressure of ~40–50 Pa [*Marchant and Head*, 2007, Table 1]. In contrast, the mean summer temperature in the coastal thaw zone is ~268 K, with a summer water vapor pressure of ~270 Pa; the latter conditions permit widespread development of a seasonally thawed active layer, surface churning, and development and degradation of ice-wedge polygons; none of which appear to be found at the Phoenix landing site today.

[14] The climate conditions measured at Phoenix are even colder and more arid than those found in the stable upland zone: typical summertime daily temperatures reached ~245 K with atmospheric water vapor pressures of ~1.8 Pa [*Hudson et al.*, 2009; *Whiteway et al.*, 2009]. Although these very low temperatures and vapor pressures are clearly inconsistent with the development of "wet" landforms typical of the costal thaw zone, they also suggest that even some processes that characterize the stable upland zone are not occurring under the extreme aridity of Mars. For example, although soil moisture at the Phoenix landing site may be sufficient to account for the observed cohesion of the soil [*Smith et al.*, 2009], and perhaps for rock pits, it is apparently insufficient to result in the formation of rock-bottom salt deposits or weathering horizons typical of the relatively wetter Beacon Valley soils [*Marchant et al.*, 2002].

5. Conclusions

[15] A morphological comparison of cold-desert landforms observed at the Phoenix landing site with those found across a variety of microclimate zones in the Antarctic Dry Valleys suggests that thermal contraction and sublimation, in the absence of near-surface melting, is the dominant process operating at the Phoenix landing site today. Ground-level geomorphological observations of the landing site suggest that cold, dry, and non-churning surface processes and the sublimation of abundant, buried, excess ice have dominated the recent geological history of the surfaces surrounding the Phoenix lander.

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