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Resurfacing time of terrestrial surfaces by the formation and maturation of polygonal patterned ground

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[1] To help interpret the polygonal patterned ground on Mars, we present recent findings about a similar form of patterned ground in a particularly cold and arid region on Earth, the Dry Valleys of Antarctica. In this region, distinct arrays of interconnected polygons, which we refer to herein simply as patterned ground, characterize many surfaces, reflecting a subsurface network of interconnected, subvertical wedges of sand that grow incrementally as sand progressively fills soil fractures. The fractures form initially as thermoelastic stresses arise during periods of rapid cooling of frozen ground, and they continue to open and close in response to thermal cycles. We describe the initiation and maturation of the patterned ground using data for the growth of sand wedges and for the evolution of crack patterns and microrelief over time scales ranging up to 10^6 years. *INDEX TERMS:* 9310 Information Related to Geographic Region: Antarctica; 6225 Planetology: Solar System Objects: Mars; 5470 Planetology: Solid Surface Planets: Surface materials and properties; 5462 Planetology: Solid Surface Planets: Polar regions; 1625 Global Change: Geomorphology and weathering (1824, 1886); *KEYWORDS:* polygons, patterned ground, Dry Valleys, Antarctica, permafrost, Mars, contraction cracks, crack patterns

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1. Introduction

[2] Recent high-resolution images show that patterned ground is widespread on Mars [*Malin and Edgett*, 2000; *Seibert and Kargel*, 2001]. Figure 1 illustrates a form of polygonal patterned ground that is prevalent in the Martian mid-to sub-polar latitudes. The inset is a view of polygons of similar size in the Dry Valleys of Antarctica that have raised, bouldery centers, outward-sloping aprons of fine-grained material, and perimeter fissures that contain many cobbles immediately below ground level. According to M. Malin (personal communication, 2001), a continuum of such features at a range of length scales occurs on Mars. These include polygons with (1) depressed interiors, raised perimeters, and no boulders; (2) depressed interiors and raised bouldery perimeters; (3) raised interiors and depressed perimeters; (4) raised, bouldery interiors and depressed, fissure-like perimeters; and (5) raised bouldery interiors, depressed perimeters but no clear fissures. There are also closely and widely spaced mounds, as well as linear arrays of mounds. As many of these diverse forms of surface texture, especially those characteristic of fretted terrain [*Malin and Edgett*, 2001, e.g., Figures 105 and 106] appear to have much in common with patterned ground on Earth, it is informative to examine terrestrial analogs.

[3] In this paper we present new results that provide insight into the rate at which patterned ground forms and deforms the ground surface in the Dry Valleys of Antarctica. The cold and dry near-surface conditions typical of this region approach those on Mars, making it an excellent natural laboratory in which to study processes that occur or may occur on Mars, including the sublimation of subsurface ice [*McKay et al.*, 1998] and the occurrence and preservation of simple life forms in permafrost [*Gilichinsky*, 2002; *Gilichinsky and Wagener*, 1995; *Rivkina et al.*, 2000].

[4] The rate at which a surface is reworked by patterned ground development is relevant to the interpretation of surface ages. For example, *Malin and Edgett* [2000] describe a fan of sediment emanating from a gully thought to have been eroded by water. The fact that the fan is not patterned, whereas the surface around it is, supports the contention that water recently ran across the Martian surface. What is meant by "recent" is unclear, however, because little is known about the rates at which such patterns form and evolve on Mars. Insight into these rates and the factors controlling the rates for terrestrial analogs would be especially useful.

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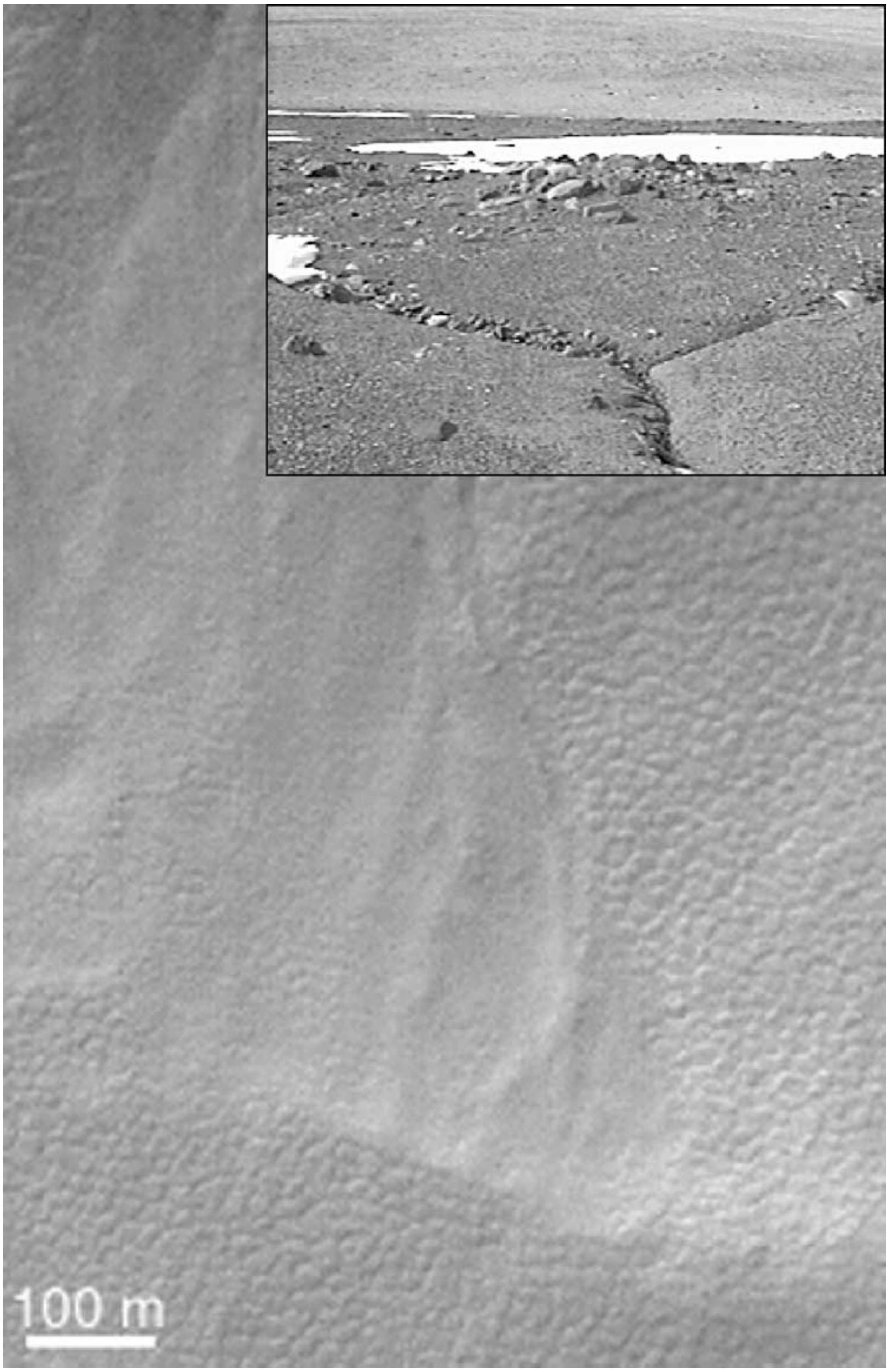

Figure 1. Patterned ground on Mars (MOC Image MO300537) with an inset showing similar features in the Dry Valleys, Antarctica (Images provided by M. Malin, with permission).

[5] We first briefly review the conditions required for fractures to form in permafrost. We then discuss how cracks tend to fill with water or sand and other fine-grained debris, fueling the incremental growth of ice-or sand-wedges and the development of microtopography. We focus on sand-wedges since these are more typical in cold, arid environment of Antarctica and presumably Mars. Results from an ongoing active study of wedge growth that was initiated nearly 40 years ago are summarized and the controls on wedge growth are discussed. We then examine the characteristics of patterned ground that have been active over time scales ranging from $\sim 10^3$ to 10^6 years to develop an

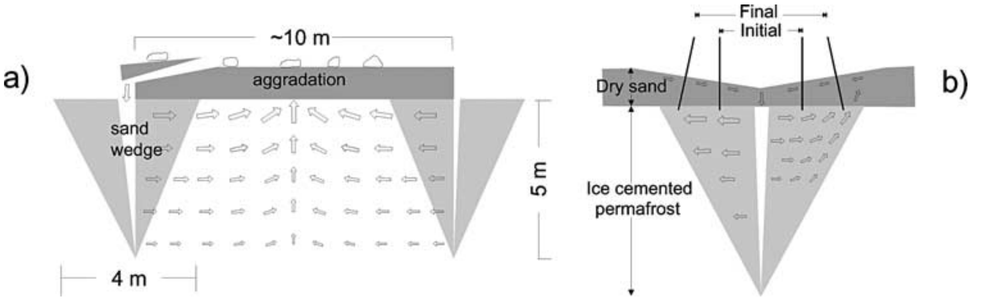

Figure 2. Hypothetical long-term soil motion in a single sand-wedge polygon (viewed in vertical section through the center): (a) Displacement field and the resulting aggradation of the polygon driven by wedge growth. The profile of the wedge and surface has been simplified to stress the equality between the volume of the inflated domain (dark gray) and that of the contributing halves of the wedges (light gray). (b) Geometry of Black's rods. The inner pair shows the initial position in 1962–1963; the outer pair shows schematically the current position and inward tilts. On either side of the crack, end member displacement fields are shown that are both consistent with observed relative rod displacements. The one on the right does not require continued wedge expansion and deformation of polygons.

understanding of the characteristic nature and time scale for the evolution of the microtopography and polygonal patterns in the Dry Valleys.

2. Sand-Wedge Polygons

2.1. Initiation of Polygonal Patterned Ground: Concept and Model

[6] The plan-form of patterned ground is established by the propagation and mechanical interaction of thermal contraction cracks. Cracks form when tensile stresses induced by the cooling of the ground surface and subsurface reach the tensile strength of the frozen soil [*Black*, 1976; *Black and Berg*, 1963; *Lachenbruch*, 1962, 1963; *Pewe*, 1974]. Prior to fracture, thermal contraction induces tensile stress parallel to the ground surface. Formation of a fracture abruptly relieves the stress in the vicinity of the fracture. Fracture intersection ultimately results in a polygonal network of vertical or near-vertical cracks, typically penetrating several meters below the surface and spaced a few meters to several tens of meters apart.

[7] In a classic paper, *Lachenbruch* [1962] calculated the tensile stress that develops in thermally contracting permafrost. He treated the ice-cemented soil as a Maxwellian viscoelastic solid, which on short time scales responds to thermal contraction by an elastic buildup of stress that relaxes viscously on longer time scales. He calculated the steady-state tensile stress that could be maintained for a constant cooling rate and rheological properties of ice near 0°C. He found that tensile stresses could reach values just exceeding the tensile strength of frozen soil for reasonably high cooling rates, consistent with observations of cracking frequency in the Arctic.

[8] *Mellon* [1997] developed a model to examine the formation of thermal contraction cracks on Mars. The model treats the ice-rich permafrost as a semi-infinite, isotropic half-space with a time dependent vertical temperature distribution that is controlled by seasonal variation in surface temperature. The model uses rheological data of ice [e.g., *Hobbs*, 1974; *Kirby et al.*, 1987; *Weertman*, 1983] and frozen ground [e.g., *Andersland et al.*, 1978; *Durham et al.*, 1992; *Tsytovich*, 1975] not available to *Lachenbruch* [1962] and considers the thermoelastic stresses arising from a soil thermal regime appropriate for Mars.

2.2. Wedge Growth and Ground Surface Evolution

[9] Thermal contraction cracks in arid regions tend to open at the ground surface during cold periods and fill partially with sand and other fine-grained debris. This infilling prevents the cracks from fully closing during warm periods. Crack-normal, horizontal compressive stresses arise during the warming phase, producing uplift along the crack (Figure 2a). With time, the ground surface on either side of the crack is warped upward to form symmetrical ridges separated by troughs formed over the cracks. During subsequent cooling periods, the cracks reopen, permitting more sand infilling, thereby incrementally forming wedges of sand. The recurrent expansion, infilling, and contraction cycles result in continued growth of shoulders surrounding the cracks and sand wedges.

[10] Similar microtopography also occurs in cold regions with more abundant moisture. In these regions, ice-wedge polygons form as snow melts or ice-rich frozen ground thaws at the surface during the warming phase, thereby filling cracks that penetrate into the frozen ground with water, which subsequently freezes to form ice wedges. Compared with sand wedge polygons, ice-wedge polygons have received considerable attention. Notably, they have been the subject of an extensive series of studies conducted by *Mackay* [1971, 1974, 1984, 1986, 1992, 1993, 2000] and *Mackay and Burn* [2002].

2.3. Kinematics of Sand-Wedge Polygons in the Dry Valleys

[11] Recent measurements at 13 sites established in the early 1960s by Robert Black show steady rates of divergence across the sand-wedges of patterned ground in the Dry Valleys. Monitoring was conducted by sequentially measuring the spacing between paired 0.6 m long steel rods hammered vertically into the ground on opposite sides of contraction cracks. The rods penetrated into the ice-cemented permafrost and were marked precisely using a

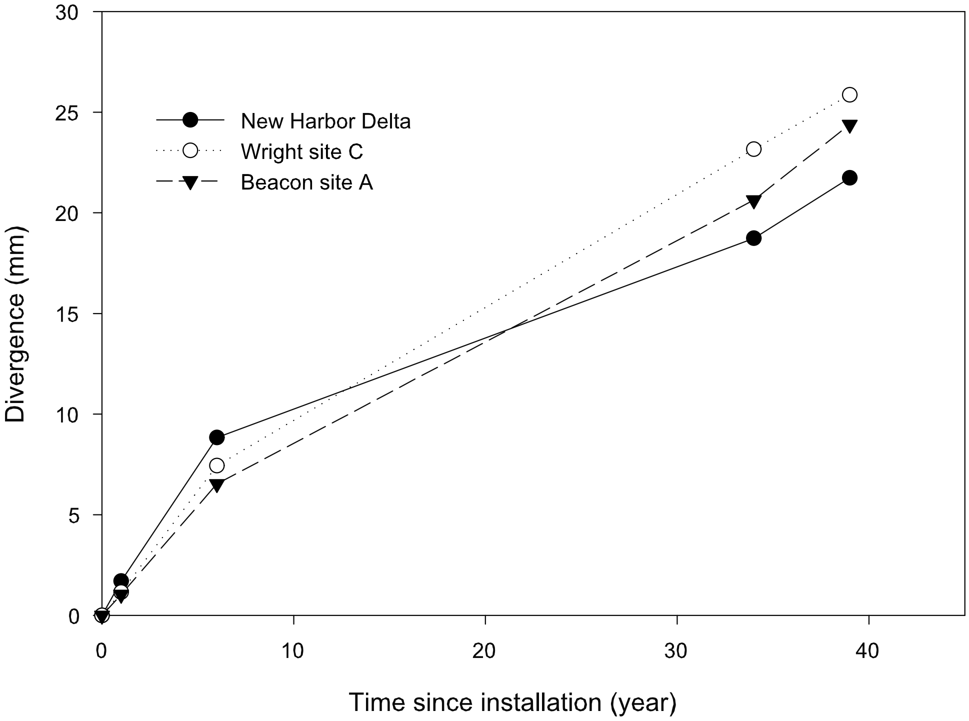

Figure 3. Mean divergence across sand wedges since initiation of monitoring in the 1961–1962 Antarctic summer at three patterned ground sites representing three developmental stages: initiation (New Harbor Delta), developmental (Wright site C on delta), and mature (Beacon Valley) stages.

scribe to allow submillimeter measurements. Black and coworkers measured the rod spacings on several occasions from 1962 to 1982 [*Berg and Black*, 1966; *Black*, 1973, 1982]. A few measurements were made in 1994 by *Malin and Rawine* [1995]. We measured the 417 pairs of rods remaining in good condition in 1996 and 2001.

[12] One of the areas studied by Black that shows the most distinct development of patterned ground is lower Beacon Valley within 1 km of the margin of Taylor Glacier. Sand wedges there reach the greatest widths (>5 m) that we have encountered in the Dry Valleys and form a distinct network of polygons 10 to 20 m on a side. The active, wide, and closely spaced sand wedges imply considerable surface reworking. This is particularly interesting because the site is located only a few kilometers down valley from a similar geomorphic surface thought to have been essentially undisturbed for millions of years [*Sugden et al.*, 1995b].

[13] Individual rod divergence rates in lower Beacon Valley were highly variable, ranging from 0.1 to 1.8 mm yr^{-1}. By 2002, the mean spacing between rod tops increased 20–25 mm (std. dev. 16–18 mm) since their installation 39 years earlier (Figure 3). The rates are remarkably steady in time and are essentially identical to those on much younger delta sites. Tilting of the rods during polygon development complicates the interpretation but is invaluable as it yields important information about both the motion of the permafrost and differential motion of the upper few decimeters of soil. Given that the rods penetrated only slightly into the ice-cemented permafrost, it is likely that the base of the rods moved outward from the crack more than the top of the rods. *Berg and Black* [1963] intended to install the rods vertically although they did not precisely set nor record the initial rod orientation. Assuming that the rods were emplaced perfectly vertically, their present systematic tilts (averaging 2.8°) toward the cracks reflect motion of the overlying ice-free soil toward the cracks relative to the underlying ice-cemented soil, as shown schematically in Figure 2b. Therefore the present inward lean of the rods suggests that the rod-top measurements underestimate the actual divergence rate of the permafrost in the central part of sand-wedges.

[14] We expect that recurrent cracking and sustained addition of sand to a depth of about 5 m generates long-term pervasive deformation in the permafrost and wedge material (Figure 2). The sand making up the bulk of the wedges in polygonal patterned ground appears to be a combination of external material and local sediments derived from adjoining polygons. Simple conservation of mass considerations indicate that the addition of external material to a system of polygons must lead to net surface aggradation, or inflation, as the density of permafrost must remain essentially constant. The likely source of external material is wind blown sand that naturally tends to be trapped in the surface troughs that form over active contraction cracks. Current rates of rod divergence in wedge centers suggest that the surface of Beacon Valley is aggrading rather rapidly, provided the recycling of local material is small compared with the rate of external material accumulation. For example, assuming straight-sided cracks 5 m deep, with the range of rates of surface widening (0.1 to 2 mm yr^{-1}) sustained entirely by addition of external material, the spatially averaged rate of surface aggradation due to the injection at depth along the entire perimeter of polygons 10 m in diameter is 0.05 to 0.1 mm yr^{-1}.

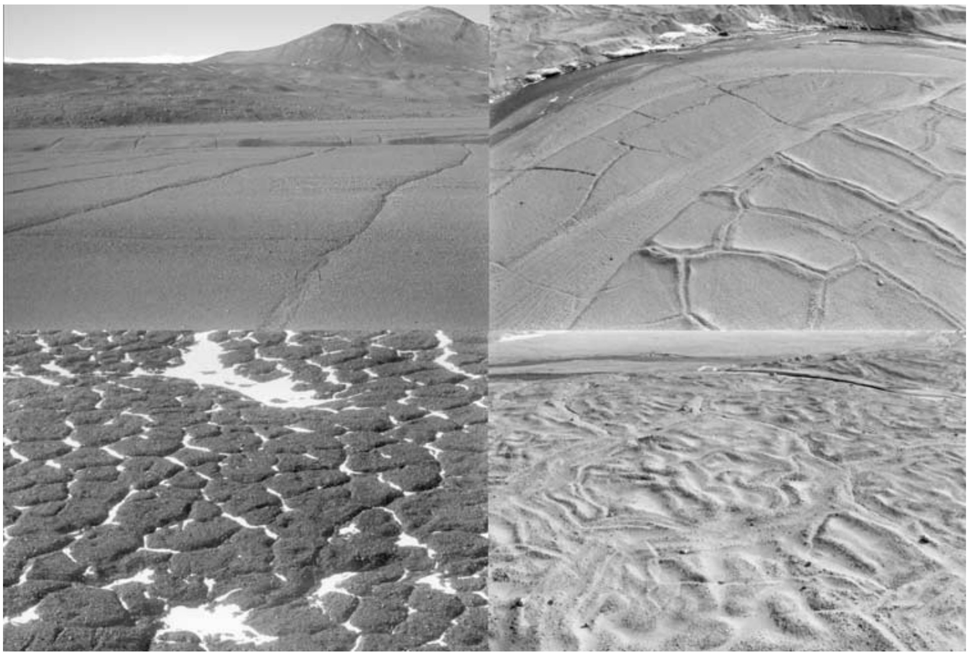

Figure 4. Oblique photographs of patterned ground illustrating various stages of development. Upper left is New Harbor, Taylor Valley showing the initial stage of formation, upper right is in Wright Valley representing both initial and the developmental stages and lower left is the mature stage in central Beacon Valley. The lower right photo shows complex form of patterned ground underlain by spatially nonuniform massive ice undergoing sublimation, Wright Valley.

[15] In areas underlain by massive ice this surface aggradation would tend to be offset by ice loss at depth due to sublimation, thereby decreasing the rate of change in ground surface elevation. Coincidentally, perhaps, independent estimates of current or recent sublimation rates in and around Beacon Valley correspond closely with this range of aggradation rates. *Stone et al.* [2000] used cosmogenic isotope concentrations in an ice core in Beacon valley to calculate long-term ($\sim 2 \times 10^5$ years) sublimation rates of 0.05 mm yr^{-1}. Based on calculated vapor transport rates, *McKay and Mellon* [1998] estimate current sublimation rates to be 0.5 mm yr^{-1} at nearby Linnaeus Terrace.

[16] The inferred pattern of permafrost motion is complex. Subsurface divergence occurs at the polygon periphery where the vertical cracks allow planar material input at depth. This gives rise to upward bulging of the polygon surface. Shallow creep of material down the local slope toward the cracks is suggested by the tilt of Black's markers toward them. Taken together, these elements comprise a long-term convection-like cycling of material through the polygons (Figure 2a). Similar motion may take place within the wedge as well, particularly if the wedge material deforms more easily than the material in the polygon center (Figure 2b). Evidence for subsurface deformation includes frozen soil layers that are often warped upward as they approach the wedge [*Pewe*, 1959] and permafrost deformation extending into the polygon center, as has been observed by *Mackay* [2000] in ice-wedge polygons in the Arctic.

[17] This complex soil motion, a form of cryoturbation, tends to pervasively disrupt geomorphic surfaces with active sand-wedge polygons. The ratio of polygon size ($\sim$10 m) to typical sand-wedge growth rate ($\sim$1 mm yr^{-1}), provides an indication of the time scale for the reworking of the ground surface, which is only $\sim 10^4$ years. In view of the notion that similar nearby geomorphic surfaces have been stable for millions of years, as proposed by *Sugden et al.* [1995a] and *Marchant et al.* [2002], we are forced to question whether the rates of wedge growth deduced from increasing separation of Black's rods over the last few decades are reliable, whether they can be extrapolated to considerably longer time scales, or whether the notion of extreme surface stability is sound.

3. Patterned Ground Evolution on Time Scales of 10^3 to 10^6 Years

[18] We now compare three sites of different ages to provide insight into the progressive evolution of patterned ground in the Dry Valleys as a function of time. The sites were selected because they have yielded considerable data on the rate of sand-wedge growth, the size of sand-wedges, and the associated polygon microrelief, all of which vary from site to site. Figure 4 shows oblique aerial photographs of representative patterned ground types in the Dry Valleys during various phases of development discussed below.

[19] The typical composition of the sand-wedge polygons in the Dry Valleys is 20–50 cm of dry soil/sediment overlying the ice-rich/cemented polygon centers. The polygons range from near massive ice ($\sim$90% ice, middle Beacon Valley) to having only $\sim$10% ice (Taylor, Wright, and lower Beacon Valley); most examples tend to be at one

extreme or the other of these values. The wedges typically have $\sim$20 cm of dry sand overlaying an ice-cemented sand wedge containing $\sim$5–10% ice. The ice-cemented polygon centers are typically more strongly cemented than the sand wedges, based on field observations.

3.1. Initiation Phase, New Harbor, Lower Taylor Valley, 10^3 Years

[20] Polygons are distinct on deltaic surfaces that have recently emerged from the sea due to isostatic rebound. GPS measurements show that the coastal region is rising approximately 4 mm yr^{-1} [*Willis et al.*, 2001]. The New Harbor delta surfaces in lower Taylor Valley are 4 to 8 m above sea level, which suggests that polygons started forming on these surfaces only 1000 to 2000 years ago (Figure 4).

[21] The site shows the initial crack network, which displays little integration. Polygons tend to be relatively large and are often delimited by orthogonal cracks that form rectilinear arrays. There is little microtopography, with only slight shouldering and a shallow trough above the sand-wedge. Excavation of the troughs reveals sand wedges 0.5 to 1 m wide. Based on the age of these surfaces and the observed range of wedge width, the average growth rate of wedges is of the order of 0.5–1 mm yr^{-1}. These rates are consistent with divergence rates for Black's rods over the last few decades and are similar to those we obtained over the last few years from continuous measurements across individual troughs using linear motion transducers.

[22] Similar patterned ground morphology is noted at Hobbs glacier delta, which is of similar age. Here the polygons are 30–50 m across; these large polygons are typical of younger patterned ground in the Dry Valleys.

3.2. Developmental Phase, Upper Victoria Valley, 10^4 Years

[23] The patterned ground in Upper Victoria Valley is developed on a former delta in a lake that extended over much of the valley floor. *Kelly et al.* [2002] estimated the surface is estimated to be slightly younger than 12,000 years based on ^{14}C dating of algae deposits. The delta sediments are well stratified and range from silts to gravel. A scattering of boulders marks the gently sloping and rather smooth delta surface, presumably having been deposited from lake ice. The delta surface provides an excellent indication of the initial state of the ground surface prior to patterned ground development.

[24] The patterned ground reflects pervasive cracking over 12,000 years, with many curving cracks joining at right angles (Figure 5). Excavation reveals that the sand wedges are 2–3 m wide, corresponding to an average growth rate of approximately 0.2–0.3 mm yr^{-1}. Equiangular triple junctions are uncommon, contrary to patterns of quasi-hexagonal polygons (Figure 5). The troughs are the surface expression of the contraction cracking and sediment falling into open cracks; their sides tend to slope 15–20° in loose sandy material.

[25] The patterned ground in Victoria Valley is distinct from the rectilinear pattern in the Hobbs and New Harbor areas. The polygons are smaller and more evenly sized. At this stage, a distinct microtopography has developed with polygons defined clearly by troughs that are bordered by raised polygon edges; the stratified sediments in the polygon centers appear undisturbed at the surface (Figure 6) and in shallow excavations. The patterned ground in Victoria Valley shows a history of cracks of various ages; it is apparent that there are older, inactive cracks as well as cracks that appear to still be forming. The younger cracks intersect older ones, progressively leading to further regularization and subdivision of the patterned ground.

3.3. Mature Phase, Beacon Valley, 10^6 Years

[26] The surface of central Beacon Valley is over 8 million years old, according to *Sugden et al.* [1995b, 2002], but may well be much younger, as suggested by the cosmogenic isotope study of *Stone et al.* [2000] and indirect indices of surface age including pedogenic development and weathering of surface boulders. The polygons in this area are considerably more regular (Figures 4 and 5). They tend to be equidimensional (10–20 m) polygons with straight sides that intersect at triple junctions at similar angles (Figure 5). At the sites in lower Beacon Valley, which are younger than central Beacon Valley but substantially older (based on dating of analogous moraines in adjacent Arena Valley by *Brook et al.* [1993]) than in Wright and Victoria Valley, the sand wedges appear to be continuous; old sand wedges underlie polygon centers entirely. The annual wedge growth discussed above averages 0.6 mm for the past 39 years. Given the considerable age of this surface, it is not surprising that the entire surface is underlain by sand wedge material. The ratio of polygon size to wedge growth rate suggests that this entire surface should be reworked within 10^5 years.

[27] A comparison of the average crack intersection angles for the patterned ground in central Beacon Valley and Victoria Valley is shown in Figure 7. The principal difference is in the relative abundance of angles near 120° for Beacon Valley compared with the peak near 90° reflecting a preponderance of quasi-orthogonal intersections in Victoria Valley. A greater abundance of 120° angles reflects a more mature patterned ground pattern. The ratios of these values provides a single useful geometric index for the pattern regularity: for Beacon Valley, $R_{120:90=}$ 1.8; for Victoria Valley, $R_{120:90} = 0.8$. That is, whereas $\sim$120° angles are about twice as common as $\sim$90° angles for Beacon Valley, in Victoria Valley $\sim$120° angles are less common than $\sim$90° angles. We caution, however, that these intersection angles are determined from intersections of surface troughs whose width can obscure local curvature, adding to the uncertainty of these angles.

[28] The surface profile, in particular the size of the shoulders and troughs provides an indication of relative age. Initially, no shoulders and minor troughs are evident at the delta sites that are only a few thousand years old and little deformation of the soil on either side of the active cracks was noted. The Victoria Valley site displays distinct shoulder and trough morphology with a total relief of about 0.3 m (Figure 6). The continued input of eolian and local sediment into the troughs leads to pronounced shouldering and deeper troughs in lower Beacon Valley (total relief $\sim$0.8 m). Early work by *Ugolini et al.* [1973] noted that the surface profile of polygons in Beacon Valley were unusually steep in places presumably due to pedogenic processes, leading to cohesion and structure in the old soils.

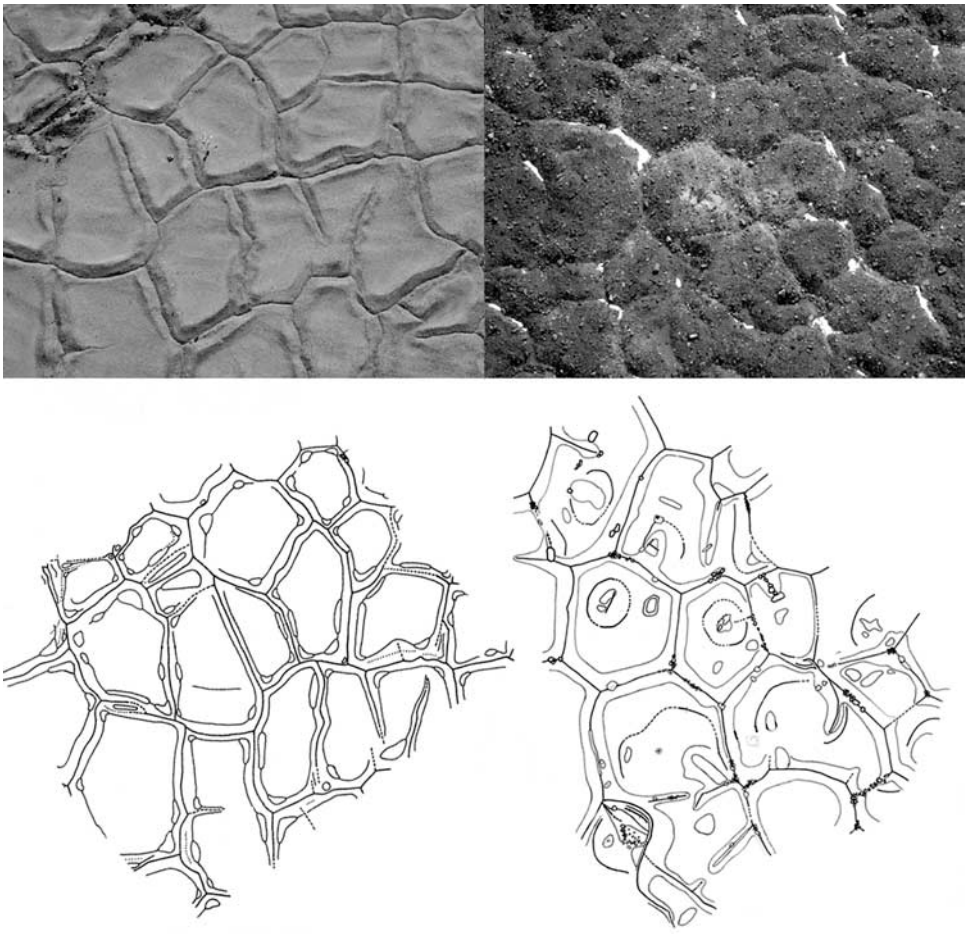

Figure 5. Photographs and corresponding map of patterned ground in Dry Valleys representing the developmental and mature stages. Polygon boundaries are delineated by triple lines, the outer two marking the shoulder tops and the centerline representing the low point of the trough (above the contraction crack). The left images are from the developmental stage of patterned ground in Victoria Valley and the right images are from the mature and more regular patterned ground in central Beacon Valley.

[29] Deeper troughs are common in central Beacon Valley probably due to the sublimation of the massive ground ice in this area [*Marchant et al.*, 2002], much as suggested by *Berg and Black* [1966] for another Dry Valley area underlain by massive ice. In younger patterned ground underlain by pervasive massive ground ice in Wright Valley that is spatially nonuniform, the surface may develop a more complex undulating pattern concurrently with the polygon development (Figure 4, lower right). Whether this type of pattern can generally be used to

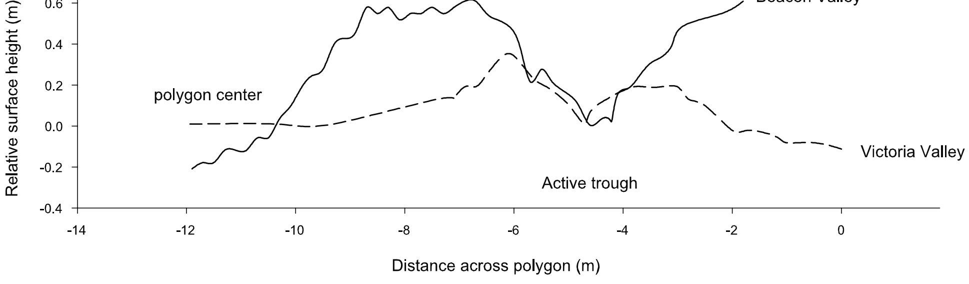

Figure 6. Topographic profile of patterned ground across troughs at the boundary of polygons for the developmental stage in Victoria Valley (dashed line) and for the mature stage in central Beacon Valley (solid line).

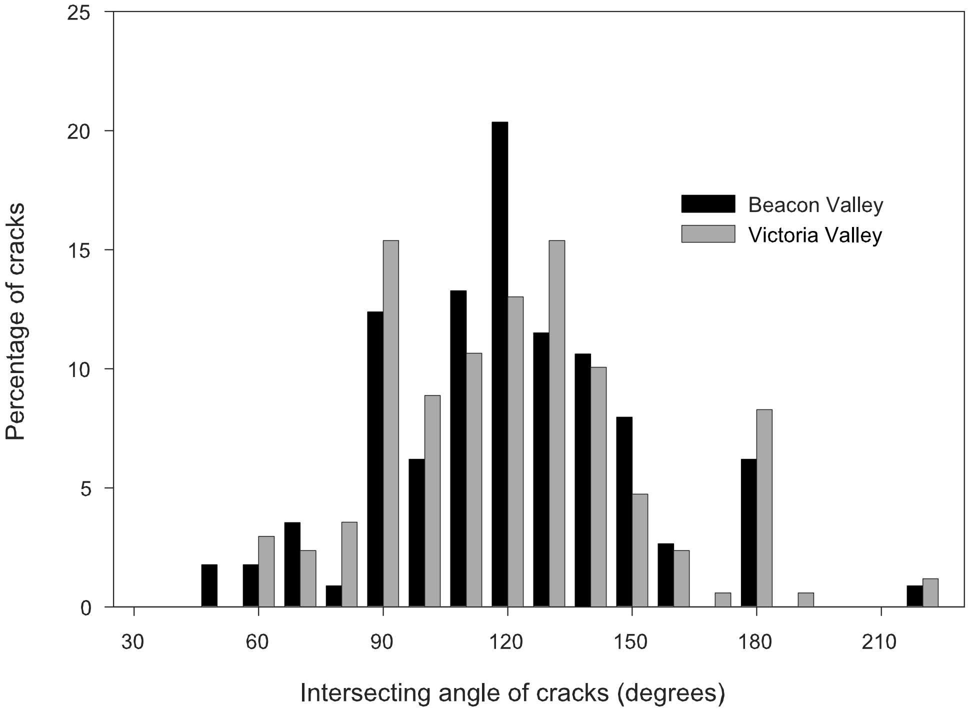

Figure 7. Histograms of angles between intersecting sand wedges in Beacon Valley and Victoria Valley. The total numbers of cracks measured in Victoria Valley are 113 and in Beacon Valley are 169.

assess the presence of massive ground ice is an active area of research.

4. Discussion

[30] Initiation of patterned ground occurs relatively quickly where the soil or sediments contains sufficient ice to cement the materials giving them the cohesion necessary to develop tensile stresses over length scales of tens of meters. Cracks propagate promptly and interconnect to form a complete space-filling network within decades or a century. Initial polygons vary considerably in size and tend to be relatively large. The surface of the polygons is still roughly planar, showing little sign of subsurface addition of sediment and soil deformation. The cracks bounding polygons are often curvilinear and typically curve to join preexisting cracks at right angles due to the influence of these early cracks on the stress field. This initial fracture network geometry is very similar to that observed in drying mud [*Kargel et al.*, 1996; *Weinberger*, 1999; *Weinberger*, 2001] and other desiccating, contracting material [*Shorlin et al.*, 2000]. It is also very similar to the patterned ground simulated by *Plug and Werner* [2001]. In this early stage, patterned ground might not be visible in current satellite images because of the lack of significant microrelief.

[31] The developmental phase is much longer, ranging from 10^3 to 10^4 years, during which some cracks become inactive and others develop. Early in this phase, there is sufficient wedge growth to deform the sediments extensively and to raise the shoulder of the polygon. At triple-junctions the deformation of the frozen ground driven by the expansion of the wedges is greatest due to geometric convergence of subsurface material, and hence the highest topographic features are formed there. The magnitude of microtopographic development depends directly on the cumulative volume of externally derived sand-wedge material that has filled thermal contraction cracks.

[32] The shouldering of material at the periphery of polygons may be of special interest to planetary studies because it reflects the sequential addition of material in cracks over a significant period of time and hence reflects not only contraction cracking, which could occur in a number of ways not necessarily involving temperature changes, i.e., desiccation. The shouldering seems to require recurrent stress oscillations that permit cracks to form and open repeatedly and to progressively fill with new material that then causes the shouldering when the surface-parallel stress becomes compressive. Repeated crack filling events are required because the volume of the shoulder exceeds, by far, the volume of cracks that are open at any one time. The spacing between adjacent shoulders is also worth highlighting because it contains information about the duration of wedge growth as it increases with the width of buried sand-or ice-wedges.

[33] The mature phase is characterized by a pattern of equidimensional and equiangular polygons with straight boundaries. Regularization of plan form is accompanied by considerable development of microrelief, especially in areas underlain by massive ice. It is apparent in Victoria Valley that old cracks are partially healing as they cease to be active while new cracks are initiated over time leading to the regularization of the polygonal pattern.

[34] The evolution we hypothesize for the Dry Valley crack patterns from initial curvilinear crack arrays dominated by orthogonal junctions to more regular polygonal crack patterns appears similar to that examined by *Jagla*

and Rojo [2002] in a very different material. They considered and simulated the initial appearance of irregular curvilinear fractures at the surface of cooling lava. The fractures penetrated with time into the material, tending to form columnar quasi-hexagonal patterns reflecting the local stresses as the fracture propagate to deeper levels. They suggested that this progressive ordering could be described as the tendency to minimize an energy functional. In contrast, cracks in patterned ground areas do not increase in depth through time, except at sites where the surface is lowered through time due ice sublimation as in central Beacon Valley. However, the periodic thermal forcing that drives the opening and closure of cracks, as well as partial healing of cracks, does provide opportunities for new cracks to form where local stresses are sufficient and old cracks to cease to be active where stresses are low [*Plug and Werner*, 2001]. This can result in the regularization of polygons at the surface to form arrays of essentially equidimensional and equiangular polygons. Simulations of surface fragmentation patterns [*Hornig et al.*, 1996] indeed show that such regular polygonal patterns can form in two dimensions due to crack propagation provided the material is relatively uniform. If the material is spatially nonuniform, however, complex and irregular cracks form by the coalescence of initially independent point defects.

[35] Comparison of pattern development from sites of different ages is instructive, but it must be viewed with caution because of the potentially confounding effect of intersite differences in substrate characteristics. Some sites are underlain with sediments cemented by ice whereas others are largely underlain by massive ice. Among the various properties of patterned ground, the microrelief would tend to be most sensitively affected by substrate type. In areas underlain by ice-cemented sediment, thermal contraction cracks constitute sites of net addition of mass, which is accommodated by lifting the ground surface, particularly along polygon perimeters. In contrast, in areas underlain by massive ice, cracks can take on dual functions, concurrently serving as net sinks of ice by accelerating sublimation along polygon boundaries and as net sources of surface-derived sediment.

[36] The loss of ice in and near the perimeter cracks, especially at shallow depth, together with accumulation of sediments at depth in the cracks would tend to form mound-like polygons with depressed perimeters, as seen over much of central Beacon Valley. The mound-like form of polygons in lower Beacon Valley, where frozen sand and not massive ice underlies most of the area, indicates that the lowering of the polygon edges by sublimation is not an essential factor, however, in the formation of mound-like forms. In areas where ice is not uniformly distributed below the surface, loss of subsurface ice by ablation and sand-wedge activity can lead to complex microtopography as seen in Figure 4.

[37] Growth of patterned ground is highly dependent on substrate properties, thermal forcing, and availability of crack-filling material. Patterned ground may not develop at all or may do so very slowly if the ground is generally so dry that it lacks cohesive strength. In the Dry Valleys, the rate-limiting step on wedge growth could be either the frequency of cracking and crack opening or the amount of wind-blown sand available to fill cracks.

[38] The growth is also dependent on the magnitude and frequency of thermal expansion-contraction, and this may be modified in complex ways by changes in soil thermal regime due either to changing climatic or permafrost-atmosphere heat transfer efficiency. For example, *MacKay and Burn* [2002], who studied the onset of ice-wedge growth at an experimentally drained lake site on the western Arctic Coast in Canada, reported that ice-wedge growth ceased within about 12 years, after growing at the highest rates ever reported (up to 30 mm yr^{-1}) for the first few years. They attributed ‘‘the gradual cessation of thermal contraction cracking to rapid vegetation growth, snow entrapment, an increase in winter ground temperatures and a decrease in the linear coefficient of thermal contraction associated with freeze-thaw consolidation of the initially saturated lake-bottom sediments.’’ This latest study points to the fact that sand-and ice-wedge growth and hence patterned ground development depend of diverse parameters and that pertinent terrestrial data are sparse.

5. Conclusions

[39] In the initial stage of patterned ground development, hierarchies of curvilinear fractures, which commonly intersect at right angles to form irregular polygons, dominate the fracture network. On a time scale of 10^4 years, permafrost deformation resulting from incremental sand-wedge growth is confined to polygon margins where material is shouldered aside; the central portion of these low-center polygons remains undisturbed. The spacing between adjacent polygon shoulders increases with time along with the width of the sand-wedge. As patterned ground develops further and matures, the growth of wedges along new contraction cracks and the cessation of activity along others leads to a regularization of the patterned ground with a predominance of regular five-and six-sided polygons with straight sides of similar length that intersect at nearly equiangular triple junctions. The average polygon size decreases as the regularization occurs. Substantial developmental changes are noted for times scales of 10^3 to 10^6 years.

[40] On Mars, patterned ground microtopography, in particular, appears to hold considerable promise as an indicator of subsurface conditions and processes, as well as changes in climatic forcing and sediment input that fuel sand-wedge growth. Especially with the prospect of acquiring higher resolution images of Mars, comparative studies of modern analogs on Earth in diverse settings merit intensified attention for studying patterned ground as a reflector of subsurface conditions. We are just starting to learn how the presence or absence of patterned ground and how the spatial variation in plan form and extent of microrelief development reflect surface ages, environmental conditions, soil properties, and the occurrence of near-surface ice.

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