ANTARCTIC DRY VALLEYS: MORPHOCLIMATE ZONATION, VARIABLE GEOMORPHIC PROCESSES AND IMPLICATIONS FOR ASSESSING CLIMATE CHANGE ON MARS.

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Introduction: The Antarctic Dry Valleys are generally perceived of as a hyperarid cold polar-desert environment with characteristics that can aid in the interpretation of geomorphic features and climate conditions on Mars. Here we further explore this analog by outlining three major microclimate environments within the Dry Valleys that are defined on the basis of differences in annual surface temperatures (and the resultant behavior of meltwater), relative humidity, and soil moisture (and the resultant types of subsurface ice): 1) a Coastal Thaw Zone, with a traditional active layer and ice wedge polygons similar to those of the Arctic; 2) an Inland Mixed Zone showing variable soil moisture and both composite and sand wedge polygons; 3) an Upland Frozen Zone, with low soil moisture <5% (ultraxerous) and without segregation ice and a traditional active layer. The subtle but important variations in these parameters among the three micro-climate environments result in considerable variation in the distribution and characteristics of geomorphic features and processes at all scales. These guidelines and analogs can be readily applied to the interpretation of similar features on Mars to help deduce individual current microenvironments and to document their change during climate fluctuations.

Morphoclimate 1: Coastal Thaw Zone (Subxerous): *Macroscale topography*. Low-rolling hills (<500 m relief) and wide valleys (>8 km) dominate the macroscale topography of the coastal thaw zone. Bedrock slopes average from 5° to 20° North-facing slopes are less steep by several degrees than south-facing counterparts. Glaciers and perennial snow banks lose mass dominantly by sublimation. A significant fraction (15-20%) of ice melting occurs at the steep cliffs that front most alpine glaciers in the coastal zone. Gullies in this zone are generally deeper and possess more rounded interfluves than counterparts in the inland mixed zone. The well-developed gullies of the coastal thaw zone likely form from a combination of runoff from snowmelt, freeze-thaw, and salt weathering. The magnitude, rate, and location of snowmelt in gullies vary considerably within the coastal thaw zone. Provided sufficient snow/ice exists in gullies, the major factors that control gully hydrology include slope angle, aspect, shielding (terrain obstructions), cloud cover, and surface albedo. Topography, at all scales, is the dominant control on solar radiation. At the largest scale, solar radiation, as averaged over monthly timescales, is greatest for north-facing slopes. This finding is consistent with geomorphic observations that show that 1) north-facing gullies are better developed than south-facing gullies and 2) that north-facing slopes are generally less steep than south-facing slopes. Slope gradients decrease with increasing solifluction, salt-weathering, and freeze-thaw processes.

Mesoscale topography. Unconsolidated sediments superposed on the bedrock topography of the coastal thaw zone are seasonally wet and display evidence for lateral flow (solifluction) and melting of subsurface ice (thermokarst). This zone displays a traditional active layer down to ~30-60 cm depth; moisture in this layer varies from ~6%-77%. The relatively mild summer conditions and traditional active-layer dynamics permit the development of rills, channels, debris flows, ephemeral ponds, and intermittent streams. The beds of intermittent streams, particularly low-gradient beds (<~20°), commonly display a boulder pavement that grades laterally into a hyporheic zone, which is saturated and permits downstream throughflow. If sufficient meltwater exists, sediments within the hyporheic zone may move downslope via solifluction. The largest and best developed streams flow from the snout of glaciers in the coastal thaw zone. Soils developed in the coastal thaw zone are classified as Anhyturbels and contain salts enriched in sodium chloride. Contraction-crack polygons are common in this zone. The seasonal influx of liquid water into open thermal-contraction cracks, and subsequent expansion on freezing, leads to the development of ice-wedge polygons with raised rims. The width of ice wedges (as measured across their top surface, ~<2.0 m) is generally smaller than that found in the Arctic, reflecting the limited availability of liquid water in the Dry Valleys. Rock glaciers are rare in the coastal thaw zone. This could reflect 1) the paucity of exposed bedrock cliffs that could produce sufficient rockfall to accumulate a surface lag on glacier ice or 2) the lack of extensive talus and colluvium on valley walls that could develop flow through the formation and deformation of segregation ice.

Morphoclimate 2: Inland Mixed Zone (Xerous): *Macroscale topography.* Heavily incised slopes dominate the macroscale topography of the inland mixed zone. On average, these slopes are steeper (by as much as 5-10°) and rougher (as measured over 10-m-scale baseline) than those of the coastal thaw zone. Gully density is about twice that of the coastal thaw zone (even in areas of similar granitic-bedrock lithology) and interfluves show greater angularity than those near the coast. There is a transition from smooth, low density gullies in the coastal thaw zone to jagged, high density gullies in the inland mixed zone. Although minor variations in bedrock structure could play a role in gully density and morphology, we suggest that excessive snowfall near the coast, accompanied by relatively high meltwater runnoff, freeze-thaw, and salt weathering may account for the relatively large size of gullies and apparent rounding of interfluves in the coastal thaw zone. The low density would thus reflect the progressive development and evolution of master gullies, which form at the expense of minor gullies and troughs that are incapable of trapping requisite snowfall. If correct, then the relatively high density of gullies in the inland zone may reflect a paucity of snow accumulation (rather than insufficient elapsed time). Insufficient meltwater runoff, freeze thaw, and salt weathering in the inland mixed zone could prevent generation of mature gully networks. We note that in contrast to the coastal thaw zone, small talus cones, rather than streams, occupy the base of many gullies.

Mesoscale topography. Slow moving gelifluction lobes with concave longitudinal profiles and ribbed, steep fronts (> 30° in some cases) represent the dominant form of mass wasting in the inland mixed zone. Gelifluction lobes may show plug-like flow with considerable velocity variation. Rock glaciers occur sporadically within the inland mixed zone. These features are morphologically similar to gelifluction lobes described above, but contain a significant percentage of buried ice that moves through shearing and plastic deformation. The rock glaciers commonly form downslope from local accumulations of snow and ice, are generally tongue-shaped in plan view, and display alternating surface ridges-and-furrows and steep termini when active. Of 32 rock glaciers surveyed in a region roughly coincident with the inland mixed zone, 38% are stagnant. Although the origin of ice in rock glaciers is commonly debated, most rock glaciers in the inland mixed zone are likely cored with secondary ice, reflecting the development and deformation of subsurface ice within pre-existing colluvium. Although some have noted that ~15% of the surveyed rock glaciers are "in transition with alpine glaciers", the link to these extant glaciers is likely through melting, percolation, and subsequent refreezing of meltwater in pre-existing colluvium, rather than through progressive burial of glacier margins. Apart from gelifluction lobes and rock glaciers, the dominant mesoscale feature of the inland mixed zone are sand- and composite-wedge polygons. Sand-wedge polygons form in a manner analogous to ice-wedge polygons except that contraction cracks are filled with sand, rather than with ice. Composite polygons contain wedges with alternating lenses of ice and sand. The growth and evolution of sand- and composite-wedge polygons have been studied extensively. The retention of open contraction cracks at the ground surface and the availability of eolian sand to fill such cracks are determining factors in polygon growth. Because cracks tend to be wider and remain open longer in soils with cohesive near-surface horizons (ice and/or salt cemented), sand-wedge polygons are most active near the margins of perennial snow banks and/or in regions that experience minor snowmelt. The sands and gravels that line the troughs of sand-wedge polygons are generally coarser-grained and show less compaction than sediment at polygon centers. Where sand-wedge polygons form over buried ice, this textural variation is particularly important in modulating the rate of underlying ice sublimation, with the highest rates occurring beneath coarse-grained sediment at polygon troughs. Ultimately, the observed variation in soil-moisture conditions in the inland mixed zone (from ~3% to > 20%) gives rise to a patchy distribution of Anhyothels and Anhyturbels, the latter showing evidence for some cryoturbation. In the field, boundaries between the coastal thaw zone and the inland mixed zone are plotted at the first indication of long-term ground stability (ancient soils, relict sand wedges, and ancient *in-situ* ashfall, as measured from the coast), even though we recognize that isolated regions with traditional active-layer cryoturbation occur sporadically throughout.

Morphoclimate 3: Stable Upland Frozen Zone (Ultraxerous): *Macroscale topography*. Straight (rectilinear) slopes topped by steep cliffs dominate the macroscale topography of the stable upland frozen zone. On average, these slopes are steeper (averaging ~25-35°) than those of the inland mixed- and coastal thaw zones, but this may be due in part to the local occurrence of cliff-forming lithologies. Minor variations in slope gradients are linked to the distribution and partial melting of perennial snowbanks. We have observed minor snowmelt on low-albedo rocks, even when atmospheric temperatures are <-10°C. Although water from snowmelt may coat surface rocks and infiltrate the upper ~10 cm of coarse-grained soils, it is insufficient to incise channels and/or produce rills in unconsolidated sediment. Most of the meltwater that intermittently moistens soils in this zone evaporates within hours to days and does not freeze to form segregation ice. Gullies are rare in the stable upland frozen zone and occur concentrated only at a few localities, such as at the margin of low-albedo dolerite sills. The presence of ash-rich avalanche deposits, as much as 6.4 Ma and 11.3 Ma, as well as bedded ashfall dated at 12.5 Ma on steep valley walls, indicates that many colluvial slopes in the stable upland frozen zone are today inactive, and have been so since at least late Miocene time. Widespread colluvial deposits, most of which are at the angle of repose, are unmarked by rills, gelifluction lobes, and rotational slumps.

Mesoscale topography. Rock glaciers dominate the mesoscale topography of the stable upland frozen zone. Most rock glaciers occur downwind from dolerite-capped cliffs. Unlike rock glaciers of the inland mixed zone, which form via deformation of segregation ice, these rock glaciers originate through direct burial of glacier ice. Surface debris accumulates from rockfall and/or sublimation of dirty glacier ice. The latter brings englacial material to the ice surface at rates dependent on the thickness, porosity, and permeability of the overlying till cover. The stratigraphic contact between ice and overlying till is smooth and dry and lacks physical evidence for melting and subsequent refreezing - even where the buried ice lies just ~35 cm below the ground surface. It has been proposed that stagnant glacier ice beneath a thin till cover ~50-cm thick in central Beacon Valley, Quatermain Mountains is as much as 8.1 Ma.

Portions of rock glaciers in the stable upland frozen zone show morphologic characteristics signaling active flow, including steep frontal lobes and concentric surface ridges. However, horizontal ice-surface velocities for these rock glaciers are an order of magnitude lower than that measured for rock glaciers in the inland mixed zone. For example, the maximum surface velocity for active regions of the Mullins Rock Glacier in the Quartermain Mountains is ~40 mm per year. This low surface velocity likely reflects minimal snow and ice accumulation and emphasizes the important role of the katabatic winds in concentrating windblown snow from the Polar Plateau. Mass balance calculations, along with estimates for direct snowfall in this microclimate zone, suggest that >85% of the snow that falls onto the accumulation area of Mullins Valley rock glacier sublimes back to the atmosphere. Beheaded rock glaciers (those where deep topographic hollows, rather than ice, occupy snow-accumulation areas) commonly occur in the stable upland frozen zone – but not in the inland mixed zone. The topographic hollows, which commonly are lined with transverse, recessional moraines, mark the former position of alpine glaciers that, due to insufficient till cover, have completely sublimed; regions downslope, where debris cover has been/is sufficient to reduce sublimation, buried glacier ice still remains but commonly shows minimal evidence for lateral flow. Sublimation polygons, a special type of sand-wedge polygon, forms in tills overlying buried ice in the stable upland zone. Coarse-grained sand wedges that form at polygon margins allow for enhanced vapor diffusion of underlying ice, relative to that beneath fine-grained, compact, and undisturbed till at polygon centers. Ultimately, this enhanced sublimation leads to the development of ice-cored till mounds separated by deep "sublimation troughs" (>3 to 5 m deep). A negative feedback prevents runaway sublimation and complete loss of glacier ice: as sublimation troughs deepen, they become preferred sites for collection of windblown snow; the downward flux of vapor from the base of these snowbanks, particularly during months when subsurface ice temperatures drop below atmospheric temperatures, creates a thin layer of ice that caps the buried glacier and effectively shuts down loss of remaining glacier ice.

Soils within the stable upland frozen zone are extremely dry (<3% soil moisture) and lack stratigraphic evidence for traditional active layer deformation. They are best classified as Anhyothels. As for most regions in the Dry Valleys, intermittent moistening of near-surface soils from minor snowmelt on low-albedo rocks leads to the development of subsurface salts. Old soils >10 Ma contain salt horizons as much as 20-cm thick. Salts are enriched in nitrates and sulfates, reflecting the dominance of westerly katabatic winds off the Polar Plateau. Detailed chemical analyses show that below 20-cm-to-30-cm depth many soils of the stable upland frozen zone retain undisturbed salt horizons that accumulated as much as 13 Ma. This indicates long-term soil stability, limited leaching, and minimal cryoturbation over million-year timescale.