LATE-STAGE PARAGLACIAL ACTIVITY ON MARS: FORMATION OF WASHBOARD TERRAIN.

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Introduction: Extensive evidence of Late Amazonian glaciation exists on Mars, predominantly in the mid-latitudes, and one of the most abundant settings for glacial deposits is crater interiors [1]. These deposits of concentric crater fill (CCF) are believed to have accumulated in periods of higher obliquity (~35°) in the last few hundred million years [2,3]. Given the low atmospheric pressure and current mean obliquity of <35° over the last few million years, ice is not expected to be stable at the surface in the mid-latitudes, so glaciation is not currently ongoing [4]. Most glaciated crater interiors contain evidence of deglaciation and resulting paraglacial modification (the response of the local crater environment to deglaciation [5,6]). A martian paraglacial period is expected to have initiated within the past ~5 Ma [3].

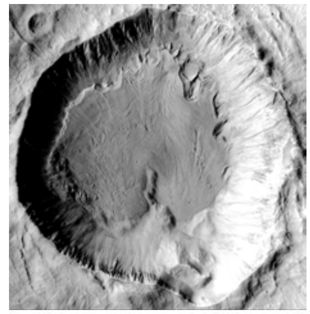
On Earth, paraglacial modification generates a suite of diagnostic features [7], a subset of which are also seen on Mars [5] including spatulate depressions, gullies, washboard terrain, crater wall polygons, and broad pits. The formation mechanisms for most of these features are well-constrained, but washboard terrain remains an enigmatic feature with a potential Earth analogue in the form of sackungen, or uphill-facing scarps, which also have a debated formation mechanism [8]. Washboard terrain, formed by sets of parallel scarps oriented normal to the crater wall slope, extends for large distances across crater walls at the same approximate elevation as gully fans [5,9].

Washboard terrain on Mars could have formed via a variety of mechanisms, including: (1) deep-seated fracturing of crater wall bedrock due to glacio-isostatic rebound, potentially similar to terrestrial sackungen [10,11]; (2) glacial crevassing caused by reinvigorated flow of a shallow sub-surface ice layer; (3) slumping and sliding of sediment on a low-friction ice layer.

This work describes a morphologic analysis of martian washboard terrain in a glaciated crater (Fig 1) to determine the location of deformation (bedrock, ice, or surficial sediment) and its formation mechanism.

Observations: Parallel sets of fractures in glaciated crater interiors have been previously identified in association with gullies [9,12,13], but few analyses have studied the fractures themselves Our analysis has yielded two populations of washboard terrain: fractures on the crater wall and within spatulate depressions.

Washboard terrain on crater walls. Fractures forming the washboard terrain are widespread in the crater interior on the eastern and northern portion of the crater wall, are oriented normal to the crater wall slope, and uphill-facing in orientation (Fig 2); the zone of deformed crater wall extends approximately from the top of the gully sediment fans downslope to the base of the crater wall, at the heads of the spatulate depressions, an average vertical distance of ~265 m (Fig 2A). Slopes in the region above the deformed crater wall and gully fans are steeper (~25-30°) than the portion of the crater wall that contains washboard terrain (~10-20°). Individual fractures are separated by ~12 m, and individual scarps can extend laterally for ~100 m (Fig 2B). Scarps do not increase in size or spacing down or across slope.



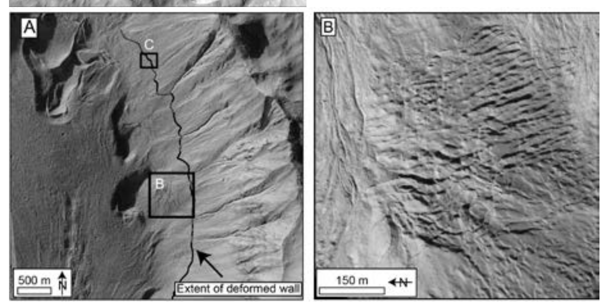


Fig 1. 10.6 km diam glaciated crater analyzed in this work 155.3°W, 40.13°S. Fig. 2. (A) Washboard terrain distribution in the eastern portion of the crater. (B) Stratigraphic relationship of washboard terrain to nearby gully fan.

The deformed wall that contains washboard terrain is morphologically distinct from the crater wall immediately upslope. The transition in morphology is indicated by a laterally-continuous, downhill-facing scarp that extends ~4400 m around the crater wall (Fig 2A).

The washboard terrain is in general stratigraphically older than gully sediment fans, as many fractures are mantled by gully sediment (Fig 2B). Small pits are present in the gully sediment fans in similar location and orientation as washboard terrain fractures.

Washboard terrain in spatulate depressions. Parallel sets of fractures morphologically similar to crater wall washboard terrain are also present inside and between spatulate depressions (Fig 3A). Although fractures are more spatially limited, fracture morphology appears to be similar to the uphill-facing scarps in the crater wall. Spatulate depressions are generally flat-floored, but local slopes within spatulate depressions are variable and exceed 30°, unlike the flatter adjacent CCF surface with slopes ~5-10°. Individual fractures extend laterally for up to ~200 m, and average fracture spacing is ~12 m, similar to the crater wall washboard terrain, although fracture spacing decreases with proximity to the outer edge of the spatulate depression (Fig 3A). Fractures appear to merge (Fig 3B), and small fractures can be seen forming perpendicular to the larger crater floor washboard terrain fractures (white arrow, Fig 3B), unlike crater wall fractures.

Washboard terrain fractures are not spatially limited to the interior of the spatulate depressions; fractures also extend onto the outer ridges of the spatulate depressions (white arrow, Fig 3A). Similar to the crater wall washboard terrain, small pits can be seen forming in the washboard terrain fractures inside spatulate depressions (black arrows, Fig 3B), as well as in a smooth gully fan deposit at the upper edge of a spatulate depression (black arrow, Fig 3A) in the same location and orientation as washboard terrain fractures.

The crater floor washboard terrain is stratigraphically older than nearby gully sediment fans. The washboard terrain is stratigraphically younger than the spatulate depressions, as the fractures are present inside the depressions and also cut the outer ridges.

Interpretations: The two groups of washboard terrain have similar morphology, spacing, and stratigraphic age, despite their distinct settings. These similarities suggest that similar formation mechanisms created both groups of washboard terrain, and similar conditions were present in a wide swath of the crater interior.

The pits observed in both groups appear consistent with mass-wasting of fine-grained material into pre-existing fractures, suggesting that the fractures formed in a subsurface layer that was present before the major period of gully fan formation. This observation supports the interpretation that the washboard terrain is forming in a subsurface, deformable ice layer rather than a surficial sediment layer. In addition the coherent, uniform size and spacing of the fractures would be difficult to create in an unconsolidated sediment layer, such as via sediment slumping or sliding. The localized distribution of the crater floor washboard terrain, restricted to spatulate depressions (Fig 3), suggests that the fractures did not form via isostatic rebound in a coherent bedrock layer, as has been proposed for terrestrial sackungen formation, but rather formed in a spatially restricted, more easily deformable layer such as an ice layer. In addition, the crater wall washboard terrain is easily distinguished from the undeformed crater wall by a laterally continuous, downhill-facing scarp. This scarp is morphologically consistent with a bergschrund, a transverse crevasse separating immobile ice at a glacier head from mobile ice downslope. Other potential bergschrunds have been identified on Mars [14,15].

Implications for Formation Mechanisms: The observations outlined above suggest that fractures within the washboard terrain formed in a subsurface ice layer. Our preferred formation mechanism for the washboard terrain is via glacial crevassing in a subsurface ice layer. On the basis of the stratigraphic relationship of the spatulate depressions and the gullies, the washboard terrain would have formed when large quantities of ice were lost in the crater, and slopes were becoming steeper and covered with debris. Quantitative analyses are currently ongoing to determine if these increases in slope were sufficient to induce glacial flow (and therefore crevassing) within the crater.

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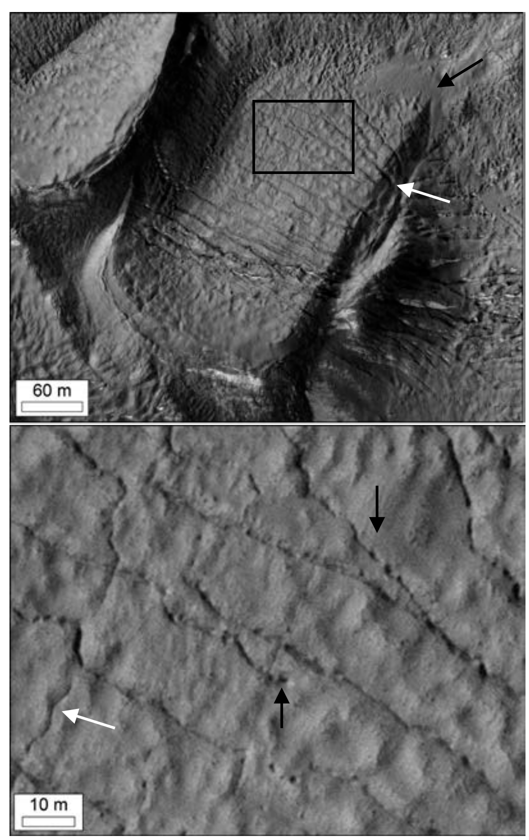

Fig. 3. Crater wall washboard terrain. (A) Distribution inside a spatulate depression. (B) Fine-scale nature of fractures and pits.