PARAGLACIAL GEOMORPHOLOGY ON MARS: A CONCEPTUAL FRAMEWORK FOR POST-GLACIATION GEOMORPHIC PROCESSES.

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Introduction: In terrestrial glaciated locations, a short stage of post-glaciation has been identified in the time directly following ice loss. Termed *paraglacial*, this period immediately follows a period of glaciation; deglaciation causes an initial instability or metastability of materials due to large-scale ice loss which is susceptible to rapid modification [1-2]. *Paraglacial geomorphology* is defined as "the study of earth-surface processes, sediments, landforms, landsystems and landscapes that are directly conditioned by former glaciation and deglaciation" [2]. Specifically, this loss of ice exposes large sediment stores which become available to erosion and modification by multiple processes; the period ends once the sediment stores have been exhausted and the system returns to a nonglacial or "equilibrium" state [2]. *Paraglacial* geomorphology differs from *periglacial*, which refers to environments and processes operating at the margins of glaciers.

Glaciation has been documented at all latitudes on Mars (polar [3, 4], high- to mid-latitude [5], mid-latitude [6], and tropical [7]), and there is clear evidence that variations in spin–axis/orbital parameters [8] throughout martian history have resulted in the repeated transport of ice across the surface [e.g., 9]. Thus, much of Mars has been subjected to both glacial processes and snow and ice loss (and therefore rapid exposure of underlying material). Therefore, the concept of *paraglacial geomorphology and landsystems* should find wide application to the understanding of these terrains in immediate post-glacial history.

In this contribution we outline the basic phenomena and processes in terrestrial *paraglacial geomorphology* as a guide to the further use of these concepts on Mars. We then focus on a more specific example of paraglacial processes in crater wall and interior fill on Mars in glacial landforms known as concentric crater fill (CCF). Specifically, many craters on Mars contain evidence for ice accumulation and flow, including CCF [10, 11], arcuate depressions [12], and spatulate depressions associated with CCF [13]. Many of these craters also contain associated features that are stratigraphically younger than the ice-related features: these include gullies, washboard terrain, and sediment fans [11, 13-14]. The association of these features suggests they are formed by related processes, and their stratigraphic position strongly suggests that they are immediately post-glacial in origin [13]. We first review the terrestrial paraglacial model, then extend this model to include the morphology seen in craters on Mars [15].

Included in this is a survey of mid-latitude martian craters bearing evidence for ice flow and ice loss. In light of this analysis, the environment seen in these craters on Mars represents a transition from a glacial to post-glacial environment.

Paraglacial Model: Paraglacial geomorphology includes six 'landsystems': 1) *rock slopes*, 2) *sediment-mantled slopes*, 3) *glacial forelands*, and 4) *alluvial*, 5) *lacustrine*, and 6) *coastal systems.* For the application to Mars, lacustrine and coastal systems will be ignored do to their unlikely occurrence during the Amazonian. These landsystems comprise a range of distinct features that represent the subsequent processes a landscape undergoes following deglaciation (Figure 1) [2].

Adjustment of *rock slope landsystems* comprise the responses to changing stresses caused by unloading and debuttressing following ice loss; this includes catastrophic failure, progressive rock-mass deformation, and small-scale slope adjustment manifested as rock slides and avalanches, graben and uphill-facing scarps, and talus accumulation [2, 16-18].

Ice loss exposes *sediment-mantled surfaces*, terrains dominated by sediment-gravity flow, or flow of poorly sorted, unconsolidated sediment and water [2]. On Earth these processes create gullies that form parallel debris flows, crosscut earlier channels, and form complex morphologies on initially steep (>30°) slopes [19-20]. Estimates attribute 83% of debris flow to rainfall-triggered failure (which is unlikely for Amazonian Mars), while 14% is caused by subsurface melt [21].

Retreating g*lacial forelands* are modified following ice loss due to aeolian or fluvial processes, mass movement or freeze-thaw. Aeolian and fluvial processes generate downwash and erosion; mass-movement is characterized by frost creep, solifluction, and gelifluction; freeze-thaw creates polygons and cracks [2].

The time span under which these features form is dependent upon the sediment supply of the system related to each feature: small-scale glacial foreland modifications on Earth can operate over 10-100 years, while rock slope failure can last $>10^3$ years [2, 22-23]. The paraglacial period ends when the exposed sediment supply is exhausted, and the system returns to nonglacial conditions and rates of sediment transport [2].

Application to Mars: Recent work studying martian glaciated craters has suggested that certain ice-related features occur due to the subsiding and halting of ice accumulation: specifically in the case of CCF, spatulate depressions represent the waning stage of

glaciation, while gullies form subsequently due to melting of residual ice and snow in alcoves [13]. Adopting the temporal relationships defined in [13], the paraglacial model described above can be applied to craters bearing evidence of glaciation.

The paraglacial phase on Mars is triggered by the halting of ice accumulation, observable in spatulate depressions found in pole-facing slopes of many craters [12]. The loss of glacial ice causes a disequilibrium in the system through (1) redistributing stresses caused by debuttressing due to ice loss, (2) exposing a supply of sediments on slopes to be reworked through sediment-gravity flow analogous to the *sediment-mantled slopes* in terrestrial paraglacial settings, and (3) exposing *glacial forelands* to modification on small scales by mass movement, freeze-thaw, and aeolian processes.

The manifestations of these paraglacial features are in agreement with features common in glaciated craters on Mars: adjustment of the *rock slope* landsystem creates antiscarps referred to as washboard terrain [15]. The *sediment-mantled slopes* landsystem is modified with the development of densely gullied surfaces. Additionally, the retreating *glacial foreland* features are analogous to the polygonal floor and wall terrain, and solifluction/gelifluction lobes are seen in many of the glaciated and deglaciated areas of the craters.

The paraglacial phase on Earth is short, and the morphology can often be erased by subsequent processes. However, these features are readily visible on Mars. We interpret this to signify that the paraglacial phase on Mars is longer in duration than in terrestrial settings, owing to lower erosion rates, and possibly to larger sediment supplies exposed by ice loss in impact crater interiors. Furthermore, the lack of vegetation and intense fluvial processes (e.g., persistent rainfall) could preserve otherwise transient paraglacial landforms.

Conclusions: The comparison of terrestrial paraglacial features to martian glaciated craters yields several conclusions: (1) the paraglacial phase fits as a transitional martian post-glacial stage; (2) glacial units in concentric crater fill (CCF) include spatulate depressions, washboard terrain, and polygonal terrain, all of which are consistent with the transition to a post-glacial stage; (3) post-glacial martian gullies are likely to be the result of paraglacial processes; (4) the transition from glacial to post-glacial processes on Mars is recorded in the morphology of various craters and is likely to be present in other glacial landforms; (5) the paraglacial stage is likely to last tens to hundreds of millions of years due to the lack of pluvial activity and general long-term topographic stability on Mars.

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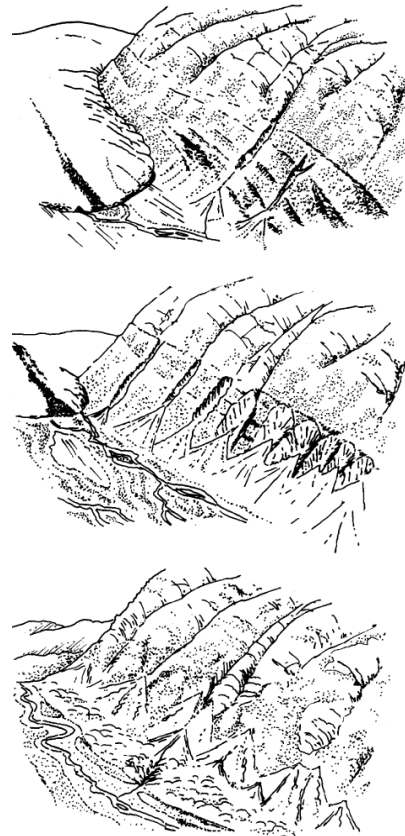

Figure 1. Three stages of the paraglacial period: (top) glacial retreat exposes slopes, triggering gully formation; (middle) gully development and debris cone accumulation; (bottom) relict debris cones and vegetated gully systems. Sediment supplies are exhausted, which halts paraglacial reworking. From [2, 19]. The third stage is not seen currently on Mars.