HOT MESS, COLD GLACIERS: CHARACTERIZING RIDGES ON MARTIAN AND TERRESTRIAL DEBRIS-COVERED GLACIERS USING OBSERVATIONS AND FLOW MODELLING C. M. Stuurman[1], J.W. Holt[1], J.S. Levy[1], and E.S. Petersen[1], [1]University of Texas at Austin, Institute for Geophysics (cassie.stuurman@utexas.edu).

Motivation: Debris-covered glaciers on Earth and Mars often exhibit characteristic surface ridges (Fig. 1). The formational mechanism of these ridges is not well established, but some evidence supports the idea that they may demarcate climate cycles. If we can better understand the relationship between ridges on debris-covered glaciers, the interior structure of debris-covered glaciers, and paleoclimate then it is possible that martian debris-covered glacier morphology may be linked to Amazonian climate variations.

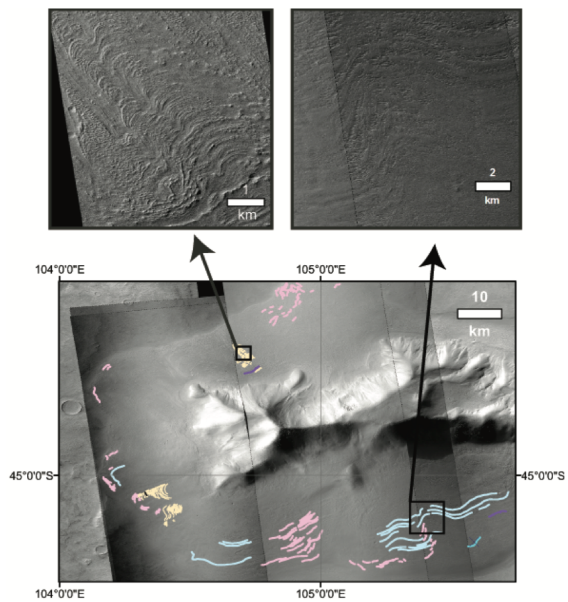

Figure 1: Mapping of ridges on debris-covered water ice at Euripus Mons, Mars. Ridges on debris-covered glaciers are typically transverse to the flow of the glacier and are often arcuate with a regular wavelength. In some cases their shape runs parallel to the shape of the headwall. Top left: Fine ridges, HiRISE image ESP_045334_1350. Top right: Smooth ridges with long arclength. CTX image G15_024064_ 1350.

Introduction: There are several hypotheses describing the formational mechanism for debris-covered glacier surface ridges. Some authors have proposed they may be shortening features, like compressional ridges observed on clean-ice glaciers [1,2]. Another interpretation involves aeolian modification [2]. Others suggest that the viscosity differential at the debris-ice interface drives buckle-folding, a phenomenon that can produce ridge-furrow morphology with highly regular wavelengths [3]. Some authors emphasize the relationship between englacial structure and surface ridges [4,5,6]. Terrestrial radar and seismic studies of debris-covered glaciers have shown that surface ridges are often associated with internal, up-glacier dipping reflectors (Fig. 2). These have been interpreted as debris-bands in some cases [5], and as thrust faults in others [6].

Here, we attempt to characterize the different kinds of ridges observed on debris-covered glaciers. These can be divided into two types: (1) Buckle/compressional folds, and (2) folds related to internal structure of a glacier. Buckle-folding ridges have been observed on terrestrial debris-covered glaciers and are the direct result of heterogeneous rheologies flowing together [3]. The geometry is dependent on the ratio of viscosity between the debris and the water ice below it. Ridges may also be caused by internal structure. Determining whether thrust faults or debris bands are responsible for ridge development is crucial for establishing a relationship between internal glacier structure and climate. Furthermore, if a ridge is related to an englacial band of debris, its method of emplacement must also be established before any conclusions about climate can be made. A recent model for the development of englacial debris bands was proposed by Mackay et al, 2014 [5]. In this model, alternating accumulation and ablation cycles driven by changes in climate can trap bands of debris within the glacier. Ridges form where these debris layers intersect the surface, thereby forming a potential relationship between glacier surface morphology and climate.

Objective: Through flow modelling and observations of terrestrial and martian glaciers, explore the relationship between surface morphology and climate through characterization of the different types of ridges found on debris-covered glaciers. Our model explores the roles of buckle folding, thrust faults, and internal debris layers in the development of ridge/furrow morphology on debris-covered ice.

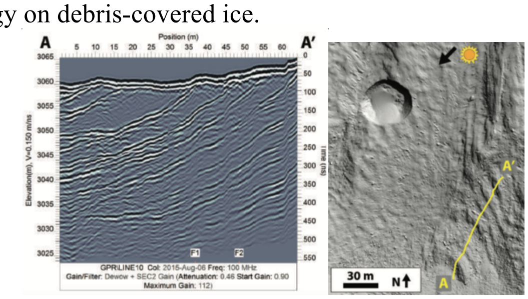

Figure 2: Internal, up-glacier dipping reflectors and associated ridges in ground-penetrating radar data from Galena Creek Rock Glacier, WY, USA. Englacial layers of debris ~1 m thick were observed in a nearby melt pond, and thus these dipping reflectors are interpreted as layers of debris.

Methods: Mapping of debris-covered glacier ridges around Euripus Mons, Mars was executed using CTX imagery, CTX-derived DEMS, and HiRISE imagery in ArcMap. Basal geometry of Euripus Mons debris-covered glaciers was derived using SHARAD. Flow modelling of debris-covered glaciers was completed using the full-Stokes, finite-element software DynEarthSol3D [7]. A HiRISE DTM was used in a Tempe Terra case study examining ridge wavelength/surface debris layer thickness ratios. Analog studies of debris-covered glaciers were performed at Galena Creek Rock Glacier, WY, USA and Sourdough Rock Glacier, AK, USA.

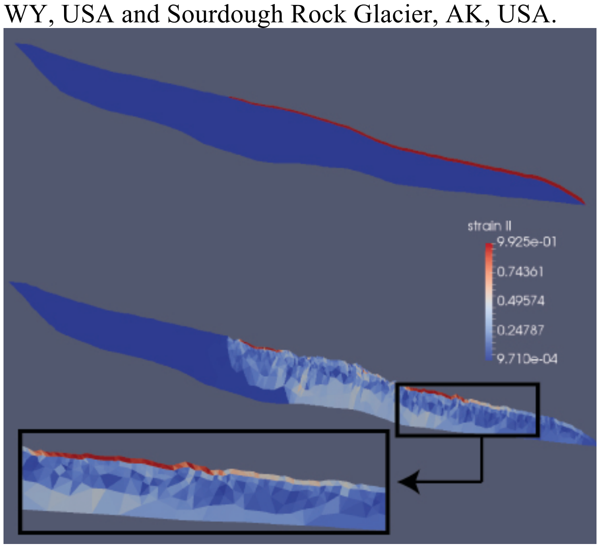

Figure 3: Model results for a cold-based simulation based on the geometry of Arolla glacier, Switzerland.. Thrust faults are observed towards the toe of the glacier.Surface ridges are observed at the intersection of the thrust fault and the glacier surface. Other ridges are observed across the glacier's surface, possibly due to buckle folding and differential velocity of the ice due to basal geometry and ice thickness variations.

Results: Buckle-fold ridges have been replicated in our models. Preliminary modelling results suggest that ridges on cold-based debris-covered glaciers may be associated with thrust faulting. It has been proposed that thrust faulting is not a significant process for cold-based debris-covered glaciers [5,8]. Thrust faults are observed in our model for both warm and cold-based glaciers.

Mapping of the debris-covered water ice surrounding Euripus Mons shows ridge morphology may take several forms. There are a variety of ridge expressions – some are very fine with inter-ridge spacings on the order of 10's of metres (Fig. 1, top left). Their amplitude is not resolvable in CTX-derived DEMs. The characteristic wavelength of these ridges is consistent with buckle-folding. These fine ridges are sometimes interspersed with rougher ridges that are typically 100's of metres in down-glacier wavelength. Their height can be resolved in CTX DEMs and are metres in amplitude. These ridges are larger in wavelength than what would be expected from buckle-fold ridges based on terrestrial viscosity ratios [3]. Others ridges are smooth, 100's of metres to km wavelength, and broad (10's of km long, Fig. 1, top right). Others are short in arclength, short but irregular wavelength, and are highly pronounced due to removal of material around them. They are often arcuate but can be either concave-up or concave-down relative to the down-glacier direction. They look like they may have been "carved" by sublimation/aeolian modification.

Analog studies have found that englacial debris layers may produce surface ridges, but the relation to climate is not always clear. Some evidence from Galena Creek Rock Glacier, WY, shows that rockfall trapping snow may produce small hummocks of glacial ice bounded by layers of debris.

Discussion: Ridges on debris-covered glaciers can be caused by a variety of mechanisms and are not always related to climate. Irregular inter-ridge spacing is expected from thrust fault ridges. Buckle folding remains a plausible explanation for some small-scale ridges with highly regular wavelengths determined by the ratio in viscosity between the ice and the debris. Other ridges have wavelengths inconsistent with the buckle-fold interpretation. Debris-band ridges are currently being explored in our modelling efforts. Mapping shows ridge expression can be complex, occurring on a variety of wavelengths and arclengths. Analog work shows debris-band ridges are not necessarily related to climate signals. Overall, there is more work to be done characterizing the different kinds of ridges and mechanisms shaping the surface of terrestrial and martian debris-covered glaciers. If the relationship between different types of ridges is better characterized, ridges on debris-covered glaciers may provide a window into the interior of glaciers on other worlds.

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[8] Moore et al. (2010), *Journal of Geophysical Research: Earth Surface*, *115*(F2).