# APPLYING KNOWLEDGE FROM TERRESTRIAL DEBRIS-COVERED GLACIERS TO CONSTRAIN THE EVOLUTION OF MARTIAN DEBRIS-COVERED ICE.

M.R. Koutnik[1,*], A.V. Pathare[2], C. Todd[3], E. Waddington[1], and J.E. Christian[1]; [1]University of Washington, Department of Earth and Space Sciences, Box 351310, Seattle, WA 98195 (*mkoutnik@uw.edu), [2]Planetary Science Institute, [3]Pacific Lutheran University.

**Introduction:** A rich literature on terrestrial debris-covered glaciers exists from decades of field work, remote-sensing observations, laboratory studies, and modeling. Debris-covered glaciers from around the world offer distinct environmental, climatic, and historical conditions from which to study the effects of debris on glacier evolution. While terrestrial glaciers exhibit some processes that are not ideal Mars analogues, numerous insights and approaches from these terrestrial studies can be applied to constrain the evolution of Martian debris-covered ice. We highlight those that are most relevant, and focus on terrestrial knowledge about 1) supraglacial debris emplacement, 2) the effects of debris on glacier-surface topography, 3) supraglacial and englacial debris transport by ice flow, 4) deformation of debris-laden ice, and 5) atmosphere-glacier feedbacks.

This review cannot be exhaustive, but draws from a rapidly growing literature base and has an emphasis on how glacier shape, glacier length, and glacier evolution are affected by debris compared to a glacier without debris cover. Rock glaciers are often considered an end-member state, but some glaciers may alternate between these states depending on the ratio of snowfall vs. debris input [e.g., 1]. We will consider the data sets, methods, and results from applicable studies and provide a perspective on how this terrestrial knowledge may be applied to constrain the evolution of Lobate Debris Aprons in the mid-latitudes of Mars as well as to polar debris-covered ice, including the South Polar Layered Deposits.

Debris-covered glaciers are found around the world, typically in mountain ranges with high relief and significant supplies of debris [2] – especially in the Himalaya, Karakoram, Caucasus, Alaska, New Zealand, and parts of the Andes, as well as in Iceland, Greenland, Svalbard and the west coast of the continental United States. There are also debris-covered glaciers in the Antarctic Dry Valleys, which harbor ice that may be at least one million years old [e.g., 3]. In order for the ablation zone of a glacier to be covered by more than ~50% debris, the debris flux needs to be relatively high and the ice-flow rate needs to be relatively low.

**Supraglacial debris emplacement:** The primary sources of debris to the surface of the glacier include rockfall, rock avalanching, and avalanching of rock/ice/debris mixtures, and at some sites lateral moraine degradation and local-slope landslides also provide debris sources. While debris may be sourced in the ablation zone of the lower glacier, at most sites the debris is sourced high on the glacier in the accumulation zone and then buried by subsequent snowfall, transported down glacier by ice flow, and emerges on the lower glacier surface by ablation. There is often a clear distinction between a lag deposit and a rock avalanche deposit, where the thicker avalanche debris has spread in grain size that decreases porosity and permeability, making the avalanche deposits more effective inhibitors of ablation [4]. In additional, volcanic ash deposition on glaciers has been well studied in Iceland [e.g., 5].

**Effects of debris on surface topography:** Since 1959 [6] we have known that a thin debris cover can enhance melt of underlying clean ice because lower-albedo debris absorbs incoming short-wave radiation, but if the debris cover is thick enough then the underlying clean ice is insulated. Melt rates decline asymptotically with increased thickness of debris, and controlled experiments found that 10-50 cm is very effective [7], including if the cover is sand, volcanic ash, or coal dust [8; 9]. However, most glaciers have an extremely heterogeneous distribution of debris and clast size, which is not as simple to quantify and can lead to surface relief on the order of meters (Fig. 1) to tens of meters on the largest glaciers.

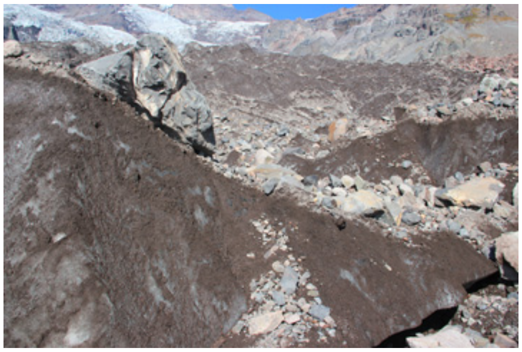

**Fig. 1:** Multi-meter scale surface relief on the debris-covered terminus of Nisqually Glacier, Mt. Rainier, WA (October, 2015). Until the debris cover is a thick, continuous insulator the surface continues to change shape each year.

The debris cover is typically well sorted with fines and small clasts concentrated near the ice surface and larger clasts and boulders on top. Debris thickness typically increases down glacier and the lowest regions of the glacier toward the terminus can stagnate, and middle regions of the ablation zone may experience the most melt. Since the debris either insulates or enhances melt, the cover significantly alters the glacier mass balance, climate sensitivity [10], the observed accumulation-to-ablation area ratio, and the surface slopes compared to debris-free glaciers [11].

**Debris transport by ice flow:** Debris can be transported directly on the glacier surface by flow and also moved downslope by mass wasting. Idealized paths of particles through the glacier will submerge in the accumulation zone and emerge in the ablation zone. Recent work has advanced modeling capabilities for temperate glaciers that receive a headwall influx of debris [12]. This work showed that melt-out of englacial debris and advection of supraglacial debris significantly affected the length and structure of debris-covered glaciers. On Earth this has important implications for interpreting the moraine record and assessing terminus fluctuations in relation to climate changes [e.g., 13].

**Deformation of debris-laden ice:** Based on the calculated englacial debris fraction through time it may be necessary to use a different constitutive relationship (stress-strain relationship) for ice flow; Moore [14] provided a comprehensive review. Existing "suspension models" are idealized but require knowing only the volumetric debris fraction and may be suitable for cold ice, up to a certain debris fraction and stress. Mechanistic relationships that modify Glen's flow law using a threshold stress above which dislocations in the ice matrix can bypass debris particles have experimental merit and are also relatively simple to apply [e.g., 15].

**Atmosphere-glacier feedbacks:** Physically based energy-balance models have been developed for debris-covered glaciers, calibrated using meteorological variables, debris thermal properties, and debris-thickness estimates and compared to available surface temperature and melt-rate measurements on select glaciers [e.g., 16; 17]. Accurate modeling is complicated because the thermal behavior between atmosphere-debris-ice is complex, controlling variables change with time, and feedback mechanisms exist. In addition, the models are most sensitive to the extent, thickness, and thermal properties (thermal conductivity, albedo, surface roughness) of the debris cover that can be difficult to measure remotely or to extrapolate to the entire glacier from ground measurements.

**Initial perspective:** It is important to recognize that debris-covered glaciers on Earth are dynamic systems, and that debris properties and emplacement mechanisms can be just as important in governing glacier response as debris thickness and extent. Models developed for terrestrial glaciers can be applied to Mars, but model assumptions must be justified for each application; we will suggest strategies from terrestrial knowledge where more data are likely available.

At present, many studies have targeted debris-covered glaciers in the Himalaya because of down-valley water-resource concerns and glacial-lake outburst hazards [e.g., 18]. While outcomes of these studies may not directly relate to Mars, these rich data sets are part of the global database and analysis methods are useful to evaluate in relation to analyses of Mars data. For example, Scherler et al. [19] compiled surface topography and surface slopes for hundreds of glaciers across High Mountain Asia and showed that glacier surfaces indicate distinct relationships between hillslope erosion, debris emplacement, and glacier flow; these low slope debris-covered valley glaciers with steep headwalls may have geometric parallels to LDAs off mid-latitude massifs on Mars.

The Antarctic Dry Valleys have environmental conditions that may be the best analogue to Mars, but given the variety of terrestrial glacier forms and differences in the histories of debris-covered glaciers on Earth it is important to consider how a range of debris-related processes affect ice flow and ice ablation – analogue processes do not necessarily have to exist in the closest analogue environments. For the conference we will explore these themes in more depth and summarize ways that the terrestrial knowledge base can be applied to constrain the evolution of Martian debris-covered ice.

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