Introduction: Debris flows examined in Alaska at the Great Kobuk Sand Dunes (GKSD, 67°N) resemble seasonally recurring flow types forming on the slopes of mid- to high-latitude dune fields in both martian hemispheres (e.g., [1–7]). Mass movement signatures are amongst the best records of historical and ongoing geologic activity on Mars; seasonally recurring alluvial mass movements suggest the erosive action of water and may indicate locations where metastable liquid water has existed at or near the martian surface within a time period of months to years.

The GKSD are a valuable terrestrial system within which to conduct a Mars-analog study for seasonal debris flow processes; our opportunistic photographic observations of debris flows along with in-situ meteorologic and erosion data provide insight into the interactions between niveo-aeolian deposition, insolation, thawing, slope aspect, and initiation of alluvial processes. The full meteorologic and site context of the observed debris flows is reported in Hooper and Dinwiddie [8]. We have used this terrestrial analog to better understand volatile emplacement mechanisms, cryo-aeolian activity, and the influence of precipitation and ground ice on bedform morphology and dynamics. In February 2014, we expanded our analog studies to include Great Sand Dunes National Park and Preserve (GSDNPP, 38°N) in Colorado. Although high-altitude rather than high-latitude, this study site provided valuable meteorologic, geomorphologic, photographic, and cryo-aeolian data to support analog studies.

Mass Movement Flow Types: The debris flows observed at GKSD consisted of a sand and liquid water mixture that cascaded down the leeward slopes of two sand dunes. Debris flows on the first dune (designated Wx2) formed under relatively “warm” conditions when continuously measured ground surface temperatures at the dune crest were within 1°C of the melting point of water for fewer than 10 minutes [8]. These debris flows originated within niveo-aeolian deposits in shallow, poorly-defined alcoves on the dune crest, became channelized down the lee face, and terminated with depositional fans displaying either lobate flow-front morphology or a more complex interdigitate (finger-like) pattern created by successive slurry-like flows (Fig. 1a). Dry granular flow is unlikely because dune slope gradients are ~10° below the angle of repose. Also observed were alluvial ripple bedforms in the debris flow channels of the largest flows. These bedforms were not related to the underlying aeolian stratification, but are a manifestation of alluvial processes that created the ripples when meltwater-derived sheetwash became concentrated in the shallow gully (or channel) and remobilized surface sand grains into ripples [8] (Fig. 1b). Debris flows on the Wx2 dune most closely resemble the small-scale dark dune spot flows active in mid-winter to early spring on Mars and are associated with defrosting.

Debris flows on the second dune (designated Wx3) formed under much colder conditions (maximum ground temperature of −12.8°C) and on steeper slopes (approximately at angle of repose) than Wx2 flows. While these debris flows had characteristics similar to grainflow avalanching, they were water-laden and the deposits resembled those of slurry-like flows of sand mixed with liquid water (i.e., small, low-viscosity debris flows) [8] (Fig. 2). Debris flows on the Wx3 dune superficially resemble scaled-down versions of Russell-crater-type gullies due to their narrow, linear, and parallel characteristics; however, they did not form levees [8]. While the lack of levees might be caused by a narrow range of available grain sizes. Russell-crater-type gullies may form by a different process altogether, such as seasonally recurrent slumping of CO₂ frost cornices [6,9].

Snow Cornices: Steidtmann [10] was the first to provide a detailed explanation of the role of snow cornices and slumping as they relate to niveo-aeolian and denivation deposits. He reported large snow cornices
(overhanging ledges of snow and sand) that formed on dune crests during winter became unstable and slid down the lee slopes during subsequent warming. Bourke [11,12] suggested that frost cornices, rounded dune slipfaces or crests, sublimation avalanches, channels, and alluvial-fan-shaped deposits are potential signatures of niveo-aeolian deposition on Mars. Recently, Dundas et al. [6] and Diniega et al. [9] proposed that m-scale CO$_2$ ice blocks may have carved these linear-to-sinuous gullies. While ice blocks did not carve the linear features observed in Figure 2, we note that snow cornices play a major role in niveo-aeolian deposition, volatile emplacement, and initiation of both mass movement and alluvial processes on cold-climate dune slopes (Fig. 3).

Discussion and Conclusion: The GKSD are an important Mars analog site for defrosting-related flows (e.g., dark dune spot flows) on high-latitude martian dunes; our recent studies at GSDNPP will also provide valuable data and insights for cryo-aeolian studies. Gullies are commonly inferred to represent debris flows. The presence of Martian gullies with a youthful appearance is a topic of considerable importance because of the possible presence of liquid water. We observed debris flows consisting of a sand and liquid water mixture that cascaded down leeward dune slopes under subfreezing conditions at GKSD. Because these flows were mobilized at subfreezing air temperatures, we hypothesize that relatively dark sand lying on bright snow produced highly localized hot spots where solar radiation was absorbed by the sand and conducted into the snowpack, enabling meltwater to form at subfreezing air temperatures and sand to mobilize through alluvial processes. Similar mechanisms may be responsible for generating certain alluvial debris flows on martian dune slopes. Localized heating and thawing at scales too small for orbital sensors to identify may yield martian debris flows at current climate conditions [8].

Figure 2. Numerous small debris flows resembling avalancheing on the lee slope of the Wx3 dune at GKSD. The snow-free source area has a wavy microtopography that is interpreted to be caused by solifluction. For scale, flow widths are 5–10 cm.

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