Icarus 230 (2014) 15–28

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Debris flows on the Great Kobuk Sand Dunes, Alaska: Implications for analogous processes on Mars

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ARTICLE INFO

Article history:
Available online 16 July 2013

Keywords:
Mars, Polar geology
Earth
Ices
Geological processes
Meteorology

ABSTRACT

We observed niveo-aeolian deposits, denivation features, and small meltwater-induced debris flows that had formed at the Great Kobuk Sand Dunes, northwestern interior Alaska in late March 2010. This high-latitude, cold-climate dune field is being studied as a planetary analog to improve our understanding of factors that may trigger debris flows on the lee slopes of martian aeolian dunes. Debris flows consisted of a sand and liquid water mixture that cascaded down the lee slopes of two barchanoid dunes on days when measured ground surface temperatures were below freezing. We hypothesize that relatively dark sand on snow caused local hot spots where solar radiation could be absorbed by the sand and conducted into the underlying snow, enabling meltwater to form and sand to be mobilized. This investigation provides insights into the interactions between niveo-aeolian deposition, slope aspect and insolation, thawing, and initiation of alluvial processes. These debris flows are morphologically similar to those associated with seasonal gullies or erosion tracks visible on the slopes of mid- to high-latitude dune fields in both martian hemispheres. Localized heating and thawing at scales too small for orbital sensors to identify may yield martian debris flows at current climate conditions.

1. Introduction

In late March 2010 we observed more than 70 small meltwater-induced debris flows on the lee slopes of two barchanoid dunes at the Great Kobuk Sand Dunes (GKSD) in Kobuk Valley National Park, Alaska (Fig. 1). The 67°N latitude GKSD, 62 km^2 in area, are the active remnants of a much larger (~10×) Pleistocene sand sea (Fernald, 1964; Kuhry-Helmens et al., 1985). The climate is subarctic, and sand transport is affected by snowcover for approximately two-thirds of the year (Koster and Dijkmans, 1988; Dijkmans and Koster, 1990). The presence of long-lived interbedded snow and ice (i.e., niveo-aeolian deposits) on the dune field likely has direct analogy to seasonal frostcover thought to influence debris flows on Mars, including the observation that high-latitude dunes on Mars are affected by CO_2 and H_2O frost mantling for two-thirds of the year (Bourke et al., 2009). In addition, the debris flows examined in Alaska resemble flows that are currently forming on the slopes of mid- to high-latitude dune fields in both martian hemispheres (e.g., Reiss and Jaumann, 2003; Horváth et al., 2009; Kereszturi et al., 2010, 2011; Reiss et al., 2010; Dundas et al., 2012; Jouannic et al., 2012) (Fig. 2). Most importantly, seasonally recurrent martian debris flows on sand dunes are of interest because they may indicate locations where metastable liquid water has existed at or near the martian surface within a time period of months to years. We report field characterization, meteorological data, and preliminary quantitative analysis of the terrestrial debris flows at the GKSD to improve understanding of analogous features and processes observed within martian aeolian dune systems.

To develop the analogy between martian and terrestrial processes, it is important to first define the subtleties of these sedimentary processes. Debris flows are distinguished from fluvial processes, such as normal streamflow and hyperconcentrated flow, in that they are abruptly forming, transitory phenomena (Smith, 1986; Pierson and Costa, 1987). Solid grain forces dominate the physics of avalanches, and fluid forces dominate the physics of floods, whereas solid and fluid forces must act in unison to produce a debris flow (Iverson, 1997; Iverson et al., 1997). By this rationale, many events identified as debris slides, debris floods, debris torrents, mudflows, mudslides, and lahars may all be regarded as debris flows (Varnes, 1978; Johnson, 1984; Pierson and Costa, 1987). The diverse nomenclature reflects the diverse origins, compositions, and appearances of debris flows, from relatively quiescent sand-rich slurries to turbulent surges of mud and boulders (Iverson, 1997; Iverson et al., 1997).

Debris flows are non-Newtonian viscoplastic or dilatent fluids having laminar flow and uniform sediment concentration profiles such that sediment concentrations range from 70 to 90 percent by weight or 47 to 77 percent by volume (Costa, 1988). Matrix strength, buoyancy, and grain-dispersive pressure support

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0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.07.006

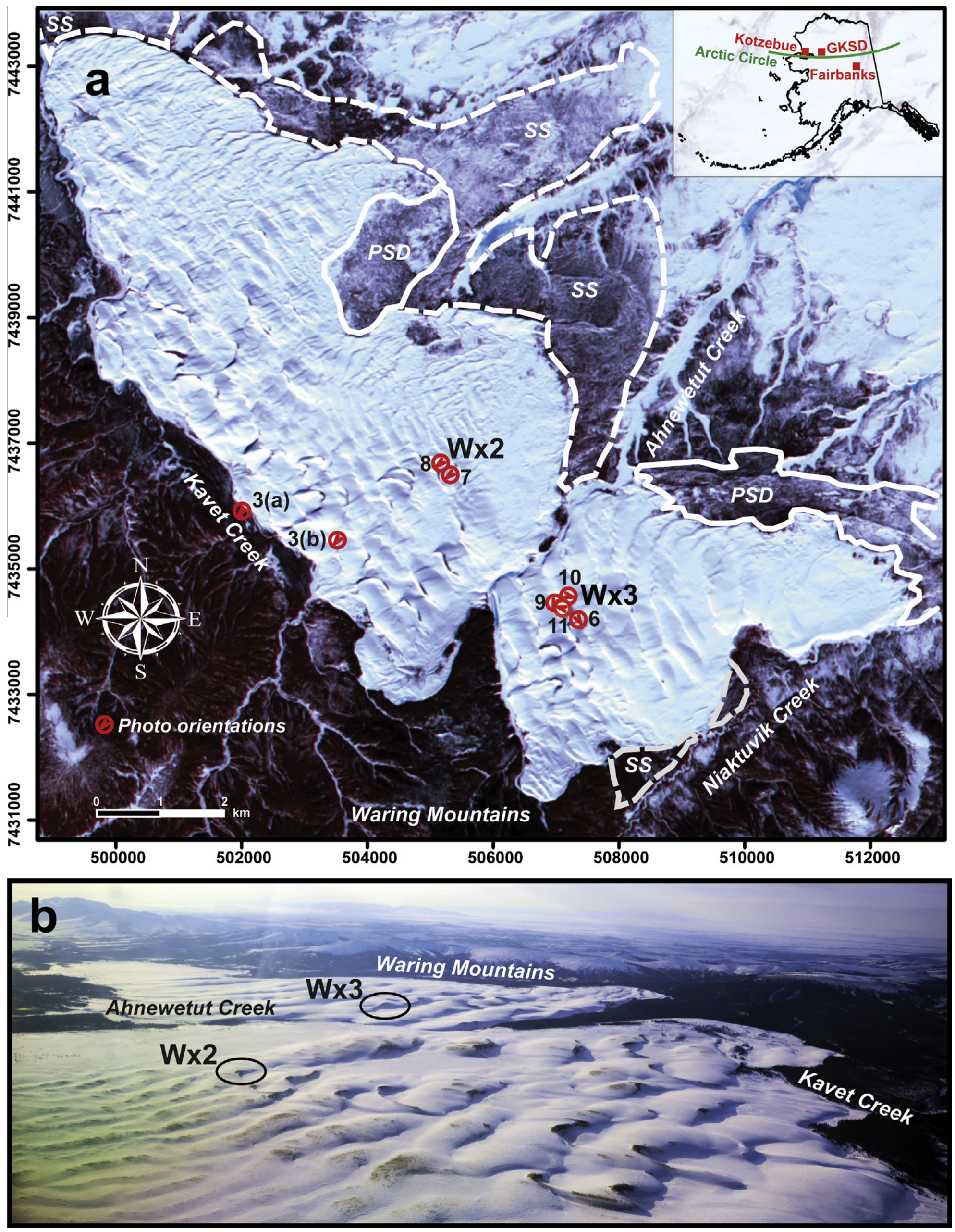

Fig. 1. GKSD. (a) Context image illustrating study and photographic sites (numerals correspond to figure numbers); debris flows were observed at Wx2 and Wx3. Sand sheets (SS) and partially stabilized dunes (PSD) are noted as defined by Swanson (2001). UTM coordinates, Zone 4, NAD 83 datum. ASTER image (courtesy of NASA LPDAAC, USGS and Japan's METI) acquired 20 March 2010. (b) Aerial photo acquired by M. Johnson, National Park Service, at 9:43 am, 3 April 2012; view to the south–southeast.

sediment within debris flows (Smith, 1986). Debris flows in which sediments and water move as a single, coherent phase may be followed by a trailing tail of hyperconcentrated flow in which sediment and water move at different speeds (Smith, 1986; Coussot and Meunier, 1996). This results in the near-instantaneous modification and erosion of the debris-flow deposits.

Landslide and debris flow processes occupy opposite ends of a spectrum of non-Newtonian flow behaviors. While debris flows exhibit pervasive, fluid-like deformation, landslide motion is more rigid with deformation localized along persistent slip surfaces or shear zones (Varnes, 1978). If mobility is enhanced by the sudden addition or entrainment of water, landslides may completely or partially mobilize to form debris flows (Iverson et al., 1997; Hooper and Smart, 2013). Pore water gives debris flows mobility that surpasses even that of dry, flowing sand (Iverson, 1997; Iverson et al., 1997).

2. Niveo-aeolian deposits and denivation features

Cold-climate dune fields are distinguished from temperate and warm-climate dune fields by the seasonal and prolonged occurrence of snow and ice. Cold-climate dunes often contain interbedded sand and snow (Fig. 3). These mixed deposits of wind-driven snow, sand, and small ice grains were called niveo-aeolian deposits by Cailleux (1974, 1978) and were later reviewed by Koster (1988), Koster and Dijkmans (1988), and Dijkmans (1990). Recently, Lorenz and Valdez (2012) documented thin niveo-aeolian deposits that formed at Great Sand Dunes National Park and Preserve, Colorado. Relatively thin primary deposits of snow and ice may temporarily collect on stoss slopes, but their exposure to erosive wind action ensures that thick accumulations do not develop. Downwind, sheltered lee slopes (or slipfaces) of large dunes,