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Debris flow initiation in proglacial gullies on Mount Rainier, Washington

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ABSTRACT

Effects of climate change, retreating glaciers, and changing storm patterns on debris flow hazards concern managers in the Cascade Range (USA) and mountainous areas worldwide. During an intense rainstorm in November 2006, seven debris flows initiated from proglacial gullies of separate basins on the flanks of Mount Rainier. Gully heads at glacier termini and widespread failure of gully walls imply that overland flow was transformed into debris flow along gullies. We characterized gully change and morphology, and assessed spatial distributions of debris flows to infer the processes and conditions for debris flow initiation. Slopes at gully heads were greater than ~0.35 m m^{-1} (19°) and exhibited a significant negative relationship with drainage area. A break in slope–drainage area trends among debris flow gullies also occurs at ~0.35 m m^{-1}, representing a possible transition to fluvial sediment transport and erosion. An interpreted hybrid model of debris flow initiation involves bed failure near gully heads followed by sediment recruitment from gully walls along gully lengths. Estimates of sediment volume loss from gully walls demonstrate the importance of sediment inputs along gullies for increasing debris flow volumes. Basin comparisons revealed significantly steeper drainage networks and higher elevations in debris flow-producing than non-debris flow-producing proglacial areas. The high slopes and elevations of debris flow-producing proglacial areas reflect positive slope–elevation trends for the Mount Rainier volcano. Glacier extent therefore controls the slope distribution in proglacial areas, and thus potential for debris flow generation. As a result, debris flow activity may increase as glacier termini retreat onto slopes inclined at angles above debris flow initiation thresholds.

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1. Introduction

Steep slopes and incompetent bedrock combine to make stratovolcanoes in the Cascade Range some of the most erodible bedrock landforms on Earth (Mills, 1976). In the Cascade Range in the northwestern United States, andesitic volcanoes stand well above the current and Quaternary-average equilibrium line altitudes of glaciers; glacial erosion at these elevations produces enormous sediment loads (Porter, 1989; Czuba et al., 2011, 2012). This sediment poses challenges to dam operators, river managers, and communities downstream by filling reservoirs, aggrading channels, and exacerbating flood risk (Czuba et al., 2010). Sediment transport and mass movement processes on volcanic slopes are therefore linked with management of downstream rivers. In addition to their role in sediment routing, debris flows threaten infrastructure immediately downstream. Moreover, recent debris flow episodes have raised concerns that increasing storm intensity, retreating glaciers, and reduced snow-packs under a warming climate may cause more debris flows in the future.

Interrelationships between glaciers, runoff, and debris flow generation remain poorly understood. Limited understanding of conditions necessary for debris flow initiation in this environment prevents assessing effects of climate change and related factors on debris flow occurrence. Recent observations on Mount Rainier (Washington, USA) suggest that debris flow initiation has occurred in gullies passing through areas dominated by loose glacial till. These gullies show evidence of wall collapse and lateral expansion along their lengths, which may represent a source of sediment for the debris flows (Copeland, 2009; Lancaster et al., 2012). Gullies also begin at or very near to glacier termini and have no apparent slope failures that could have contributed debris flows from upstream glacier surfaces. Thus, debris flow initiation apparently occurs within gullies in the presence of, and perhaps in response to, surface runoff. Bed failure and/or progressive addition of sediment to surface runoff are possible mechanisms for debris flow initiation within gullies (Gabet and Bookter, 2008; Prancevic et al., 2014). The latter process is commonly referred to as sediment bulking (Wells, 1987). Debris flow initiation in gullies contrasts with more commonly discussed initiation style where shallow landslides on hillslopes liquefy

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and mobilize as debris flows in the absence of overland flow (Iverson et al., 1997). Debris flows beginning as landslides commonly initiate from hillslope hollows and run-out to and along channels downstream (Dietrich and Dunne, 1978).

Debris flow initiation induced by surface run-off is generally lesser understood than debris flow initiation from shallow landslides (Iverson, 1997; Coe et al., 2008; Kean et al., 2011; Prancevic et al., 2014). Prior studies of debris flows initiated in channels and gullies suggested bulking as the cause (Wells, 1987). Debris flows initiated in gullies are commonly observed in areas recently burned by wildfire (Cannon and Reneau, 2000; Gabet and Bookter, 2008; Santi et al., 2008). Monitoring of debris flow initiation by runoff has revealed that bed topography and resulting flow surges are important initiation variables (Kean et al., 2013). Recent theoretical formulations and supporting flume experiments find that channel bed failure at steep slopes is a primary debris flow initiation mechanism (Prancevic et al., 2014). Above channel slopes ranging from 15°–30°, critical Shields' stresses for fluvial sediment transport exceed those for debris flow transport, causing sediment transport by debris flows to become dominant (Lamb et al., 2008; Prancevic et al., 2014).

Studies of debris flows initiated in channels and gullies in environments recently burned by wildfire reveal possible analogs of sediment delivery to channels in glaciated environments (Wells, 1987; Meyer et al., 1995; Meyer and Wells, 1997; Cannon and Reneau, 2000; Gabet and Bookter, 2008; Santi et al., 2008). Reduced vegetation cover and ash deposition from burned vegetation reduce infiltration capacity, enhance runoff generation, and cause drainage networks to abruptly expand (Gabet and Bookter, 2008; Gabet and Sternberg, 2008). Material released during channel and gully expansion provides sediment that has been connected with progressive transformation of overland flow to debris flow (Gabet and Bookter, 2008). Whereas glaciated catchments do not experience analogous changes in infiltration capacity, gullies often expand through recently deglaciated and unchannelized surfaces (O'Connor et al., 2001; Lancaster et al., 2012). It is therefore plausible that these young gullies actively expand during the largest storms in a manner similar to gullies in recently burned areas.

This study focuses on a set of seven debris flows that originated from proglacial areas of Mount Rainier during an intense storm in November 2006. Studying debris flows within a single meteorological event and roughly similar meteorological and hydrologic conditions across basins allows us to focus on the geomorphic conditions that influence debris flow initiation. The 2006 storm was unprecedented for the number of debris flows that initiated from separate basins; no prior historical events on Mount Rainier had so many debris flows (Fig. 1). Debris flows impacted infrastructure directly and indirectly by inducing channel avulsions. All told, debris flows and flooding inflicted $36 million in infrastructure damage within Mount Rainier National Park boundaries (National Park Service, 2014).

This study seeks to characterize the landscape controls on debris flow initiation. Data are used to: (1) characterize the nature, setting, and change of debris flow gullies in detail, and (2) analyze basin-scale attributes that set local conditions for debris flow initiation. Aerial imagery and high-resolution topography derived from airborne laser swath mapping (ALSM) permit us to measure the morphology and change of debris flow gullies, and infer dynamics of debris flow initiation in areas inaccessible to field observation (James et al., 2007). Much of the analysis takes a comparative approach by analyzing differences in debris flow-producing basins (DFBs) and non-debris flow-producing

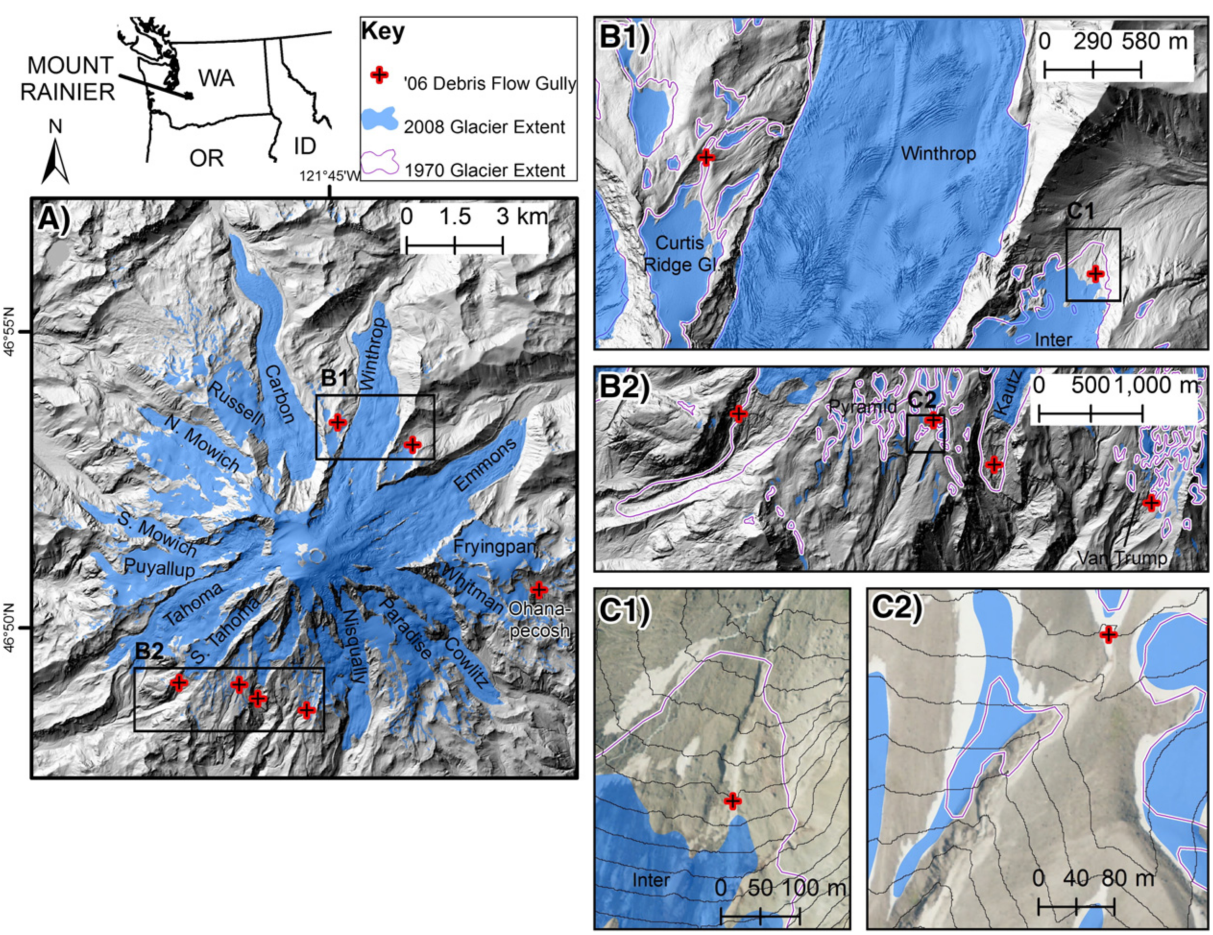

Fig. 1. Location map of Mount Rainier and debris flow gullies from the 2006 storm. (A) Hill-shaded topography of Mount Rainier. (B1 and B2) Hill-shaded topography produced from ALSM data. (C1 and C2) NAIP aerial images taken in 2009 with 10-m elevation contours.

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