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Title: Recent Periglacial Debris Flows from Mount Rainier, Washington

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Debris flow initiation is controlled by a complex interaction of geology, geomorphology, climate, and weather. In the Cascade Range of Pacific Northwest and mountainous areas globally, patterns of temperature and precipitation are being altered by climate change, which may in turn impact debris flow initiation. Temperature has increased and patterns of precipitation have changed, potentially impacting the timing, geography, and triggering mechanisms of debris flows. Glacier retreat since the end of the Little Ice Age has exposed volumes of unstable sediment on steep slopes prone to debris flow initiation. Earlier spring snowmelt extends the snow-free window when rainstorms may mobilize sediment, resulting in debris flows.

To ascertain the presence of a climate change signal we examined the timing, geography, and initiation mechanisms of recent (2001 to 2006) non-volcanic debris flows from Mount Rainier, Washington, the highest volcano in the Cascade Range with the

largest ice-volume in the conterminous United States. Debris flows damage infrastructure, requiring costly repairs. Debris flows also deposit volumes of sediment in streams, potentially exacerbating future flood hazards. To characterize recent debris flows, field reconnaissance was conducted summer 2008 along suspected debris flow paths from initiation to deposition. Results from summer fieldwork were used in conjunction with analysis of aerial photography, Light Detection and Ranging (LiDAR), and other data to determine characteristics of debris flow initiation sites, such as elevation, slope, orientation, upslope contributing area, and proximity to glaciers. Recent debris flow initiation sites were also examined in reference to glacier characteristics, such as elevation of glacier termini, glacier retreat, orientation, area, and volume, for the years 1913, 1971, and 1994 from past work by Nylen (2004). Characterization of debris flow initiation sites and definition of the locations of longitudinal transitions in debris flow behavior allows estimation of future debris flow hazards also allows inferences to be drawn regarding initiation mechanisms to be inferred and suggests a trajectory for changing debris flow hazards due to climate change.

Debris flows at Mt. Rainier occur in late summer through fall and recent events were no exception, occurring from August through November. A total of twelve debris flows occurred in six stream channels during the period of 2001 to 2006. Three channels not previously known to have experienced debris flows, two south-facing and one north-facing, were impacted. Debris flows tracks led up to glacier meltwater fed, steep-walled channels or gullies in unvegetated, unconsolidated Quaternary-age material immediately downslope of glacier margins. Debris flows initiated at an average elevation of 2181 m and an average channel gradient of 39°. While glaciers appear to play a key role in debris flow initiation, simple glacier metrics could not be used to distinguish glaciers near debris flow heads from those without proximal debris flows heads.

All but one of the twelve debris flows initiated during rainfall. The single debris flow that occurred during dry-weather is described by Vallance et al. (2002). Rainfall induced debris flows in 2003, 2005, and 2006 were not associated with landslide scarps, rockfalls, or other indications of large slope failures. Rather, debris flows initiated in steep-walled gullies fed by glacier meltwater that were visible on aerial photography prior to the first known debris flow initiation in a particular channel. The steep flanks of Mt. Rainier contain many similar gullies that have not previously been associated with debris flows, but debris flow producing gullies are at higher elevations than gullies not associated with debris flows.

The small population of recent debris flows and incomplete historic record of debris flows for the periods 1926 to 1985 and 1993 to 2001 limits analysis of changes in debris flow timing, geography, or triggering mechanism. The magnitude of recent events may have initially appeared greater than historic events as the 2005 and 2006 storms are the only ones known to have produced multiple debris flows in the recorded history of Mt. Rainier National Park. Yet much of the damage initially attributed to debris flows was due to widespread, severe flooding. Ongoing, detailed record keeping and possibly reconstruction of past events through paired geomorphic reconnaissance and dendrochronology is needed before conclusions regarding the impacts of climate change on debris flow initiation can be reached.

RECENT PERIGLACIAL DEBRIS FLOWS FROM MOUNT RAINIER, WASHINGTON

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes the release of my thesis to any reader upon request.

Elizabeth A. Copeland, Author

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Chapter 1- Introduction

Geomorphic Impacts of Climate Warming

Climate warming has caused ongoing glacial retreat creating or exacerbating hazards in mountainous areas worldwide. Hazards include formation and failure of ice and moraine dams, rockfalls, and slope failures including landslides, all of which can subsequently transform into debris flows. Debris flows, fast-moving mixtures of unconsolidated sediment, organic debris, and water, form when steep slopes become saturated and fail. Debris flows may travel kilometers from their source at speeds of meters per second and exacerbate flooding by transporting and depositing large volumes of sediment in river channels. Debris flows are associated with short-term aggradation and channel widening or the stripping of riparian vegetation (Benda and Dunne, 1997). Debris flows can destroy roads and other infrastructure, either through erosion, deposition of material, or associated flooding (Takahashi et al., 1981; Scott et al., 1992; Zimmerman and Haeberli, 1992; Walder and Driedger, 1994; Iverson, 1997; Rickenmann, 1999; Huggel et al., 2008; Glade, 2005; Chiarle et al., 2007).

Debris flow initiation is impacted by antecedent patterns of temperature and precipitation, and therefore it is expected that climate change will alter the characteristics of debris flow initiation through exposure of unstable material, promotion of slope instability, and changing patterns of precipitation (O'Connor and Costa 1993; Evans and Clague, 1994). Debris flow initiation is not a record of climate change nor is the occurrence of debris flows a piece of evidence needed to validate the existence of ongoing climate change. It is well documented that annual temperatures have increased by 1.5° to 3° globally since the Little Ice Age (LIA) which lasted from approximately 1650 to 1850 (Climate Impacts Group, 2009) and that increases in temperature can alter hydrologic patterns (Senior, 2002; Barnett et al, 2005). Numerous studies examining the potential impacts of climate change on debris flow initiation in European Alps currently exist (Zimmerman and Haeberli, 1992; Haeberli et al., 1993; Haeberli et al., 1997; Rebetez et al., 1997; Blijenberg, 1998; Haeberli and Beniston, 1998; Berti et al., 1999; Gruber et al., 2004; Jomelli et al., 2004; Stoffel and Beniston, 2006; Jomelli et al., 2007; Huggel, 2008; Pelfini and Santilli, 2008). In addition to the Alps, a much smaller body of literature regarding climate change and debris flows also exists for the Andes of Peru (Vilímek et al., 2005), Alps of New Zealand (Korup and Tweed, 2007), and the Himalayas (Richardson and Reynolds, 2000), the Coast Mountains of British Columbia, Canada (Clague and Evans, 2000; Jakob and Weatherly, 2003; Holm et al., 2004), and the Cascade Range of the Pacific Northwest (PNW) (O'Connor and Costa, 1993; O'Connor et al., 2001). Potential climatic impacts on debris flow initiation might result in changes to the timing of debris flow initiation, the geography of initiation sites, and debris flow initiation mechanisms. In this study, recent debris flows from Mt. Rainier, Washington were interpreted to ascertain how ongoing glacial retreat and climate warming might alter the risk profile from debris flows in the PNW.

Potential geomorphic impacts of climate warming that could contribute to debris flow initiation include further destabilization of already unstable, steep sediment due to glacier retreat or the loss of interstitial ice, changing rainstorms characteristics, rapid snowmelt, changes in glacier dynamics resulting in glacier outburst floods, and the accumulation and release of glacier meltwater from glacier lakes (**Table 1**). Debris flows typically occur as a result of rainfall-induced saturation of steep slopes (Iverson, 2000). Rainfall thresholds for debris flow initiation are variable globally as a result of local variations in climate and geology (Hungr et al., 2001). In addition to rainfall, other mechanisms that lead to saturation of loose debris include hydrothermally induced rapid melting of glacial ice, drainage of glacier or moraine dammed lakes, glacier outburst flood from sub- or en-glacial storage also known as by the Icelandic term jökulhlaup, the transformation of landslides, debris avalanches, or other slope failures into debris flows in-channel or following the breach of landslide dam of a stream channel, slumping of saturated sediment from stream banks or valley walls into stream channel, overland flow leading the initiation of sediment motion in rills or gullies, and in-channel entrainment of bedload due to high stream stage during flooding. Climate change may alter patterns of when and where debris flows occur and also new or greater occurrence of certain debris flow triggers. For example, debris flows may begin to occur earlier or later in the summer season, the interval of time between debris flow events may decrease, the location of geography of debris flow initiation sites may shift to new drainages or higher elevations, and certain triggers for debris flow initiation, such as hydrothermal activity, glacier lake outbursts, glacier outbursts, landslides, rockfalls, slumping, overland flow, or in-channel entrainment, may be observed for the first time or observed more frequently. These changes in timing, geography, and mechanism may reveal the influence of ongoing climate change that will impact the nature of mountain hazards in the future.

Table 1. Potential geomorphic impacts of climate warming.

Mechanism:	Possible effects(s):	Possible impact(s) on debris flow initiation:		
Warmer summer temperatures:		Timing	Geography	Initiation mechanism
Glacier retreat	Exposure of unstable sediment	Y	Y	Y
Loss of interstitial ice	Exposure of unstable sediment	Y	Y	Y
Earlier snowmelt	Exposure of unstable sediment	Y	Y	Y
	Altered hydrologic routing	Y	Y	Y
Changing precipitation patterns:				
Warm, fall rainstorms	Mobilization of sediment	Y	Y	Y
Increased storm frequency	Mobilization of sediment	Y	Y	
Increased storm intensity	Mobilization of sediment	Y	Y	Y

Debris flows have been recorded in recently deglaciated areas worldwide (Jackson et al., 1989; Rebetez et al., 1997; Haeberli, 1997; Zimmerman and Haeberli, 1992; Bovis and Jacob, 1999). The majority of glaciers worldwide are at their historic minima and are projected to continue to retreat due to climate warming (Oerlemans, 1994). Glacier retreat exposes unstable, unconsolidated sediment prone to debris flow initiation. Retreat and fragmentation of glaciers creates debris-covered stagnant ice masses and steep edifices of unstable glacial material. In British Columbia, landslides and other slope failures post LIA glacial thinning are common near glacial trim lines and along oversteepened lateral moraines (Holm et al., 2004). Debris flows in the Cascade Range frequently initiate at or near glacier margins or stagnant ice in steep, unconsolidated morainal or periclastic material as documented on Mt. Shasta by Osterkamp et al. (1986) and Blodgett et al. (1996), on Mt. Rainier by Walder and

Driedger (1994), on Three Sisters by O'Conner et al. (2001), on Mt. Hood (Pirot et al., in progress), and on Mt. Jefferson by Sobieszczyk et al. (2008).

Climate warming also contributes to the loss of permanent or seasonally frozen ground. Permafrost degradation can lead to slope instability (Zimmerman and Haeberli, 1992; Haeberli and Beniston, 1998; Gruber and Haeberli, 2007; Kneisel et al., 2007; Huggel, 2008). Permafrost can also act as an aquiclude that promotes saturation of loose debris above a slide horizon, thereby reducing slope stability (Kneisel et al., 2007). Loss of ice buttressing leading to slope sagging, sometimes referred to as "sackung" or distortional movements that may have no displacement discontinuity, has been reported by numerous authors (Bovis 1982, 1990; Evans and Clague, 1994; Bovis and Evans, 1996; Moore et al., 2009). Fluctuations in temperature can cause rockfalls or debris avalanches that create streams of debris sometimes called "sturzstroms" (Hsu, 1975; Gruber et al., 2004; Holm et al., 2004; Gruber and Haeberli, 2007; Huggel, 2008).

Rainfall is a primary control on debris flow initiation worldwide. There are numerous regional rainfall thresholds for debris flow initiation and associated research regarding the development of saturated ground, perched aquifers, and changes in groundwater level that lead to debris flow initiation (Jomelli et al., 2004). The hydrologic cycle is projected to intensify under climate warming in some regions, thereby increasing the frequency and intensity of storms (Senior et al., 2002; Barnett et al., 2005). In the Swiss Alps, an increase in the number of intense rainstorms capable of triggering debris flows has been described by Rebetez et al. (1997). While Rebetez et al. (1997) does not report an increased frequency of debris flows, Chiarle et al. (2007) notes that the largest debris flows in the Alps are triggered by heavy and prolonged rainfall, rather than short bursts of rainfall or any other type of debris flow triggering mechanism. In the PNW, increased variability and persistence of winter precipitation has led to increased flood risk (Hamlet and Lettenmaier, 2007). Snowmelt occurs earlier in the spring across the western United States (Mote, 2003) and the timing of peak runoff has shifted to earlier in the spring (Stewart et al., 2005). Some mountainous areas in the PNW are projected to receive greater contributions of winter precipitation as rain (Nolin and Daly, 2006). The combination of decreased winter snowfall and earlier snowmelt may result in a longer duration period where the ground is snow-free and debris flows are likely to occur as snow-free areas respond rapidly to rainfall (Collins, 1998).

Glacier outburst floods from the release of en- or sub-glacial storage of water (Richardson, 1968; Driedger and Fountain, 1989; Walder and Driedger, 1994; Blodgett et al. 1996) and glacier or moraine dammed lakes (Clague and Evans, 2000; O'Connor, 2001; Davies et al., 2003; Anderson et al., 2005; Korup and Tweed, 2007) can be triggering mechanisms for debris flows. Glacier outburst floods have been recorded in association with surging of glaciers in Alaska (Mayo, 1989; Anderson et al., 2005), volcanic activity under Icelandic ice caps (Björnsson, 1992, 2003), and periods of rainfall and or high temperatures in the European Alps (Haeberli, 1983), the Cascade Range of the PNW (Richardson, 1968; Driedger and Fountain, 1989; Walder and Driedger, 1994), and elsewhere. Proglacial lakes exist in the Peruvian Andes, European Alps, Himalayas, Central Asia, and North America. In some locations, glacial lakes are forming or growing as a result of climate warming induced glacier recession, thereby increasing the hazards associated with their subsequent drainage ((Richardson and Reynolds, 2000; O'Connor and Costa, 2001; Vilímek et al., 2005).

Debris Flows and Related Phenomena

A multitude of terms have been applied to slope failures and mass movements similar to debris flows, including debris torrents, debris floods, mudflows, mudslides, mudspates, hyperconcentrated flows, and lahars (Hungr et al. 2001). The wealth of terminology is a result of the occurrence of debris flows in mountainous regions worldwide and lack of agreement for the criteria that define debris flows and similar phenomena. Debris flows are defined as channelized mass movements involving saturated mixtures of rock, sediment, organic material, and water or more precisely, the channelized movement of any saturated loose unsorted material of low plasticity produced by mass wasting, weathering, glacier transport, and explosive volcanism (Hungr et al., 2001). The distinction between debris flows and debris avalanches from steep slopes was first made in the United States by Sharpe in 1938 (cited in Jakob and Hungr, 2005). Sharpe (1938) described debris flows as rapid channelized flows of saturated, unsorted debris and debris avalanches as unchannelized shallow landslides. Debris flows and other mass movements can be distinguished on the basis of movement mechanism, material type, grain size distribution, concentration of solids or water content, volume of the failure, travel speed, shear strength and shear rates, and the presence or absence of a channelized travel path (Hungr et al., 2001).

A debris flow is the rapid movement of saturated non-plastic debris in a steep channel (Hungr et al. 2001). Iverson (1997) defines debris flows as gravity-driven flows of poorly sorted, water-saturated sediment that transition between solid and liquid phases while undergoing irreversible deformation. Debris flows have properties of both dry-granular mixtures such as avalanches and water floods and therefore are incredibly destructive (Iverson, 1997). Debris flows can occur suddenly and without warning, like rock avalanches, and can travel long distances and damage large areas, like floods (Iverson, 1997). Debris flows are also hazardous as the mass of material in the initial slope failure may increase dramatically through erosion of the bed and banks, process sometimes referred to as bulking, while mixing with stream water may cause a debris flow solid concentration to decline (Iverson, 1997). Debris flows initiate due to gravitational failure of saturated hillslopes at or near the angle of repose (Iverson, 1997). Both solid and fluid forces define debris flows, therefore neither models of dry-granular or flood flows accurately describe debris flow behavior (Iverson and Delinger, 2001). Most debris flows are the result of slope failures (Iverson, 1997) and water needed for mobilization of materials exists within the mass when failure occurs (Iverson and Delinger, 2001). The balance between driving and resisting stresses for such a slope failure may be approximated by the Coulomb criterion:

$$\tau = (\sigma - \rho) \tan \phi + c$$

where τ is the average shear or driving stress and resisting stress is composed of effective normal stress $(\sigma - \rho)$, or the compressive normal stress in excess of pore fluid pressure, and ϕ is the bulk friction angle, and c is cohesion of particles. Resistance to motion after the initial slope failure depends on changes in pore pressure and effective stress, as cohesive bonds are broken during failure (Iverson, 1997). Debris flow mobility is controlled by pore fluid pressure and granular temperature, which depends on the intensity of grain velocity fluctuations and the degree of agitation of the particles (Iverson, 1997). Motion in turn contributes to granular temperature and non-equilibrium fluid pressures. Granular temperature is the conversion of translational energy to grain vibrational energy and is dependent on shear rates, grain properties, boundary conditions, and the ambient fluid viscosity and pressure (Iverson, 1997). Higher granular temperatures and greater water content will aide debris flow mobility (Iverson, 1997). Debris flows have liquefied interiors with nearly lithostatic pressures that help maintain mobility and course-grained fronts with high friction and low pore fluid pressure that aid debris flow deposition (Iverson, 1997; Major and Iverson, 1999). Maintenance of the liquified debris flow core with pore fluid pressures that exceed static equilibrium occurs through the compressibility and limited permeability of debris (Iverson, 1997). Coarse grain debris flow snouts are created by kinetic sieving or selective transport of large clasts due to gravity and boundary forces (Iverson, 1997). Small clasts can move into gaps that open below while force imbalances or particle rotations push clasts of all sizes into different layers of the debris flow (Vallance, 2000). These processes help to bring boulders to the surface of the debris flow, where the velocity is the highest, helping to create a boulder snout and reverse grading (Vallance, 2000). Grain-to-grain contact at the bed and margins of the debris flow causes boulders to be deposited sometimes resulting in the formation of boulder levees (Major and Iverson, 1999; Vallance, 2000).

Debris flows are characterized by zones of initiation, transport, and deposition. Transitions in debris flow behavior from erosion, to transport, and ultimately deposition, are governed by changes in slope, the confinement of the debris flow channel, topographic roughness in the debris flow path, and the volume of water relative to sediment (Jakob and Hungr, 2005). Debris flows from a variety of initiation mechanisms typically initiate on slopes of 20 to 45º, zones of debris flow transport are usually steeper than 10º, and the gradient of debris flow deposition varies widely depending on material type and particle size of debris flow snout and channel topography (Jakob and Hungr, 2005). Debris flows may initiate or later transition into debris floods, also called bedload floods or hyperconcentrated flows. Hyperconcentrated floods have a smaller sediment concentration than that of debris flows, but definitions are variable and highly difficult to measure (Costa, 1984; Pierson, 2005). Peak discharge is another way to distinguish between the two events where stream gaging instrumentation is available. Debris floods have discharges similar to water floods, but debris flows have peak discharges orders of magnitude greater than floods (Hungr et al., 2001). The high water content of hyperconcentrated flows allows their movement in much lower gradient channels than those impacted by the downstream extent of debris flows (Hungr et al., 2001).

Distinguishing Debris Flow Initiation Mechanisms

Debris flow initiation mechanisms may or may not leave clear geomorphic signatures that can be identified after the occurrence of a debris flow: multiple initiation mechanisms may interact, subsequent debris flows typically erase evidence of previous events, and no single piece of evidence is diagnostic of a particular initiation mechanism (**Table 2**). Hydrothermal activity can cause the formation of a glacier lake or an en-glacial reservoir and the subsequent glacial lake outburst flood or glacier outburst flood. In locations where hydrothermal activity commonly leads to glacier outburst floods, such as Iceland, melt features on the surface of a glacier are indicative of this process (Björnsson, 2002). Glacier or glacier lake outburst floods can also occur without hydrothermal activity. Yet, glacier lake outbursts are always accompanied by the presence and subsequent drainage of a proglacial lake. Glacier outbursts, from en- or sub-glacial water storage, cannot be monitored remotely like proglacial glacial lakes, but they typically occur during hot, dry weather during late summer or fall and their occurrence can cause rapid, noticeable incision of proglacial sediments (Walder and Driedger, 1994). Glacier outburst floods could undercut the toe slopes of stream banks resulting in downslope landsliding or discrete failures along stream banks, or slumping. Seismic activity can also result in failure of ice or moraine dams leading to glacier lake outburst floods or landsliding, rockfalls, or other slope failures. The ultimate cause of slope failures may be inferred from review of both meteorologic and seismic records. Landslides leave evidence of headscarps or failure planes. Rockfalls are associated with talus slopes of angular clasts and rock headwalls with evidence of fresh surfaces. Slumping may cause subtle widening of the stream channel. Debris flows can also occur when overland flow or high stream stage mobilizes sufficient sediment. Overland flow might result in the formation or widening of rills or gullies, but might be confined to ice lenses or ash-mantled slopes of unknown spatial extent in the highly permeable volcanic soils of the Cascade Range. In-channel entrainment of sediment would leave little geomorphic evidence and is rarely reported as a debris flow initiation mechanism. For many of the mechanisms discussed, including overland flow, in-channel entrainment, and slumping, the lack of existing high spatial and temporal resolution topographic data limit analysis of geomorphic change following debris flows or other events.

Table 2. Geomorphic evidence indicative of debris flow triggering mechanisms.

Initiation Mechanisms	Evidence	Location	Conditions
Hydrothermal activity	Melt features on glacier ice	Proglacial areas	Dry or wet weather
Glacier lake outburst	Rapid drainage of glacier lakes	Proglacial areas	Dry or wet weather
Glacier outburst	Antecedent hot, dry weather	Proglacial areas	Dry weather
Landslide	Scarps, failure planes	Steep slopes	Wet weather
Rockfall, debris avalanche	Talus slopes, angular clasts	Rockwalls	Dry or wet weather
Slumping	Widening of gullies	Stream banks	Wet weather
Overland flow	Presence of rills, enlargement of gullies	Frozen ground	Wet weather
In-channel entrainment	No evidence	Stream channels	Wet weather

Previous Work in the Cascade Range

The seasonal timing of non-volcanic debris flows in the Cascade Range **(Fig. 1)** has been described previously and suggests the importance of antecedence temperature and precipitation regimes for debris flow initiation. Debris flows from Mt. Shasta in California, at the southernmost extent of the Cascade Range, have been recorded in summer only (Blodgett et al., 1996). At the northern extent of the range, debris flows from Mt. Rainier in Washington typically occur in late summer during dry weather and in fall during rainstorms (Walder and Driedger, 1994). Historically, heavy rain has been reported as a debris flow trigger in the Cascades without concern for the specific mechanism by which sediment entrainment occurred (Blodgett et al., 1996). Slope failures may be the result of either seismic activity, precipitation induced landsliding on a failure plane, or incision of stream banks due to high stream discharge from heavy rain, snowmelt, or flow surges from collapse of snow bridges (Blodgett et al., 1996). Slope failures have been reported Mt. Shasta by Osterkamp et al. (1986) and Blodgett et al.

(1996), on Mt. Rainier by Walder and Driedger (1994), on Three Sisters by O'Conner et al. (2001), on Mt. Hood (Pirot et al., in progress), and on Mt. Jefferson by Sobieszczyk et al. (2008). Slope failures resulting in debris dams that cause flow impoundment of a stream has been reported on Mt. Shasta (Blodgett et al., 1996). Material slumping from stream banks or valley walls into stream flow to initiate a debris flow has been observed at Mt. Shasta and Mt. Rainier (Blodgett et al., 1996; Vallance et al., 2002). Drainage of moraine-damned lakes has occurred at Three Sisters and Mt. Jefferson, Oregon (O'Conner and Costa, 1993; O'Connor et. al, 2001). O'Connor et al. (2001) describes a rockfall leading to glacier lake breach. Rapid glacier ablation caused by hot, dry weather and subsequent glacier outburst flood from sub- or englacial storage was interpreted as a debris flow initiation mechanism at Mt. Rainier (Walder and Driedger, 1994) and Mt. Shasta (Blodgett et al., 1996). Overland flow yielding surface erosion in the form of sheetwash, rills, gullies, and in-channel entrainment of sediment has been reported as a primary debris flow initiation mechanism in areas of recently burned soils (Cannon et al., 2001). Rainfall that results in overland flow or high stream flow stage that could result in-channel entrainment of material would also likely cause incision and failure of unconsolidated material that comprises the stream channel. Therefore, overland flow or in-channel entrainment of material may be masked by landsliding or slumping from stream banks and would not be a primary debris flow initiation mechanism.

Figure 1. Cascade Range of Washington, Oregon and California (Figure courtesy of B. Medley).

Previous Work at Mt. Rainier

Prior to 2001, small volume, non-cohesive debris flows were recorded in the drainages of South Tahoma, Kautz, Nisqually, and Winthrop Glaciers (Walder and Driedger, 1994; Vallance et al., 2002) with the majority of debris flows occurring in association with South Tahoma and Nisqually Glaciers (Walder and Driedger, 1994). The earliest recorded debris flow occurred in 1926 from Nisqually Glacier (Walder and Driedger, 1994). The largest known non-volcanic debris flow occurred October 2 to 3, 1947 in Kautz Creek as a result of heavy precipitation from October 1 to 3 (Walder and Driedger, 1994). Ultimately, four debris flow pulses deposited 38 to 50 million m^3 of material (Scott et al., 1995). A complete chronology of debris flows from Mt. Rainier is only available from 1985 to 1993 due to the work of U.S. Geological Survey (USGS), David A. Johnston Cascade Volcano Observatory (CVO) scientists Walder and Driedger (1994, 1995), which was in response to an possible cluster of debris flows from South Tahoma and Kautz Glaciers during the period 1967 to 1971 and concerns regarding damage to Park infrastructure. At the conclusion of the Walder and Driedger study, no records of debris flows from Mt. Rainier were kept until 2001, when a debris flow was observed and described by Vallance et al. (2002). Incomplete historic records during the periods before and after the Walder and Driedger study cannot be fully reconstructed as debris flows frequently initiate in the same channels and more recent or larger magnitude debris flows can easily overprint or erode evidence of previous, smaller debris flow activity. Yet, Mt. Rainier is an ideal location to study debris flows as similar duration historic records exist for few other Cascade Range volcanoes. Informal study of debris flows from 2001 to present by Paul Kennard, Regional Geomorphologist for Mt. Rainier

National Park (P. Kennard, personal communication, 2008) and fieldwork conducted in the summer 2008, renews study of non-volcanic debris flows on Mt. Rainier.

Goals, Research Questions, and Approach

The overarching goals of this project were to identify recent (2001-2006) debris flow initiation sites on Mount Rainier for the purposes of: 1) characterizing topographic, geographic, and hydrologic factors contributing to debris flow initiation; 2) interpreting potential initiation mechanisms; 3) characterizing runout paths with respect to zones of erosion, transport, and deposition, and 4) describing how debris flow behavior might change in the future. My goal was to determine whether a detailed examination of recent debris flows and their behavior could reveal clues useful for evaluating future risk to Mount Rainier National Park and its resources. Although the prospect of climate change and its impact on the location and extent of glaciers within the Park provided a useful context for interpreting debris flow initiation, this study was not primarily intended to resolve the question of whether debris flow frequency or behavior was changing as the result of climate warming. Despite previous research, the chronology of historic debris flows on Mount Rainier is too limited and incomplete to provide compelling evidence of climate-driven shifts in frequency. My focus was on improving understanding of how recent debris flows may have initiated, and considering how a changing climate might affect such initiation mechanisms. The results of this study and the additional questions it raises should be used to inform and constrain future research regarding the factors contributing to debris flows initiation on glaciated slopes.

The specific research questions I addressed were:

1) Where did recent debris flows initiate with respect to elevation, slope, aspect, and proximity to active glaciers or stagnant ice?

2) What geomorphic evidence is present at initiation sites that could be used to discriminate among different initiation mechanisms?

3) What role did the history of recent glacier retreat at Mount Rainier play in debris flow initiation?

4) Where did recent debris flows travel and what factors might determine their path length?

To address these questions, I used a combination of field reconnaissance and analysis of historical records, aerial photos and other data. All but one of the recent debris flows occurred during fall rainstorms, and I therefore focus primarily on this type of event, while recognizing that dry season debris flows have also been documented (Walder and Driedger, 1994). Recent debris flow activity is interpreted in terms of the changing environment of Mt. Rainier and implications for Park resources.

Study Site Description

Geomorphology

At 4393 m, Mt. Rainier is the tallest volcano in the Cascade Range of Washington, Oregon, and California. The upper slopes Mt. Rainier are composed of unconsolidated Quaternary-age volcaniclastic and morainal material in steep edifices. The slopes also contain numerous glaciers and perennial bodies of snow and ice, as well as debris-covered stagnant ice masses of unknown spatial extent (C. Driedger, personal communication, 2008). Mt. Rainier is drained by five major glacier meltwater-fed braided rivers; Carbon, White, Cowlitz, Nisqually, and Puyallup **(Fig. 2)**. The headwaters of these rivers are located within canyons, often 300 to 900 m deep, formed by lateral moraines from Pleistocene glaciers below adjacent ridges (Crandell, 1971). Stream gradients on the upper flanks of the mountain, above tree line, are 0.13 to 0.15 m/m and at the confluence with major rivers, near park boundaries, 0.019 to 0.078 m/m (Crandell, 1971). Tree line is located between 1600 and 2000 m (Hemstrom and Franklin, 1982). Forests cover over 56% of Mt. Rainier National Park and the majority of the forests are over 350 years old (Hemstrom and Franklin, 1982). Soils are mainly from colluvium and tephra and have been described as podzolics and lithosols (Hemstrom and Franklin, 1982). Fire is the major disturbance at Mt. Rainier followed by snow avalanches and lahars (Hemstrom and Franklin, 1982). Humans have inhabited and modified the landscape of Mt. Rainier National Park since the end of the last ice age (Hemstrom and Franklin, 1982 cites Dryden, 1968).

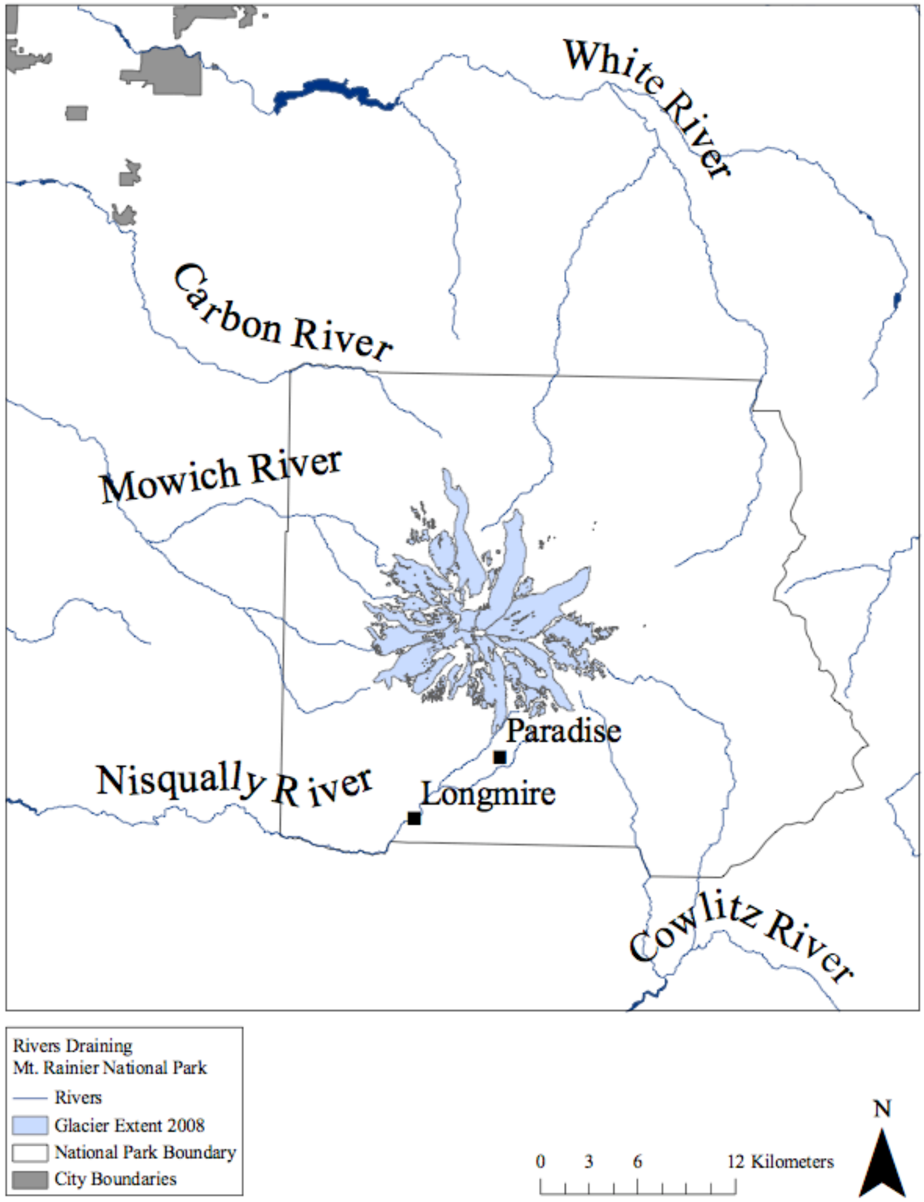

Figure 2. Major rivers draining Mt. Rainier.

Geology

Mt. Rainier and the entire Cascade Range formed through the subduction of the Juan de Fuca Plate under the North American Plate. Mt. Rainier formed over highly eroded middle Tertiary age rocks of the Ohanapecosh, Stevens Ridge, and Fifes Peaks Formation that were intruded by the Tatoosh pluton (Fiske et al., 1963). The volcano was built through progressive layers of thin lavaflows, breccias formed by violent steam explosions, mudflows, pyroclastic flows, and infrequent pumice and ash eruptions (Fiske et al., 1963). The volcano first erupted about half a million years ago; other significant eruptions have occurred 2,500 and 1,000 years ago (Sisson, 1995). Minor steam eruptions were recorded in the 1840's (Sisson, 1995). The interbedded structure of a stratovolcano leads to inherent instability, as materials of different compositions, internal frictions, and permeabilities are juxtaposed. Hydrothermal activity further weakens the edifice. A sector collapse 5,000 years ago produced the Osceola Mudflow (Scott and Vallance, 1993).

Lahars

Due to the location of Mt. Rainier National Park, 70 km east of the Seattle-Tacoma metropolitan area, Mt. Rainier is one of the most potentially deadly volcanoes in the United States due to the potential for a future volcanic eruption or initiation of a lahar. Lahars are triggered by volcanic or seismic activity and failure of hydrothermally altered rock results in a clay content sufficient to retard dilution and drainage of the flow and cause deposition outside of park boundaries. Debris flows are of a much smaller magnitude than lahars and as a result, do not exit park boundaries. The United States Geological Survey maintains extensive work regarding hazard zonation for lahars (**Fig. 3**). Lahar deposits from Mt. Rainier cover much of the Puget Lowlands. The largest known lahar, the Osceola mudflow, inundated the Puyallup River valley 5,000 years ago, depositing 3 km^3 of material over 24 km^2 (Scott and Vallance, 1995). A much smaller lahar, named Paradise Lahar because of its origin in the Paradise Valley, also originated at approximately the same time as the Osceola mudflow (Crandell, 1971). Lahars known as the Round Pass Mudflow and the National Lahar originated 2,600 to 2,200 years ago and traveled the Puyallup and Nisqually Rivers, respectfully (Crandell, 1971). The Electron mudflow, 550 to 600 years ago, is the second largest lahar recorded from Mt. Rainier, after the Osceola mudflow. The mudflow was the result of a sector collapse not related to volcanic activity (Crandell, 1971; Scott and Vallance, 1995). The mudflow traversed the Puyallup River and deposited 0.26 km^3 of material over 36 km^2 of the Puget Lowlands (Scott and Vallance, 1995).

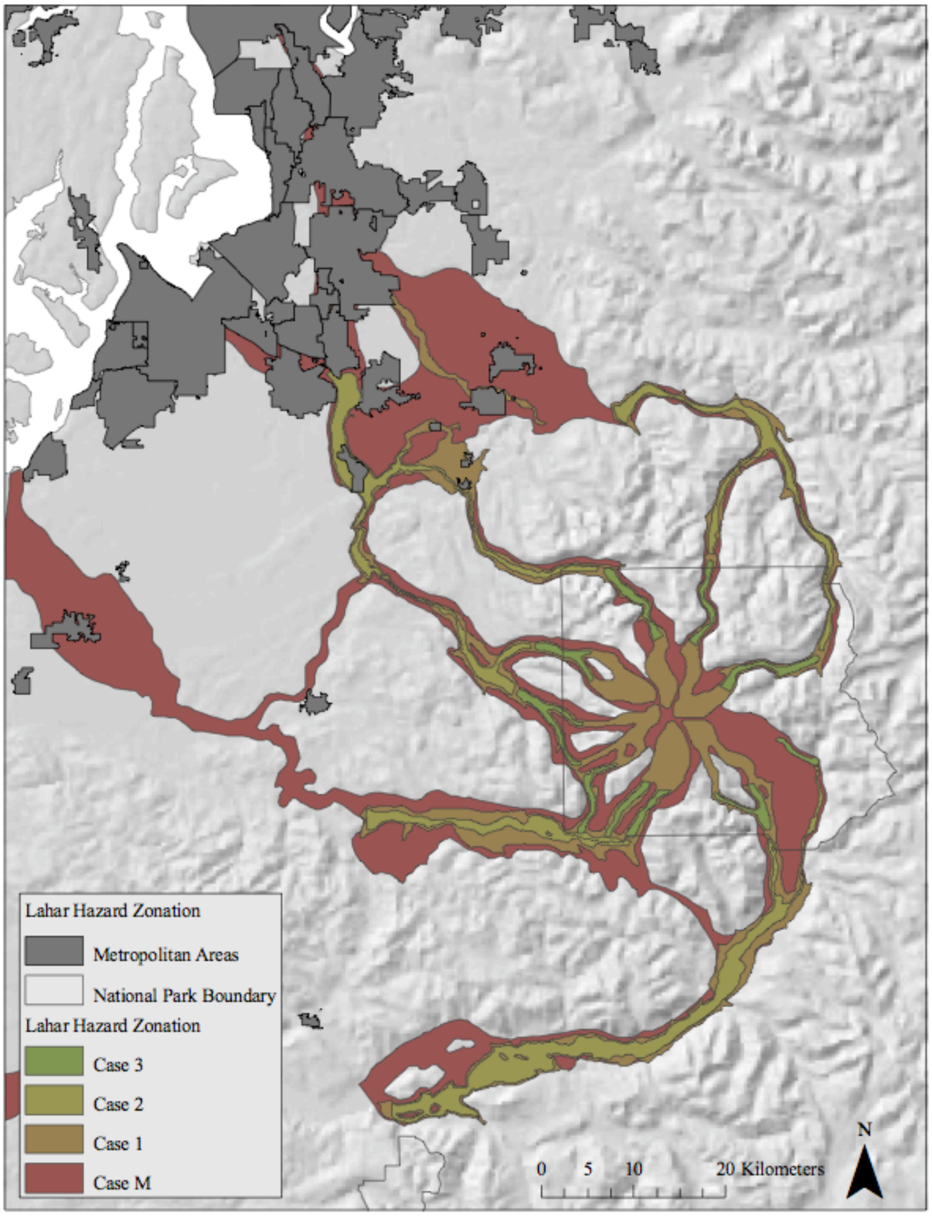

Figure 3. Lahar hazard zonation for the Puget Sound Lowlands. Lahar hazard zonation from Hoblitt et al (1998). Case M is the maximum lahar hazard zone, which is equivalent to the Osceola Mudflow event 5000 years ago. Case 1 is defined as areas that could be affected by cohesive debris flows that originate as avalanches of chemically weakened rock with an average time between events of 500 to 1000 years. Case 2 is defined as areas that could be affected by large non-cohesive debris flows that originate as avalanches of weakened material with an average time between events of 100 to 500 years. Case 3 is defined as areas that could be affected by moderately large debris avalanches or small non-cohesive debris flows of non-eruptive origin with an average time between events of 1 to 100 years.

Climate

The Cascade Range is influenced by a maritime climate characterized by 2.5 m of precipitation annually, making it one of the wettest places in the United States. The climate of Mt. Rainier from October through May is cool and dominated by precipitation, but the modified maritime climate also results in hot, dry summer months (**Fig. 4**). The northeastern and eastern sides of the mountain receive less precipitation as they are in the rainshadow of the dominant winter storm winds from the southwest and west (Hemstrom and Franklin, 1982).

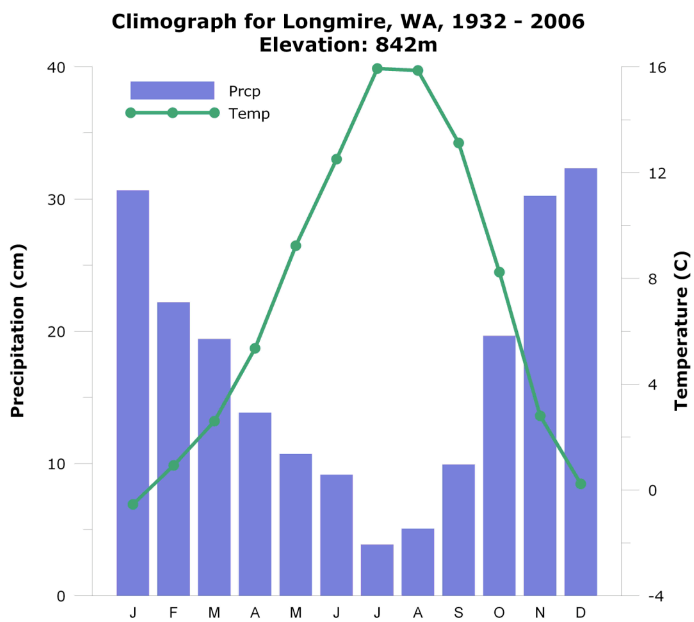

Figure 4. Climograph for Longmire, Washington (Figure courtesy of B. Medley).

Glacier History

During the last ice age, 25,000 to 15,000 years ago, nearly all of Mt. Rainier National Park was glaciated (Driedger, 1993). During the Little Ice Age, or from the14th century to 1850, the slopes of Mt. Rainier also contained glaciers (Driedger, 1993). Presently, Mt. Rainier holds approximately 25 named glaciers, which comprise the largest ice volume of any peak in the conterminous United States or approximately 4.4 billion m^3 (Driedger and Kennard, 1984) (**Fig. 5**). The vast majority of glaciers have retreated significantly since the end of the LIA (Driedger, 1993; Nylen, 2004). Glacier recession was generally slow from 1880 to 1920 and much more rapid from 1920 to 1950 (Driedger, 1993). Nylen (2004) reports a loss of 18.5% of total glacier cover from 1913 to 1971 with south and north-facing glaciers diminishing 26.5% and 17.5%, respectively. A few glaciers with source areas at or near the summit have retreated minimally and a minority of glaciers, including Carbon, Cowlitz, Emmons, and Nisqually Glaciers, advanced during the 1970s and 1980s as a result of precipitation patterns in the 1960s (Driedger, 1993; Nylen, 2004). Yet, even glaciers that have retreated minimally or advanced briefly in the 1970s and 1980s are currently at their historic minima since the end of the LIA (P. Kennard, personal communication, 2008). Short-term glacier advance is masked by a much larger, long-term trend in glacier retreat. Since the 1980s all glaciers have thinned, retreated, or fragmented (Nylen, 2004). Nylen (2004) reports that winter snowfall at the Paradise Ranger Station meterological station on Mt. Rainier has decreased 5.1 $cmyr^{-1}$ during the period 1954 to 1994 while there have been no significant trends in summer temperatures during the same period.

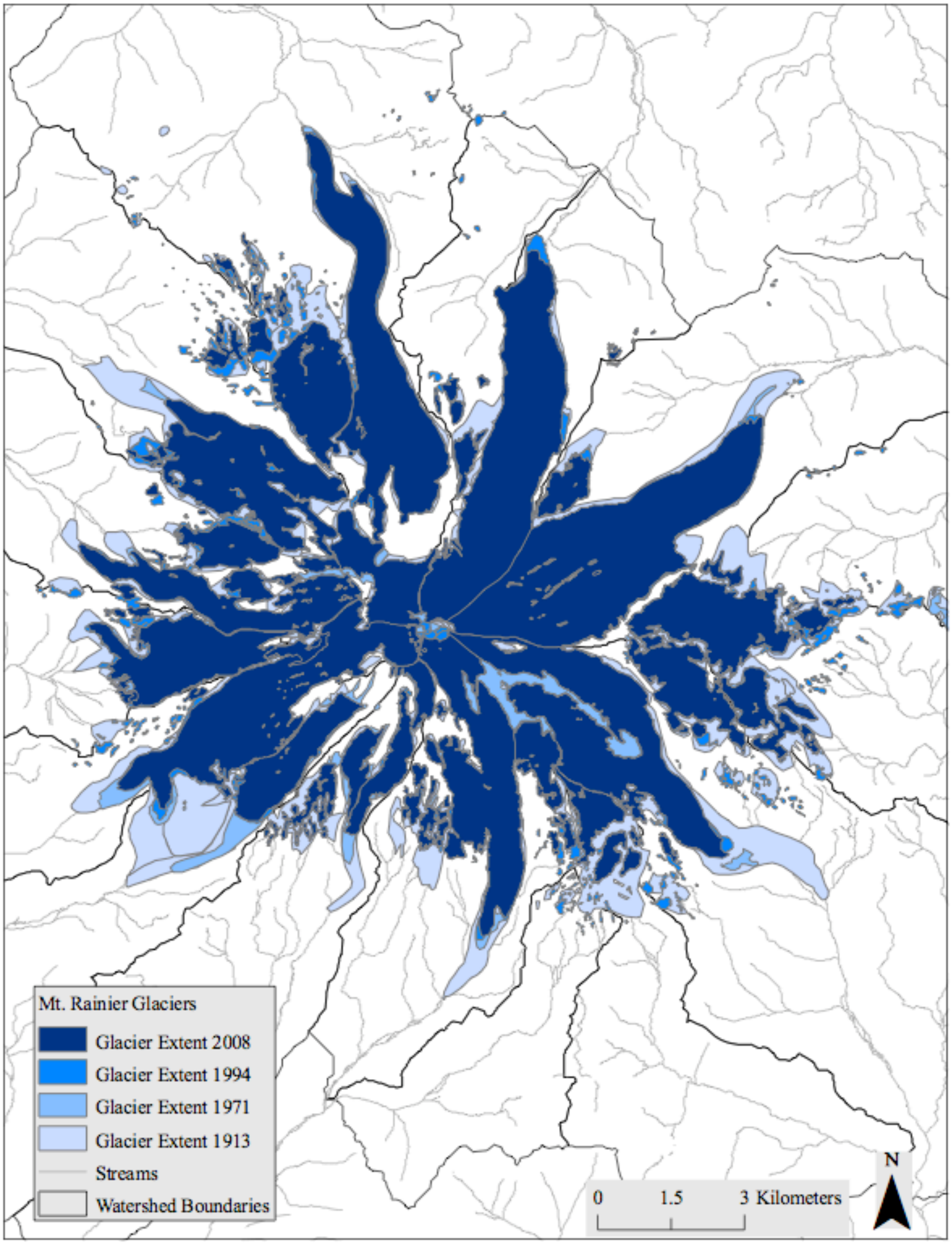

Figure 5. Retreat of Mt. Rainier glaciers from 1913 to 2008. Historic glacier areas are from the previous work of Nylen (2004).

Chapter 2 – Methods

A combination of image analysis and fieldwork was used to quantify and characterize debris flows that occurred between 2001 and 2006. Analysis of aerial photographs and other remote sensing imagery augmented and helped to constrain fieldwork. The first objective of fieldwork was identification of all channels that were impacted by debris flows in 2006. Channels impacted by debris flows in 2001, 2003, and 2005 were previously identified by Vallance et al. (2002) and P. Kennard (personal communication, 2008). The upstream reaches of confirmed debris flow tracks from 2006 were then examined using aerial photographs and other data to locate debris flow initiation sites. Metrics of initiation sites, including distance to glaciers, elevation, slope, and aspect were quantified using LiDAR and other data. Debris flow behavior along the length of the flow path was qualitatively assessed in the field and through analysis of aerial photographs to define transitions from erosion, to transport, and ultimately deposition. Characterization of debris flow initiation sites and flow paths allowed inferences regarding future debris flow hazards to be made and analysis of the metrics that defined each initiation site allowed initiation mechanisms to be deduced. Ultimately, understanding of the timing, geography, and initiation mechanisms of debris flows will provide a deeper understanding of how future climate may alter debris flow initiation.

Identification of Debris Flow Tracks

Channels that were impacted by debris flows were identified through extensive field reconnaissance. All channels suspected or identified as being impacted by a 2006 debris flow were field surveyed. Identification of debris flow deposits during field surveys relied on the presence of boulder levees and reverse grading. Damage to vegetation was not diagnostic of debris flows as it was widespread due to flooding from a November 2006 storm. Field methods were similar to those of Wilford et al. (2004) and guided by the classification scheme for differentiation between debris flows and floods by Pierson (2005) (**Table 3**). The length of stream channels, from glacier termini to confluence with a major river, was surveyed as terrain and snow cover permitted. Field surveys of debris flow tracks included photo documentation, mapping, estimation gradient and channel confinement, comparison of historic oblique photos and aerial photos with current field conditions, and qualitative description of deposition, erosion, and damage to vegetation. Field observations were later used to define transitions in debris flow behavior from erosion, to transport, and ultimately to deposition.

Table 3. Indicators of floods and debris flows modified from USGS Publication "Distinguishing between Debris Flows and Floods from Field Evidence in Small Watersheds" (Pierson, 2005).

Indicator	Flood	Debris Flow
Stratification	Sorted, normal grading	Poorly sorted, normal or inverse grading
Coherency	Friable, loose	Coherent, semi-indurated
Deposit surface	-	Frequently concave-up
Clasts	Rounded or subrounded	Angular or subangular
Location of coarse clasts	Longitudinal bars	Margins and toe of deposit
Bedforms	Yes (ripples and dunes)	No
Gravel or boulder levees	No	Yes
Imbrication of clasts	Yes	No
Mud line	No	Yes
Terraces	Yes (receding flow)	No
Severity	Moderate or light	Severe
Broken trees	No (flattened or bent)	Yes
Gravel embedded in trees	No	Yes
Erosion of tree bark	Minimal and irregular	Broken or stripped on upstream side

Initiation Site Location and Characterization

Debris flow initiation sites were located by examining the upstream reaches of channels impacted by a 2006 debris flow for the geomorphic signatures of different types of debris flow initiation described in **Table 4** that might be visible during field reconnaissance or image analysis. Data utilized in conjunction with field reconnaissance included an archive of oblique and aerial photographs from the National Park Service, 2002 IKONOS, a 2006 National Agriculture Imagery Program (NAIP) orthophoto, and Light Detection and Ranging (LiDAR) completed during the summer of 2008 (**Table 4**). The archive of aerial photography housed at Mt. Rainier National Park includes images from approximately the past seventy years acquired at a variety of locations and spatial resolutions. IKONOS is a commercial satellite with high-resolution multispectral and panchromatic imagery, 1 m spatial resolution and 11 km swath width. NAIP images are orthorectified with a spatial resolution of 1 to 2 m. The LiDAR data were used to produce a bare-earth surface elevation model and images of pulse return intensity (Watershed Sciences, Inc., 2009) with a vertical accuracy of 3.7 cm and an average of 7.3 points per m^2 in priority drainages and 5.7 points per m^2 in all other areas. All data was analyzed using ArcGIS software.

Table 4. Data available for analysis

Data	Date	Coverage	Resolution	Source
Aerial Photography	Various Dates	Variable	Variable	NPS
Historic Glacier ArcGIS Shapefiles: Area, Volume	1913, 1971, 1994	Parkwide	-	Nylen, 2004
Paradise Ranger Station meteorological data	1920s to present	-	-	National Climatic Data Center
Mt. Rainier National Park Infrastructure ArcGIS shapefiles: Roads, Trails		Parkwide	-	NPS
Tahoma Creek LiDAR	2000	Tahoma Creek	-	NPS
IKONOS	2001/2002	Parkwide	1m	NPS
Aerial Photography	2007	Parkwide	1m	NPS
Orthophoto	Summer 2006	Parkwide	1m	National Agriculture Imagery Program
Aerial Photography	2007	Parkwide	1m	NPS
LiDAR	Completed 2008	Parkwide	1m	Watershed Sciences, Inc., 2009

Initiation sites were located using a combination of the 2006 NAIP orthophoto, 2007 aerial photos, and LiDAR completed in 2008 depending on the snow-covered area present in images and the chronology of debris flows in a particular channel. LiDAR data were used to calculate initiation site characteristics such as gradient, aspect, and channel geometry, as well as distance to glaciers, glacier area, glacier volume, glacier debris covered area, and the upslope contributing area to each site.

Distance from initiation sites to historic glacier margins was calculated using glacier coverages from Nylen, (2004) who synthesized information from historic topographic maps, aerial photographs, and field surveys to reconstruct the glacier extents on Mt. Rainier for the years 1913, 1971, and 1994. Nylen (2004) analyzed glacier terminus position, area, debris covered area, and volume. These characteristics for glaciers associated with debris flows and those not yet associated with debris flow were compared in order to understand if these factors are important for debris flow initiation. Nylen's 1913 glacier coverage is based on three years of field mapping by the USGS in 1910, 1911, and 1913 that was eventually published as a map in 1955 (Nylen, 2004). The 1913 map, published in 1955, was revised using aerial photogrammetry to create the 1971 map. Further revisions were made using aerial photos to create the 1994 map. Information regarding glacier terminus position is available for years in addition to 1913, 1971, and 1994 from mylar overlays on aerial photos (Driedger, 1986) and from terminus positions measured in the field for accessible glaciers such as Carbon, Emmons, Nisqually, and South Tahoma (Nylen, 2004). Nylen only considered the active glacier terminus in his analyses, not the stagnant ice of the inactive terminus. Changes in terminus position were measured along glacier centerlines. For glaciers with a common boundary Nylen divided the glaciers based on ice flow directions derived on surface contours. The divide between any two particular glaciers is altered by changes in the surface topography. Therefore, changes in glacier area may reflect glacier retreat or advance or may simply reflect alteration of the position of glacier boundary. Information regarding glacier volume is the result of basal and surface contours from radar surveys by Driedger and Kennard (1984) and estimation methods used by Mennis (1997, 2001). Where information regarding basal topography did not exist Nylen used an empirical relationship defined by Meier and Bahr (1997) from 144 glaciers around to world to relate glacier area to volume. Nylen notes that major sources of error in his work are due to the construction of original 1913, 1971, and 1994 maps and digitization of the original maps so that they could be analyzed with ArcGIS software. The remote, hazardous terrain of Mt. Rainier likely limited mapping efforts of early surveyors, particularly at high elevations. Distinguishing between debris covered ice from debris covered ice-free areas, seasonal snow from snow covered glaciers, active glacier ice from stagnant glacier ice near a glacier terminus, and glacier ice from permanent bodies of snow or ice is extremely difficult in the field or from aerial photo analysis. Therefore, a great deal is known about accessible, lower elevation glaciers such as Carbon, Emmons, Nisqually, and South Tahoma, and far less is known about remote, high elevation glaciers and particularly those glaciers that have fragmented and retreated. Please see Nylen's 2004 masters thesis for detailed information regarding each of his analyses and the associated errors.

I created a 2008 glacier coverage to be used in addition to historic glacier data from Nylen (2004) for certain analyses. I edited a copy of the 1994 glacier coverage by Nylen (2004) to match the glacier margins visible on the 2006 NAIP orthophoto and LiDAR intensity images captured during the summers of 2007 and 2008. This methodology was recommended by USGS CVO scientist T. Sisson (personal communication, 2008) who used a similar process to update the USGS surficial geology map of Mt. Rainier using the 2006 NAIP orthophoto, as numerous glaciers have retreated and exposed bedrock. This process is also similar to how historic glacier terminus positions were derived in Nylen's work. Most permanent snow and ice bodies were not analyzed when creating the 2008 glacier coverage. Nylen (2004) was able to include numerous bodies of snow and ice, some of which are defined as glacier fragments, in the 1994 glacier coverage, but analysis of aerial photographs from several different years would be necessary to accurately address changes in the size and shape of these glacier remnants independently of yearly variations in snowfall and snow cover. Glacier area from the 2008 coverage should not be compared with Nylen's data as omission of glacier fragments may have led to an underestimation of total glacier area, while snow cover in the images used to create the 2008 coverage may have led to overestimation glacier margins at high elevations. Analysis of changes in glacier area uses only Nylen's 1913, 1971, and 1994 glacier coverages. Similarly, only Nylen's data was used to analyze glacier volume, perimeter, and debris-covered area to compare glaciers associated with debris flow and glaciers without a history of debris flow initiation. The 2008 glacier coverage was used to analyze the size of glaciers that were associated with debris flows from 2001 to 2006. The 2008 glacier coverage was also used to address changes in the position of glacier termini, as LiDAR data was sufficiently snow free at lower elevations to allow the identification of termini (**Fig. 6**). Analysis of changes in glacier terminus location and elevation included both the 2008 glacier coverage and Nylen's data.

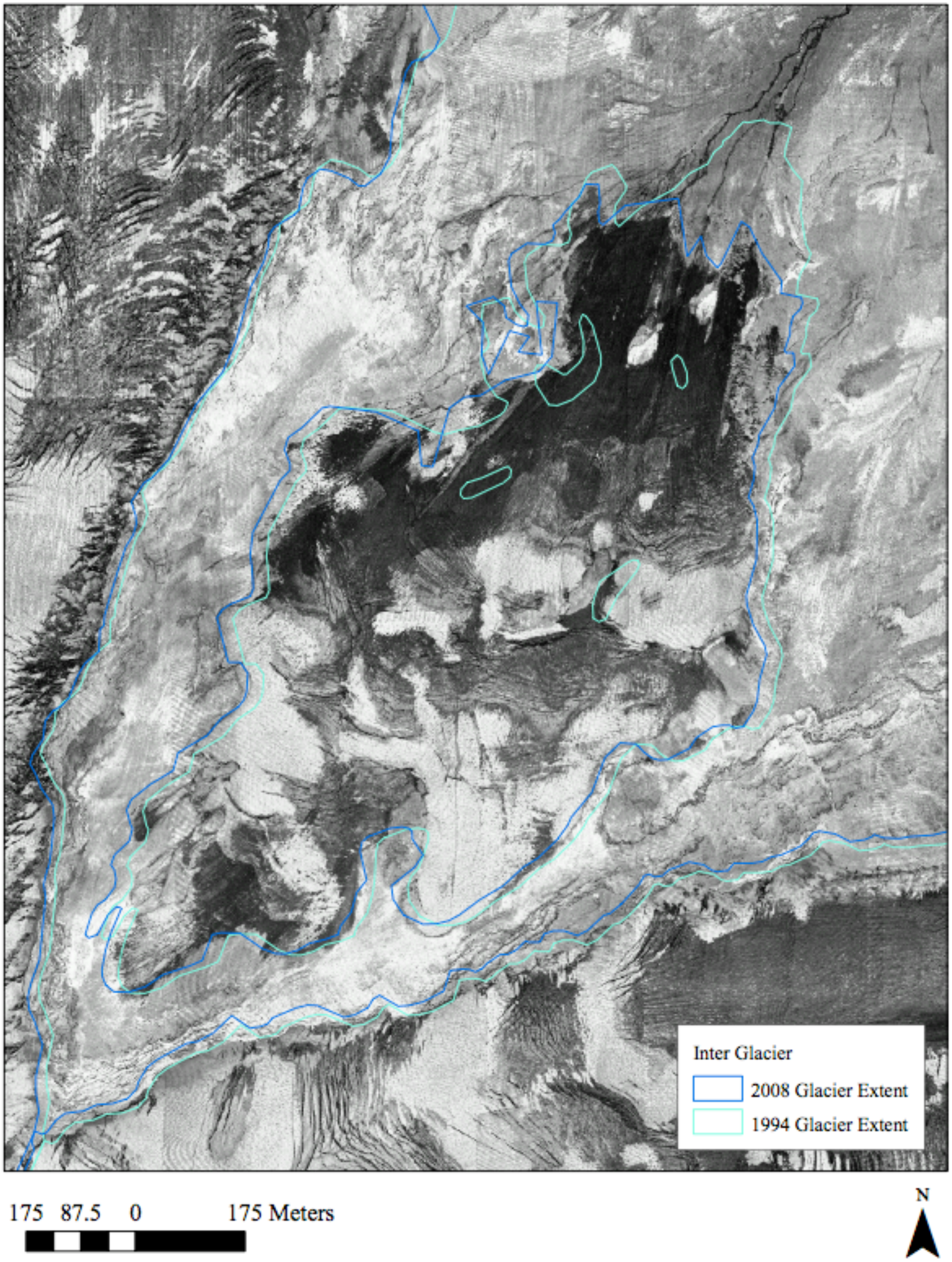

Fig 6. Example of 2008 glacier extent derived from LiDAR intensity images compared with the 1994 glacier extent from Nylen (2004) for Inter Glacier.

Flow accumulation calculations for debris flow initiation sites were made using bare-earth LiDAR and hydrology tools included in ArcGIS software. Flow accumulation is the number of cells contributing flow to a cell downslope. Flow accumulation was calculated without differentiation between the exposed slopes of Mt. Rainier and glacier ice. Drainage divides for a glacier will not solely depend on ice topography, but also ice thickness and the topography of the glacier bed. The problem of calculation of upslope contributing area in glaciated landscapes without the benefit of ice radar data has been tackled by few authors (Kennett et al., 1997). While not considered in this work, basal contours for many of Mt. Rainier glaciers exist due to the work of Driedger and Kennard (1984) and could be used to refine flow accumulation calculations.

Characterization of Debris Flow Behavior

Zones of erosion, transition or transport, and deposition were defined through qualitative descriptions of debris flow behavior made during field reconnaissance and analysis of aerial photographs and other data. The erosion zone for each debris flow included the length of the gully the debris flow was assumed to have initiated in, as well as the extent of channel where riparian vegetation has been removed or upstream of the first presence of riparian vegetation. Some debris flow tracks stripped significant riparian vegetation and erosion could be confirmed through analysis of imagery, but other tracks did not have riparian vegetation present at high elevations and erosion cannot be confirmed. Therefore the erosion zone extends from the head of the gully the debris flow initiated in and extends downstream to the first possible location where erosion might have been recorded by the removal of riparian vegetation but was not. The transport zone of a debris flow was defined from the end of the gully to the most downstream location of evidence of localized erosion. This zone was characterized by both erosion and deposition of sediment, as well as alternation between debris flow, hyperconcentrated flow, and flood behavior. The deposition zone extends from the most upstream location of localized deposition to the most downstream location of deposition or confluence with a major river. The zone of deposition was characterized by significant aggradation. Overlap between erosion and transport zones and transport and deposition zones are the zones where debris flow behavior transitioned (**Table 6**). Aerial photography and LiDAR data were used to quantify the length of zones, slope and channel confinement at transitions in behavior, and distance from the debris flow track to park infrastructure.

Table 5. Evidence used to define the upstream and downstream most extent of zones of erosion, transport or transition, and deposition.

<table>
<tr><td>Head of gully</td><td rowspan="3">Erosion</td><td></td><td></td></tr>
<tr><td>Downstream extent of gully</td><td rowspan="4">Transport</td><td></td></tr>
<tr><td>Upstream extent of riparian vegetation</td><td></td></tr>
<tr><td>Farthest upstream location of deposition</td><td></td><td rowspan="3">Deposit</td></tr>
<tr><td>Farthest downstream location of erosion</td><td></td></tr>
<tr><td>Downstream extent of deposition or confluence with major river</td><td></td><td></td></tr>
</table>

Chapter 3 – Results

Identification of Debris Flows

Twelve debris flows initiated in six drainages in 2001, 2003, 2005, and 2006 based on work by USGS CVO and National Park Service personnel (Vallance et al. 2002; P. Kennard, personal communication, 2008) and fieldwork conducted during the summer of 2008 (**Table 5**). All debris flows were associated with rainstorms, with the exception of a debris flow August 14, 2001 from Kautz Glacier that flowed into Van Trump Creek (Vallance et al., 2002). On October 20, 2003, 20.0 cm rain again produced a debris flow in Van Trump Creek. On September 29, 2005, 15.3 cm of rain fell in 48 hours on minimal snow cover and resulted in four debris flows, including one in Van Trump Creek. In the exceptional storm of November 5 to 7, 2006 that delivered 45.7 cm rain in 36 hours, all of the streams impacted by debris flows in 2005 again experienced debris flows in addition to two other stream channels. Storms in 2005 and 2006 are noteworthy as no previous storms are known to have produced multiple debris flows (Walder and Driedger, 1994; P. Kennard, personal communication, 2008).

Table 6. Identification of channels impacted by debris flow initiation during the period 2001 to 2006.

Year	Date	Glacier	Stream Channel	Boulder Levees	Broken trees	Source	Conclusion
2006	4-6-Nov	Van Trump	Van Trump Cr.	Y	Y		Debris Flow
		Pyramid	Unnamed, Pyramid Cr.	Y	Y		Debris Flow
		Winthrop	W. Fork White R.	Y	?		Debris Flow
		Inter	Inter Fork White R.	Y	Y		Debris Flow
		South Tahoma	Tahoma Cr.	Y	?		Debris Flow
		Kautz or Pyramid	Kautz Cr.	Y	Y		Debris Flow
		Fryingpan	Fryingpan Cr.	N	N		Flood
		Carbon	Carbon R.	N	N		Flood
		Cowlitz	Muddy Fork Cowlitz R.	N	N		Flood
		-	Shaw Cr.	N	N		Rockfall
2005	29-Sep	Pyramid	Pearl Cr.	Y	Y	1	Debris Flow
		South Tahoma	Tahoma Cr.	-	-	1	Debris Flow
		Pyramid	Kautz Cr.	-	Y	1	Debris Flow
		Van Trump	Van Trump	-	-	1	Debris Flow
2003	20-Oct	Van Trump	Van Trump Cr.	-	-	1	Debris Flow
2003	~ 12-Sep	South Tahoma	Tahoma Cr.	-	-	1	Slope failure
2001	14-Aug	Kautz	Van Trump Cr.	-	-	2	Debris Flow

Data Sources:

(1) Paul Kennard, personal communication 2008
(2) (Vallance et al., 2002)

Geomorphology of Initiation Sites

All debris flows that occurred from 2001 to 2006 initiated in gullies above tree line in steep, unconsolidated Quaternary age volcanic and morainal material downstream of glacier ice or permanent bodies of snow and ice. Gullies are fed and presumably maintained by glacier meltwater or snowmelt and predate the first recorded debris flow initiation. Gullies that initiated debris flows in 2006 were located on images from 1989, the date of the oldest available park-wide aerial photos. For some debris flow tracks, multiple tributaries converge upstream of the last observed evidence of a debris flow and all tributaries show evidence of erosion, possibly due to debris flow initiation or from normal fluvial processes. In these cases, a single initiation site cannot be determined. It is possible that all or only some of the meltwater channels that converge to form the main channel could have contributed to debris flow initiation. Initiation site locations indicated on subsequent figures and used in analyses correspond to the head of all possible contributing gullies

The steep slopes of Mt. Rainier also contain numerous gullies that have not previously been associated with debris flow initiation. I have identified all gullies on Mt. Rainier in order to compare debris flow producing gullies with gullies not associated with debris flows. Gullies are identified by two approximately parallel linear features with steep slopes that are downslope of glaciers or snowfields and upslope of the mapped stream network (**Fig. 7)**. All gullies contain a headwall that is located at glacier ice or permanent snow that is visible on LiDAR intensity images or is located at stagnant, debris-covered glacier ice that is not visible on LiDAR intensity images but has been described by previous researchers (Walder and Driedger, 1994; P. Kennard, personal communication, 2008). On LiDAR intensity images gullies may appear dark due to the presence of glacier meltwater. On slope imagery derived from bare earth LiDAR, the steep slopes of gully walls are immediately visible when steep gradients are represented by a light color on a two color gradational scale. Points indicating the head of each gully were placed immediately downslope of the gully headwall or where the steep gully walls converged (**Fig. 8**).

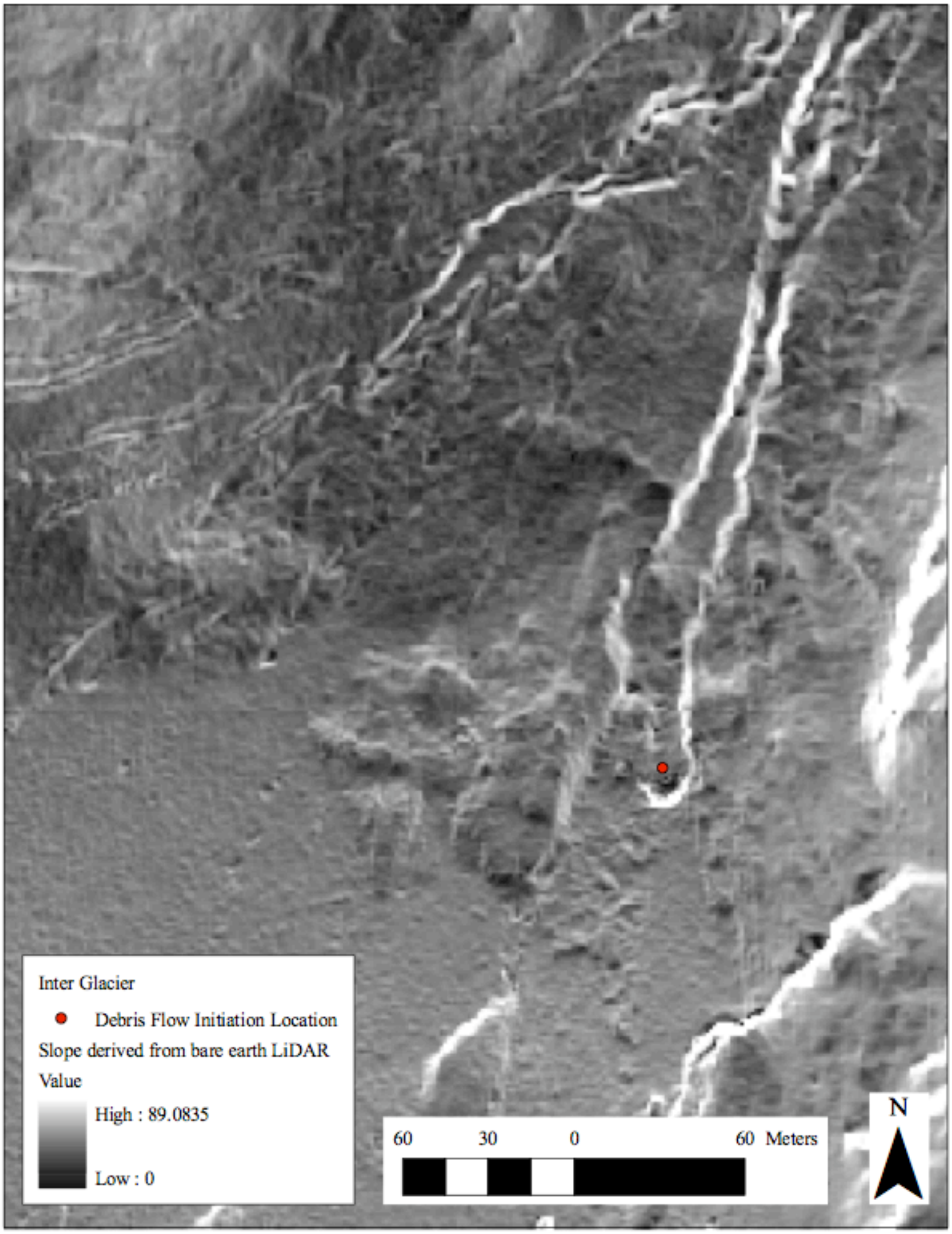

Figure 7. An example of the criteria used to define all possible gullies on Mt. Rainier. Slope derived from bare earth LiDAR for Inter Glacier with gully headwall marked by red dot. Gullies are defined as steep-sided (light-colored) linear features downstream of glaciers that are proximal to the stream network.

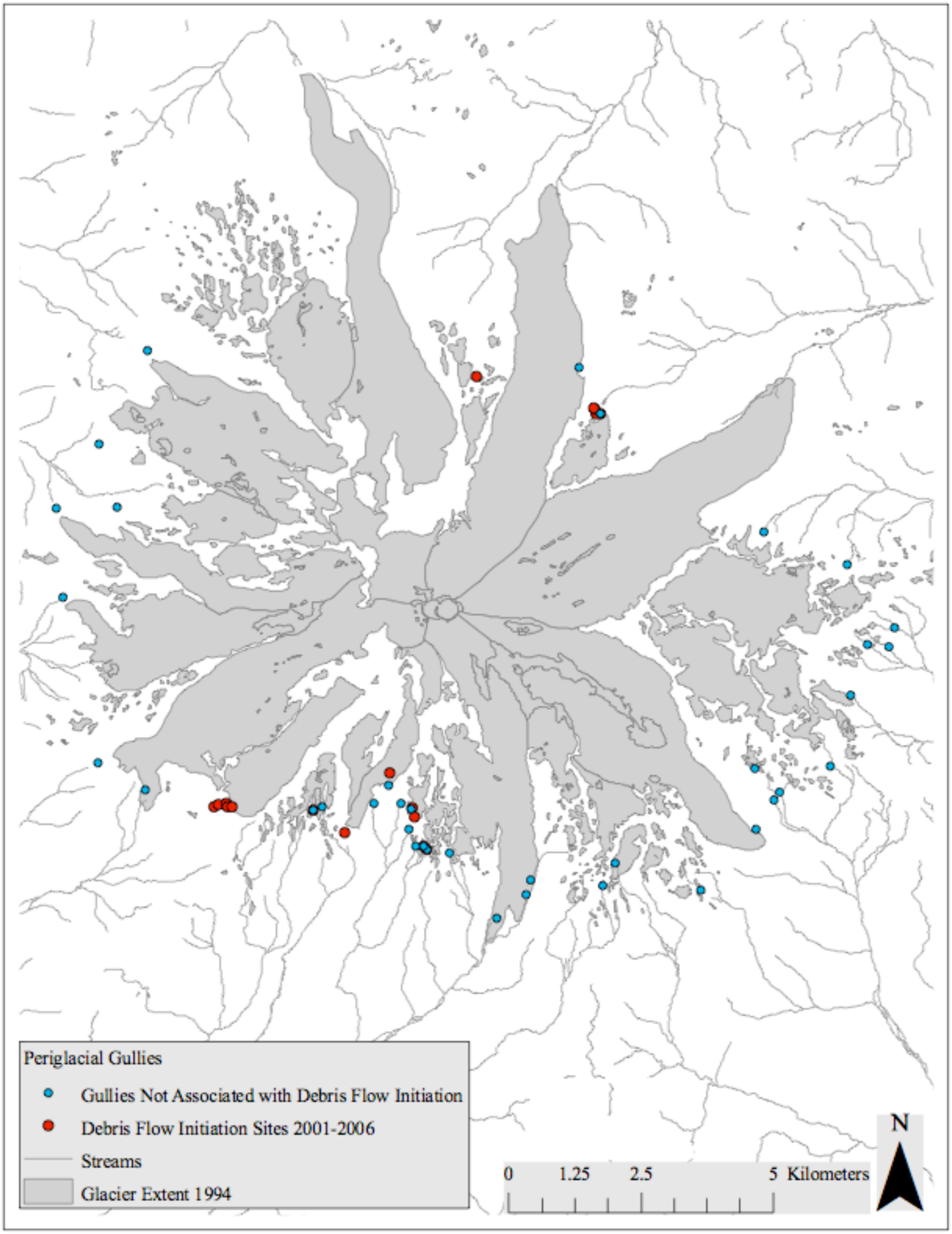

Figure 8. Debris flow initiation sites 2001 to 2006 and all gullies identified on Mt. Rainier.

Gullies with and without a recorded history of debris flow initiation were examined using LiDAR and ArcGIS software to ascertain the width, depth, gully wall slope, channel gradient, elevation, and upslope contributing area of all identified gullies (Appendix A). Using Welch's two sample t-test, only gully elevation was found to be statistically different for debris flow producing gullies and gullies not associated with debris flows **(Table 7)**. Debris flow producing gullies are located at a median elevation of 2182 m while gullies not associated with debris flows are at a median elevation of 1805 m. Initiation sites for debris flows in Van Trump Creek are not well known, but results of each two sample t-test remained consistent with and without the inclusion of possible Van Trump Creek debris flow initiation sites.

Table 7. **Comparison of gullies associated with debris flow initiation and the total population of gullies identified on Mt. Rainier through analysis of LiDAR.**

	t-statistic	df	p-value
Width (m)	-1.4	32	0.17
Depth (m)	1.4	15	0.17
Wall slope (degree)	0.87	73	0.39
Elevation (m)	5.7	23	8.9E-06
Aspect (degree)	-0.40	38	0.69
Upslope contributing area (sq. km)	-0.09	31	0.93
Slope (degree)	0.035	38	0.97

Timing of Debris Flow Initiation

Debris flow frequency in Tahoma Creek below South Tahoma Glacier has been described as nearly annually (Walder and Driedger, 1994). Other channels that have recently demonstrated the capability of producing debris flows nearly annually include Pyramid, Van Trump, and Kautz Creeks.

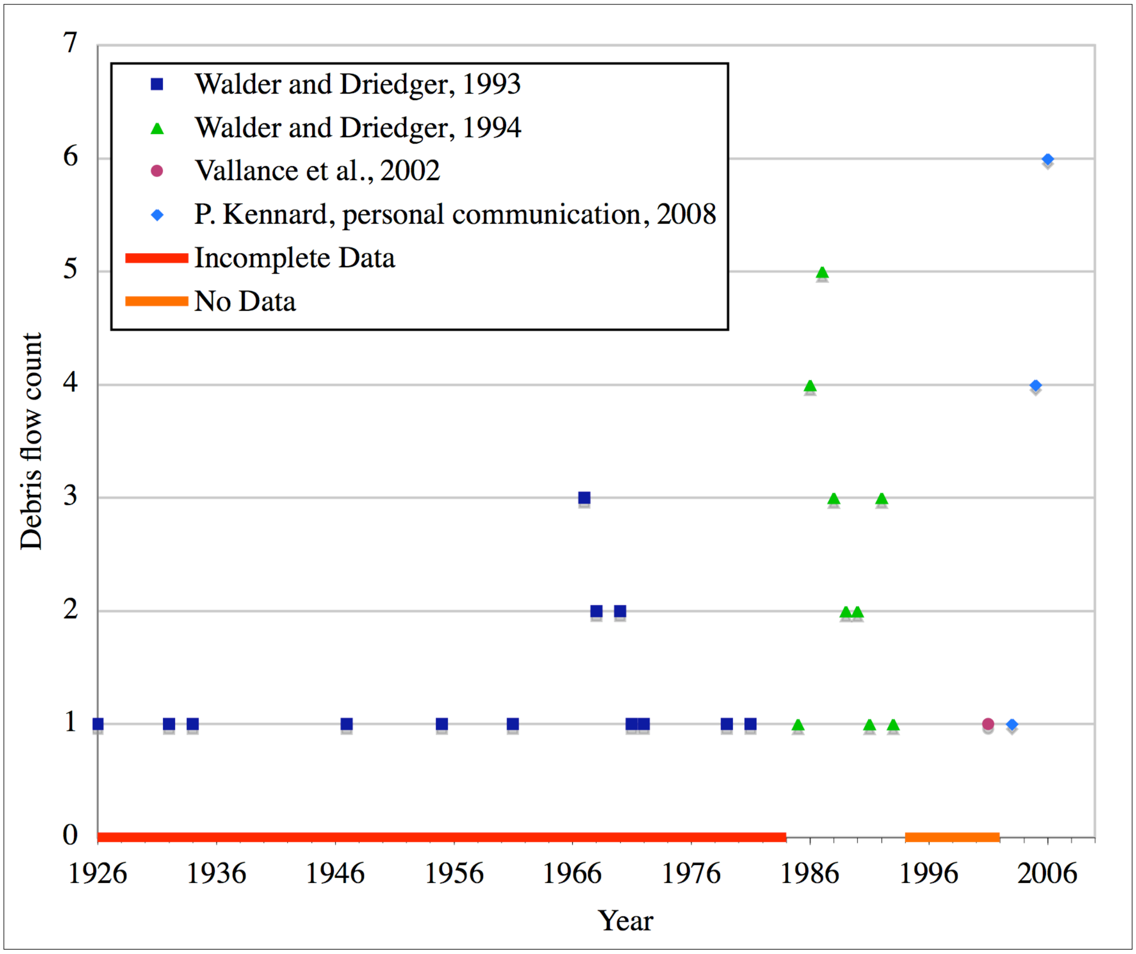

Figure 9. Chronology of debris flows from Mt. Rainier by data source. Prior to 1985, typically only the year the debris flow occurred and the channel it occurred in was recorded.

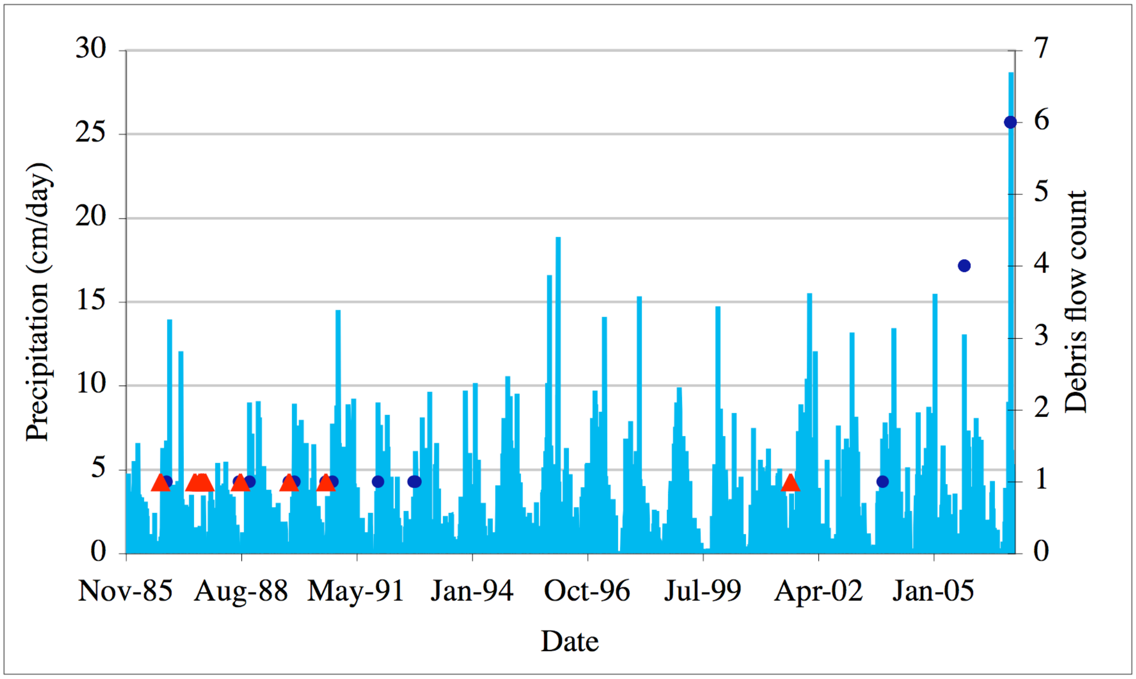

Figure 10. Chronology of debris flows from Mt. Rainier with known date of initiation for the period 1985 to 2006 and daily precipitation from the Paradise Ranger Station meteorological station.

Table 8. Chronology of all known debris flows associated with particular glaciers of Mt. Rainier from 1926 to 2008.

Year	S.Tahoma	Pyramid	Kautz	Van Trump	Nisqually	Winthrop	Inter	Sum	Source
1926					1			1	A
1932					1			1	A
1934					1			1	A
1947			1					1	A
1955					1			1	A
1961			1					1	A
1967	3							3	A
1968	1				1			2	A
1970	1				1			2	A
1971	1							1	A
1972					1			1	A
1979	1							1	A
1981	1							1	A
1985			1					1	B
1986	2		1		1			4	B
1987	4					1		5	B
1988	3							3	B
1989	2							2	B
1990	2							2	B
1991	1							1	B
1992	3							3	B
1993	1							1	B
2001				1				1	C
2003	NA			1				1	D
2004								0	D
2005	1	1	1	1				4	D
2006	1	1	1	1		1	1	6	D

Source of debris flow records: "A" Walder and Driedger (1993), "B" Walder and Driedger (1994), "C" Vallance et al. (2002), and "D" P. Kennard (personal communication, 2008)

The difference in the seasonal timing between summer dry-weather and fall wet-weather debris flows has previously been described by Walder and Driedger (1994). Debris flows included in this study conform to this model, with the only dry weather debris flow occurring in early August and all wet-weather debris flows occurring in September through November (**Fig. 11 and 12).**

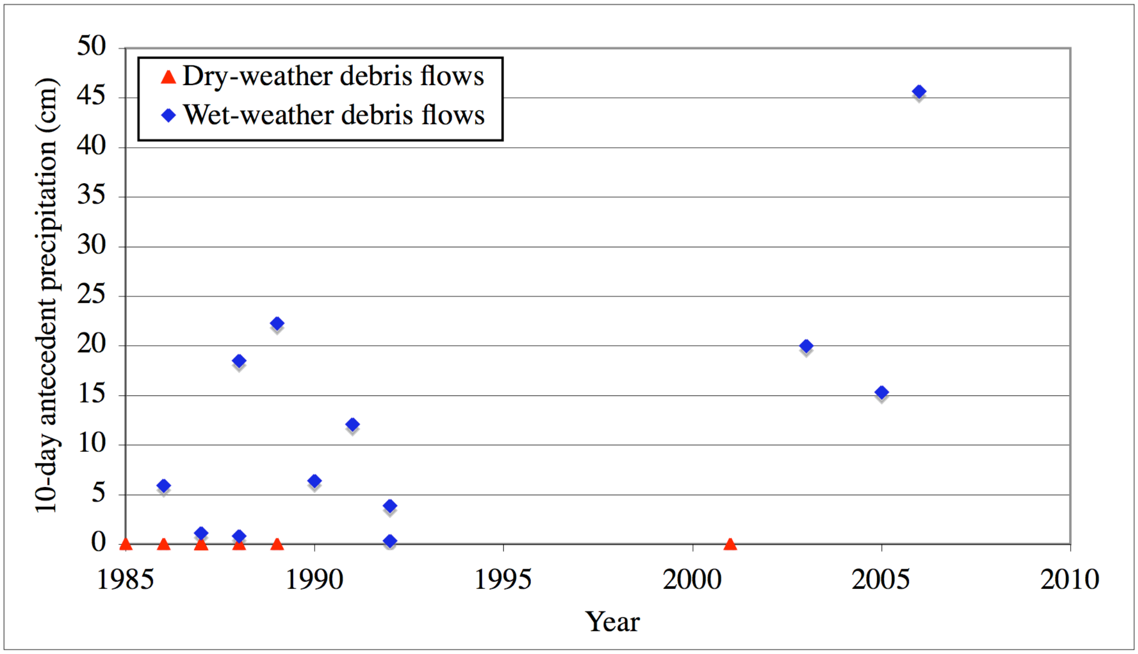

Figure 11. Chronology of dry and wet weather debris flow initiation. Ten-day antecedent precipitation for all debris flows with known date of initiation is the Paradise Ranger Station meteorological station.

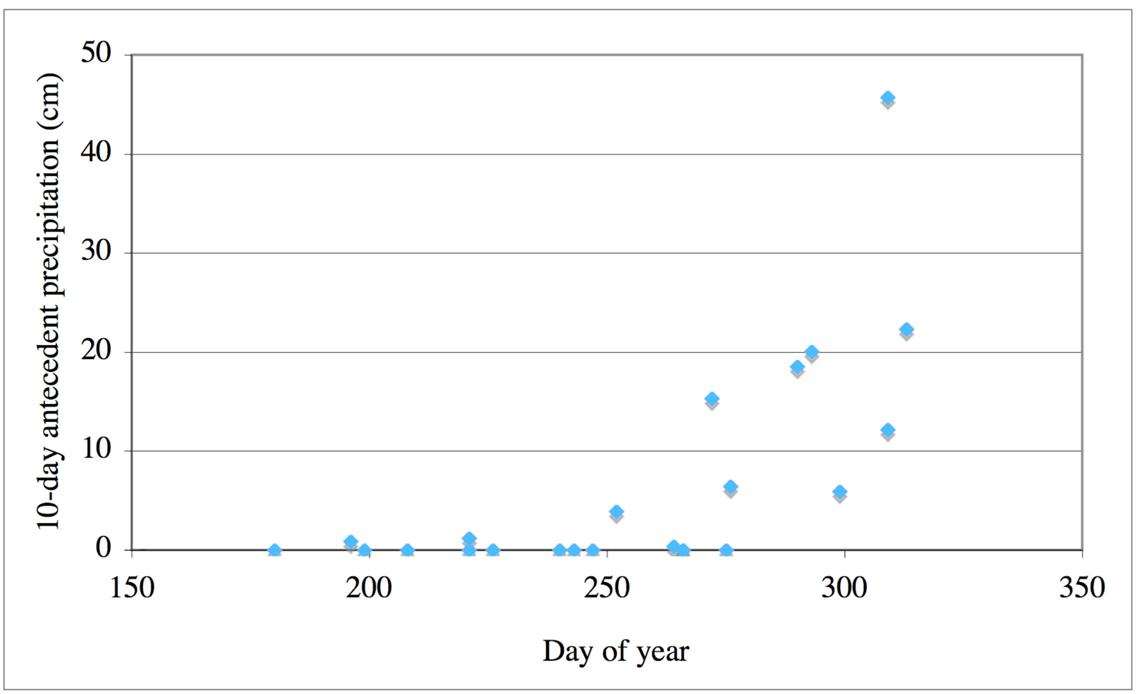

Figure 12. Seasonal timing of dry and wet weather debris flows. Ten-day antecedent precipitation for all debris flows with known date of initiation is from the Paradise Ranger Station meteorological station.

Geography of Debris Flow Initiation

Twelve debris flows have occurred since 2001 in a total of six drainages, three of which have not previously experienced debris flows. New debris initiation sites since 2001 include Van Trump Creek in 2001, Pyramid Creek in 2005, and the Inter Fork of the White River in 2006 (**Fig. 13)**. While it is unlikely that two of the new channels have previously experienced debris flows due to the proximity to infrastructure, the third site could have had a debris flow without detection. Van Trump Creek crosses the Nisqually-Longmire Entrance Road at the Christine Falls bridge, a national historic structure and Inter Fork of the White River was originally paralleled by the both the Glacier Basin Trail and the Emmons Moraine Trail. Pyramid Creek, however, has numerous confluences with Kautz Creek and there is evidence of debris flows migrating between the two channels (**See Appendix B**). Pyramid Creek debris flows damaged a backcountry campsite and forced it to be relocated, but damage to the campsite could be evidence that debris flows are following new trajectories and not that there has been a new initiation site.

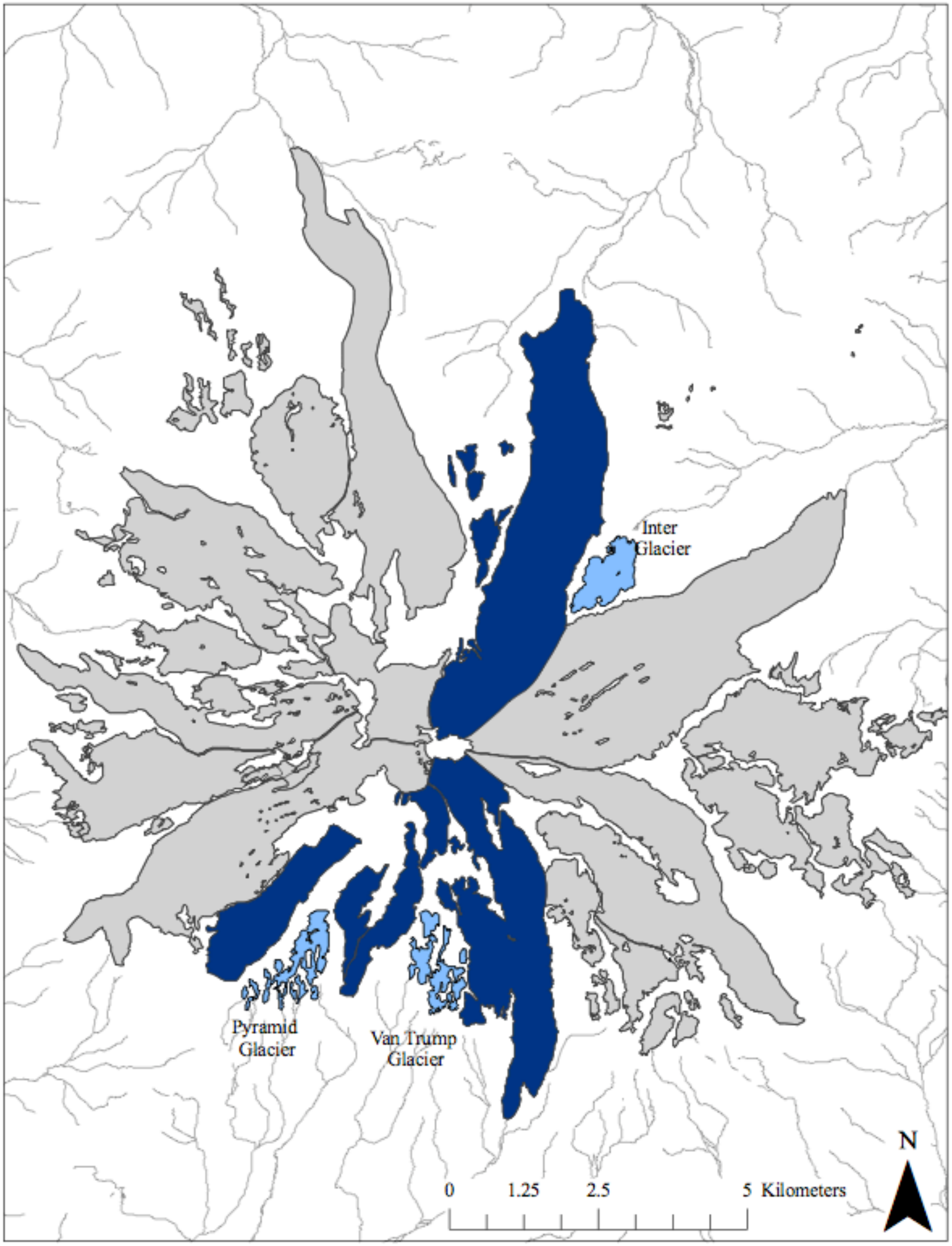

Figure 13. Glaciers recently associated with debris flow initiation include Pyramid, Van Trump, and Inter Glaciers. Glaciers that have triggered debris flows since 2001 are highlighted in light blue. All glaciers associated with debris flow initiation since 1926 are highlighted in dark blue.

Initiation Mechanisms

Debris flow initiation mechanisms for debris flows were inferred through a combination of field reconnaissance and image interpretation. Field reconnaissance provided ample evidence of mobilization of sediment in rills and gullies associated with debris flows. During image analysis, all debris flow channels were traced to meltwater gullies with crenulated walls, suggesting that discrete mass wasting or slumping into the stream channel had occurred, possibly in association with localized overland flow or in-channel entrainment of sediment. Measurement of changes in gully width following a debris flow is hindered by snow-cover in images. Change in gully width pre- and post-debris flow initiation can only be addressed for the 2006 Pyramid Creek debris flow. Gully width was measured at 50 m intervals using the summer 2006 NAIP orthophoto and summer 2008 LiDAR from the initiation site to the downstream extent of the erosion zone as snow cover permitted. The average change in width was 0.7 m while the median change in width was zero. Changes in gully width cannot necessarily be attributed to debris flow activity as other geomorphic change likely occurred between available images. Image analysis of channels impacted by debris flows in 2001, 2003, and 2005 also suggests that slumping from steep-sided gully walls facilitated debris flow initiation. While the movement of material in rills and gullies is apparent from fieldwork, it is difficult to quantify geomorphic change using the available imagery. Multiple dates of LiDAR data only exist for Tahoma Creek below South Tahoma Glacier. Analysis shows that mass has been lost from the proglacial area and stagnant ice zone described by Walder and Driedger (1994) as a zone of erosion (**Fig. 14**). Mass has accumulated near the stream channel in the downstream reaches near the Westside Road possibly due to a combination of fluvial transport, debris flows, and slope failures from valley walls.

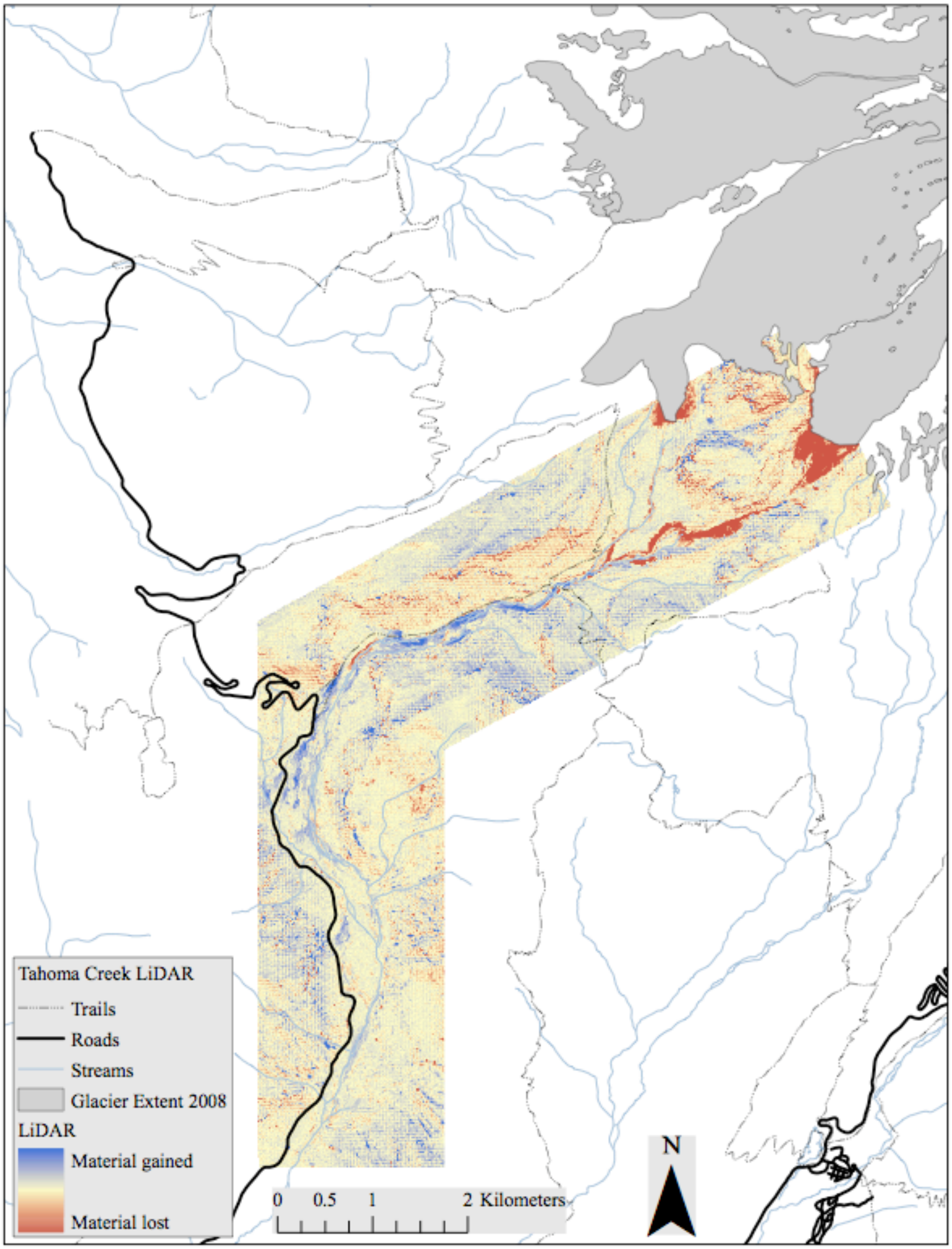

Figure 14. LiDAR data analysis of transport of material from the proglacial zone of South Tahoma Glacier into the downstream reaches of Tahoma Creek. LiDAR was acquired for only Tahoma Creek in 2000 and LiDAR was acquired for the entire mountain in 2008.

In addition to the widespread distribution of steep-walled gullies, image analysis of the debris flow initiation sites from 2006 also revealed that one of the six debris flows initiated near a proglacial accumulation of water, at an elevation not accessible during summer fieldwork due to extensive snow cover. Field identification of the West Fork of the White River debris flow channel led to identification of the initiation site near a lake adjacent to a fragment of Winthrop Glacier. The 2006 West Fork of the White River debris flow may have initiated as the result of a perturbation of this pool of water. The possibility of a glacier or glacier lake outburst flood contributing to debris flow initiation cannot be confirmed or disregarded, as available images are not of a sufficient temporal resolution to reveal changes in volume of the proglacial lake. The lake terminates at two gullies that connect to the lateral margin of Winthrop Glacier.

Fieldwork and image analysis revealed that no debris flow channel from 2006 was associated with a glacier with meltwater ponding or other indication of hydrothermal activity nor did any debris flow initiate at a scarp or fresh rock face and talus slope, which would indicate a landslide or rockfall, respectively. The 2003 Van Trump Creek debris flow was initially interpreted as a rockfall by P. Kennard, but photographic or other evidence is not available, and the proposed initiation mechanism cannot be confirmed. Field reconnaissance by P. Kennard shortly after the 2003 debris flow revealed that boulders had fallen or rolled on top of snowfields (P. Kennard, personal communication, 2008). While analysis of the 2006 debris flows did not provide evidence of landsliding or rockfall, it is important to note that high spatial and temporal resolution imagery is lacking for the events described in 2003 and little field evidence persists in a dynamic environment.

Analysis of ancillary data was used to further constrain possible debris flow initiation mechanisms for flows in 2003, 2005, and 2006. The debris flow from Van Trump Glacier in 2001 was reported by Vallance et al., 2002 as the result of a glacier outburst flood due to helicopter reconnaissance during a pulse of the debris flow. Unlike the 2001 Van Trump debris flow, all subsequent debris flows in 2003, 2005, and 2006 have occurred during rainstorms, rather than antecedent hot, dry weather that might lead to the accumulation and release of glacier meltwater. Walder and Driedger (1994) inferred that even wet-weather debris flows are the result of changes in glacier drainage networks, but in later work they suggest that glacier outburst floods may be less common than first thought (C. Driedger, personal communication, 2008). Meteorological data also suggests that earthquakes are not the underlying cause of slope instability leading to debris flow initiation. The 2001 Van Trump Creek debris flow was not a result of an earthquake as seismographs on the slopes of Mt. Rainier recorded the passage of the debris flow (Vallance et al, 2002). Furthermore, earthquakes are not assumed to be a trigger for debris flows in 2005 and 2006, as multiple debris flows occurred on Mt. Rainier during these rainstorms and debris flows also occurred on nearby Mt. Hood during the 2005 storm (L. Parker, 2008).

Table 9. Evidence of debris flow initiation mechanisms.

Year	Date	Glacier	Stream Channel	Mechanism	Evidence
2006	4-6-Nov	Van Trump	Van Trump Cr.	Slumping	Gully
		Pyramid	Unnamed, Pyramid Cr.	Slumping	Gully
		Winthrop	W. Fork of the White R.	GLOF, Slumping	Proglacial lake
		Inter	Inter Fork of the White R.	Slumping	Gully
		S. Tahoma	Tahoma Cr.	Slumping, GOF	Gully
		Kautz or Pyramid	Kautz Cr.	Slumping	Gully
2005	29-Sep	Pyramid	Pearl Cr.	Slumping	Gully
		S. Tahoma	Tahoma Cr.	Slumping, GOF	Gully
		Pyramid	Kautz Cr.	Slumping	Gully
		Van Trump	Van Trump	Slumping	Gully
2003	20-Oct	Van Trump	Van Trump Cr.	-	Possible Rockfall
2001	14-Aug	Kautz	Van Trump Cr.	GOF	Vallance et al., 2002

Notes: Glacier lake outburst flood (GLOF) and glacier outburst flood (GOF).

Possible Contributing Factors for Debris Flow Initiation

Debris flow initiate due to a combination of water, steep slopes, and loose material, but the relative importance of each contributing variable depends on the geology and climate of a particular study area. Debris flow initiation sites were quantified using numerous indices of water availability, slope instability, and material available for transport in order to infer debris flow initiation mechanisms and explore why some proglacial areas and not others seem prone to debris flow initiation. Metrics related to the abundance of water at a debris flow initiation site might include distance to glacier ice, glacier area, and glacier volume. Summertime ablation of glaciers, particularly large glaciers, could provide the needed moisture for debris flow initiation through melt or glacier outburst floods. Other metrics related to water availability might include upslope contributing area, elevation, orientation, or the fractional debris-covered area of glacier ice. Upslope contributing area is a topographic index related the zone upslope that may impact a point downslope. Sites at greater elevations might experience greater orographic enhancement during rainstorms. The orientation of initiation sites may elucidate the importance of the predominant storm direction. The debris-covered area of glacier ice might indicate that the glacier surface is partially insulated from ablation and therefore less likely to contribute meltwater for debris flow initiation. The importance of steep slopes for initiation would be revealed through analysis of gradient. Elevation might also serve as a proxy for gradient, as the flanks of Mt. Rainier generally become steeper at higher elevations. Metrics related to the availability of unconsolidated material might include the timing and magnitude of glacier retreat because retreat exposes unstable material. Elevation may also be a proxy for the abundance of unconsolidated material as sites at lower elevations might experience a shorter duration of snow cover or frozen ground, which might facilitate sediment mobility and debris flow initiation.

Glacier Retreat

Based on image analysis and field surveys, all recent debris flow initiation sites on Mt. Rainier are located in gullies headed by glaciers, ice bodies, or permanent snowfields. Therefore, all debris flow initiation sites are located within the extent of the historical glacier coverage and within the zone of the most recent period of glacier retreat for a particular glacier (**Fig. 15 and 16**). Debris flow initiation sites associated with small glaciers that have retreated and fragmented, such as Pyramid and Van Trump Glaciers, are located within the 1913 extent of glacier coverage (Nylen, 2004). Debris flow initiation sites associated with large glaciers that have retreated, but remained predominantly single, massive bodies of ice, such as South Tahoma, Kautz, and Winthrop Glaciers, are located within the 1971 extent of glacier coverage (Nylen, 2004). Lastly, a debris flow initiated at a medium size glacier that has retreated minimally, Inter Glacier, where initiation sites are located within the 1994 extent of glacier coverage (Nylen, 2004).

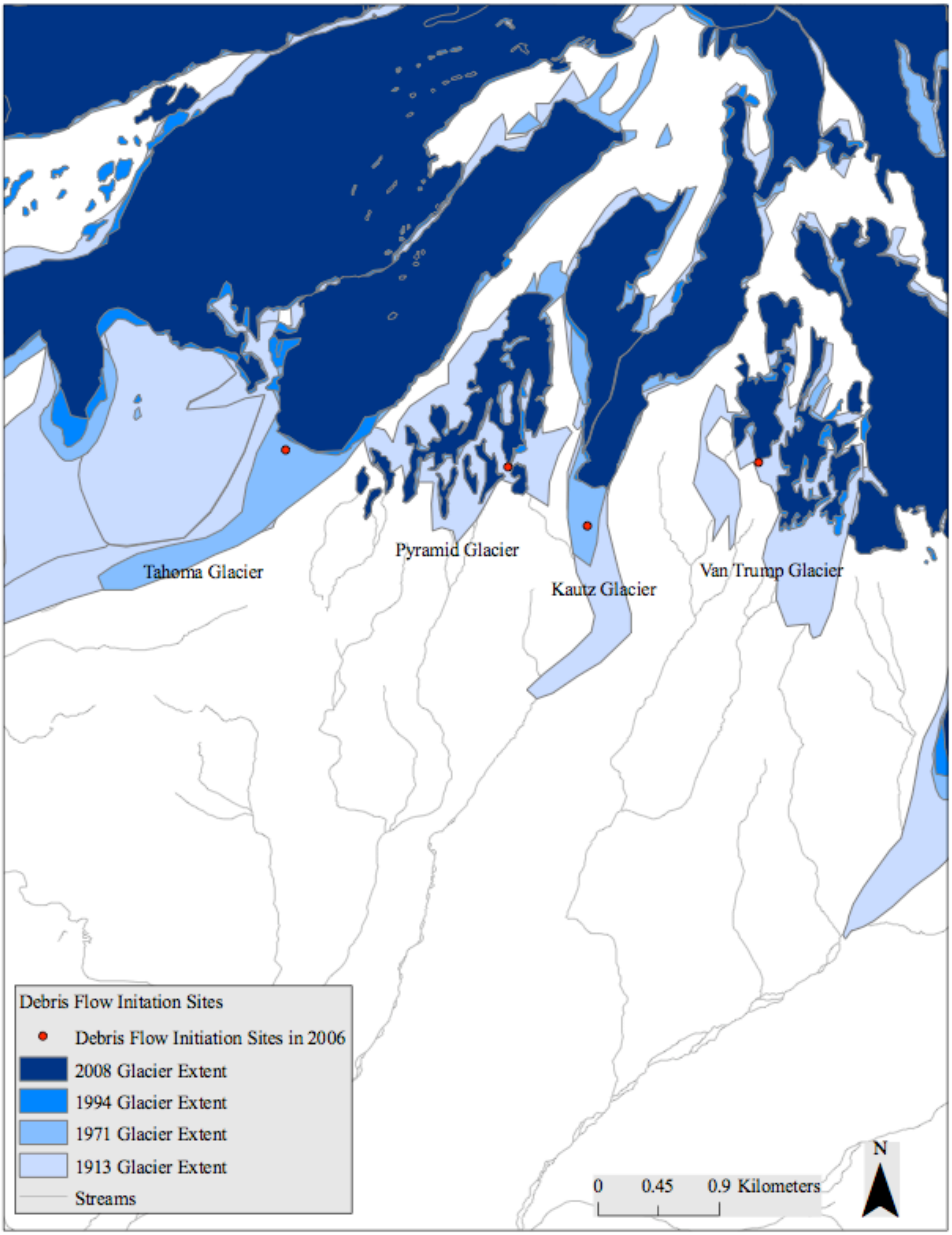

Figure 15. Spatial extent of south-facing glaciers for the year 1913, 1971, and 1994 from Nylen (2004) with all gullies that contributed to debris flow initiation in 2006 indicated.

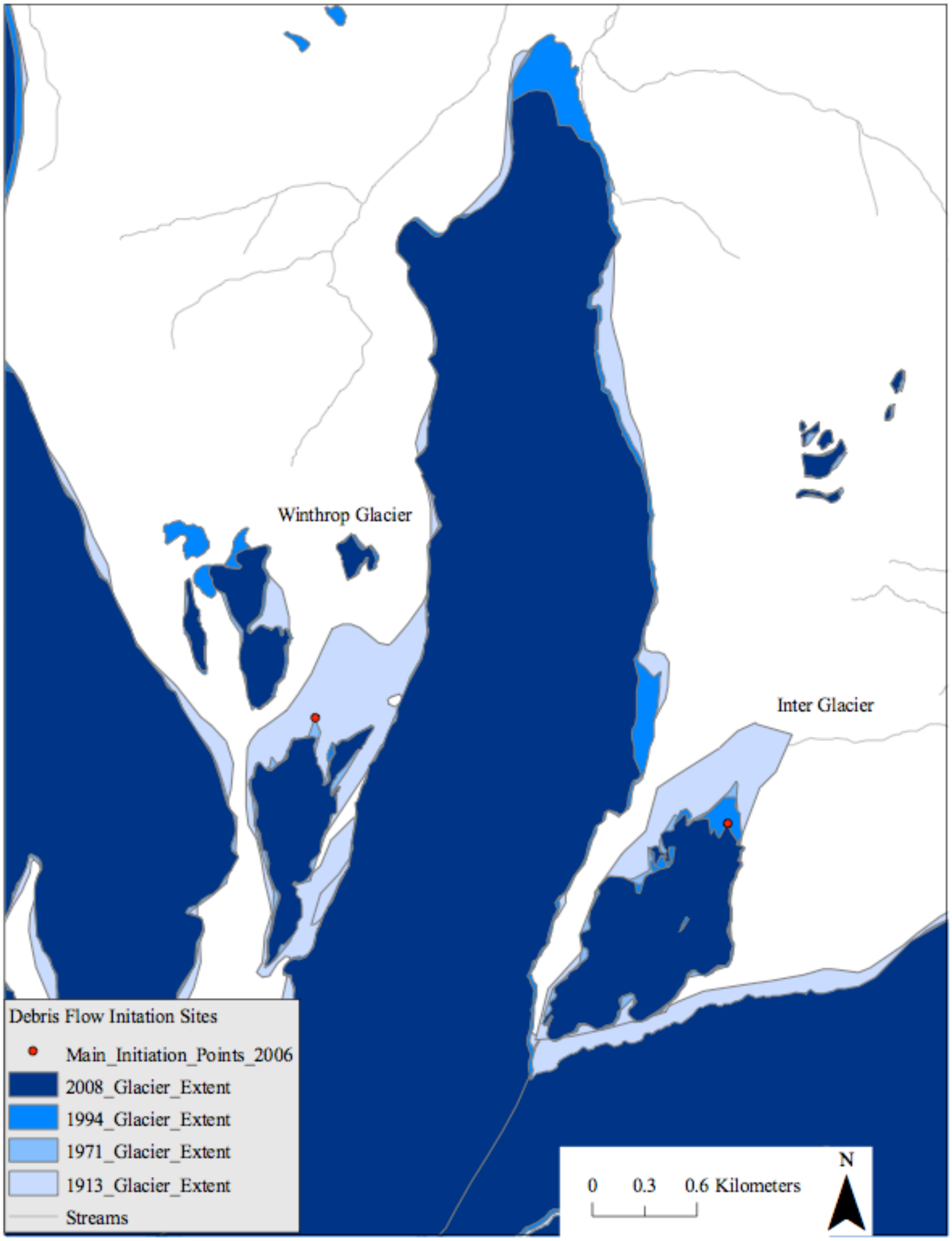

Figure 16. Spatial extent of north-facing glaciers for the years 1913, 1971, and 1994 from Nylen (2004) with all gullies that contributed to debris flow initiation in 2006 indicated.

Distance from the head of the gully that contributed to debris flow initiation to the 2008 glacier or glacier remnant is zero for all initiation sites except those of South Tahoma, Kautz, and Winthrop Glaciers. The gullies that contribute to debris flows in Tahoma Creek are located on stagnant ice, over 100 m from the active terminus of South Tahoma Glacier, deposited by glacier retreat over tiered bedrock (C. Driedger, personal communication, 2008). The large debris covered stagnant ice terminus of Kautz Glacier (Nylen, 2004) is nearly 500 m downslope of the active glacier terminus and is incised by a channel that drains glacier meltwater and may have contributed to the 2006 debris flow in Kautz Creek. The debris flow that occurred in 2006 in the West Fork of the White River initiated below a fragment of the 1913 extent of Winthrop Glacier. The gully is separated from the fragment of Winthrop Glacier by a proglacial lake approximately 200 m in length.

Debris flows are only located in area exposed by glacier retreat. Loss of glacier ice can be measured in a number of ways, including retreat of the terminus of a glacier, total change in glacier area or volume, and glacier fragmentation. The three glacier termini that have retreated the farthest during the period 1913 to 1994 are that of South Tahoma, Nisqually, and Kautz Glaciers, with 2677, 2131, and 1589 m retreat along the midline of the glacier termini, respectively (Nylen, 2004). These glaciers have been associated with more debris flows during the period 1926 to 2008 than any other glaciers on Mt. Rainier or 28, 8, and 6 debris flows, respectively (Walder and Driedger, 1994). South-facing glaciers, such as South Tahoma Nisqually, and Kautz, have been associated with debris flows more often than north-facing glaciers and the average retreat of south-facing glaciers 1913 to 2004 was 1755 m where it was only 530 m for north-facing glaciers (Nylen, 2004). Yet, it is important to note that since 1980, the termini of all glaciers on Mt. Rainier have retreated, with the exception of Emmons, Winthrop, and Cowlitz Glaciers (Nylen, 2004). The termini of the majority of Mt. Rainier glaciers have retreated during the period 1913 to 1994 and few glaciers have experienced debris flows **(Fig. 17).** Glacier terminus position change, or cumulative retreat and advance, from 1913 to 1994 using data from Nylen (2004) for glaciers associated with debris flows and glaciers not associated with debris flows during the same period is not significantly different (Welch Two Sample t-test: t-statistic = -1.32, df = 3.65, p-value = 0.264). Change in glacier area during the period 1913 to 1994 for debris flow and non-debris flow producing glaciers during the same period does not appear to be different **(Fig. 18)**. The majority of glaciers on Mt. Rainier lost zero to fifty percent of the 1913 area during the interval 1913 to 1994 (Nylen, 2004). Change in total glacier area from 1913 to 1994 for debris flow producing glaciers and glaciers not associated with debris flows during the same period is not significantly different (Welch Two Sample t-test: t-statistic = -0.968, df = 8.08, p-value = 0.361). Glacier volume has typically remained constant or decreased during the period 1913 to 2004 for the glaciers analyzed by Nylen (2004) (**Fig. 19).** Of the glaciers associated with debris flow initiation, South Tahoma, Kautz, and Winthrop Glaciers have each decreased in volume and Nisqually Glacier, which last experienced a debris flow in the 1980s, increased in volume slightly during the period 1913 to 2004. Many of the glaciers associated with debris flow initiation in 2006 have fragmented and retreated. Fragmentation may be quantified through changes in glacier perimeter during the period 1913 to 1994, as fragmentation would lead to an increase in glacier perimeter. Change in glacier perimeter during the period 1913 to 1994 for debris flow and non-debris flow producing glaciers appear similar (**Fig. 20)**. Glacier change, whether defined by terminus position, area, volume, or perimeter, does not appear to define glaciers associated with debris flow initiation. Yet, debris flows that initiated in 2006 are predominantly associated with small glaciers or glacier fragments less than 2.3 km^2 in size (**Fig. 21)**. The difference between 2008 glacier area for glaciers associated with debris flows during the period 1994 to 2008 and glaciers not associated with debris flows during the same period is significant (Welch Two Sample t-test: t-statistic = -3.57, df = 19.7, p-value = 0.002). The average size of a glacier associated with a 2006 debris flow is 1.1 km^2, while the average size of all glaciers on Mt. Rainier is 3.8 km^2.

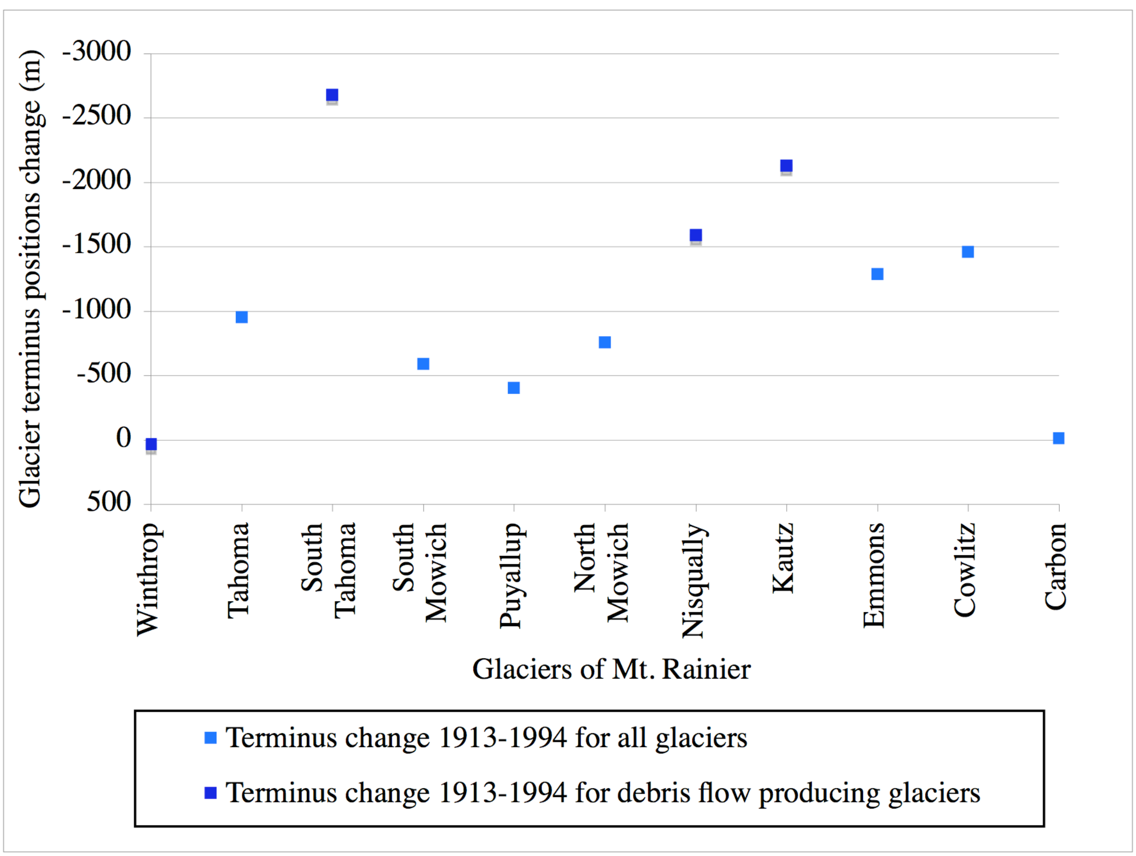

Figure 17. Cumulative change in glacier terminus position from 1913 to 1994 for debris flow producing glaciers and all other glaciers (Nylen, 2004).

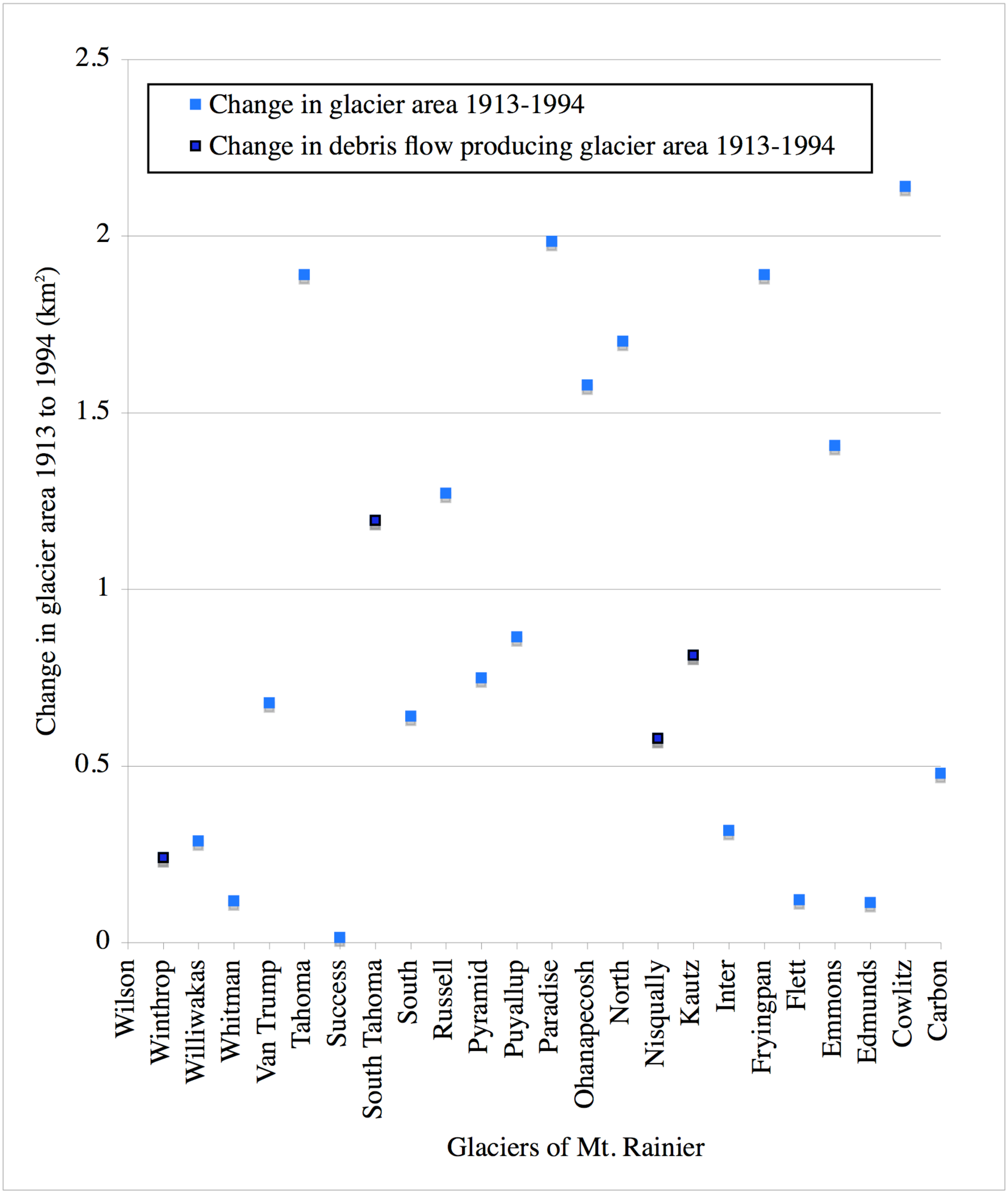

Figure 18. Cumulative change in glacier area from 1913 to 1994 for debris flow producing glaciers and all other glaciers (Nylen, 2004).

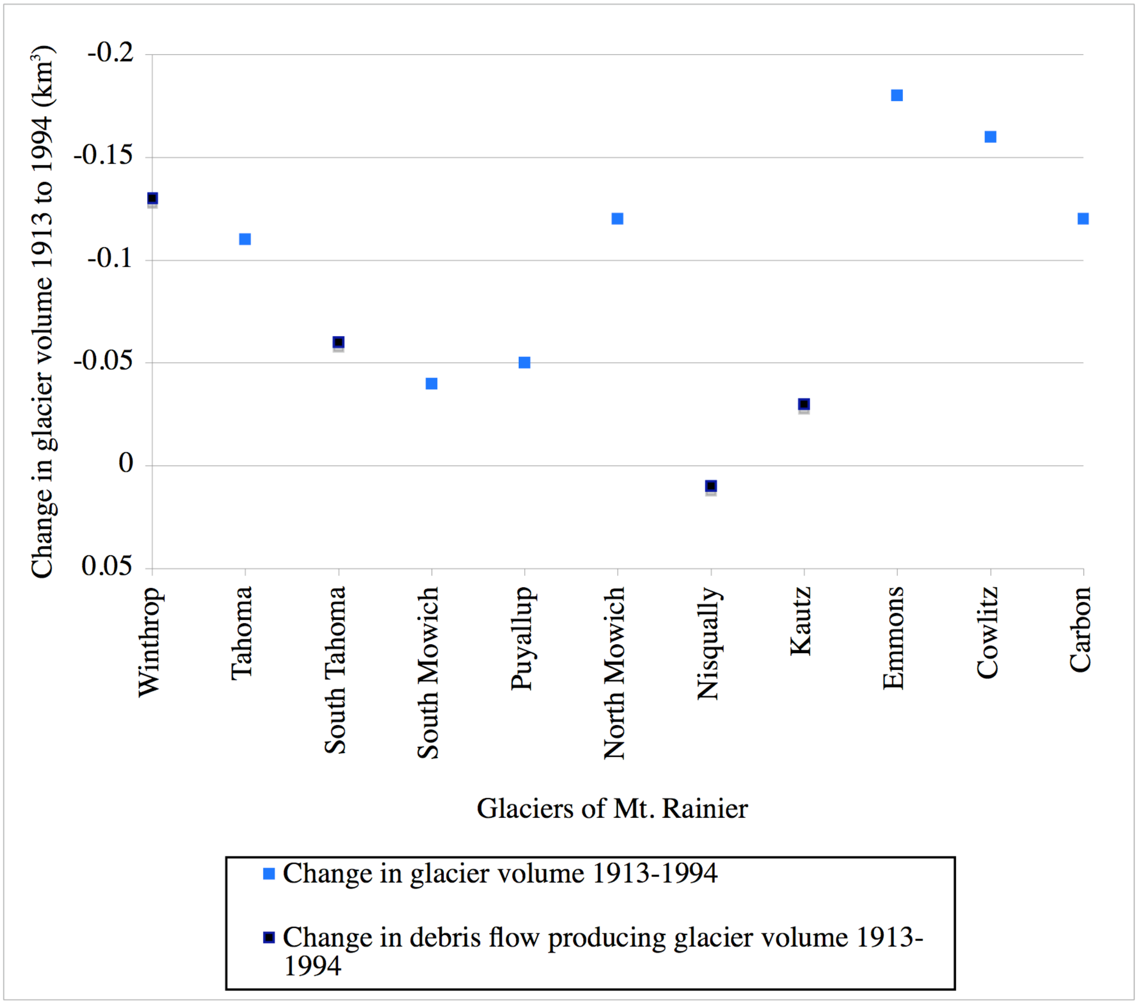

Figure 19. Cumulative change in glacier volume from 1913 to 1994 for all glaciers and debris flow producing glaciers (Nylen, 2004). Negative values indicate glacier thinning.

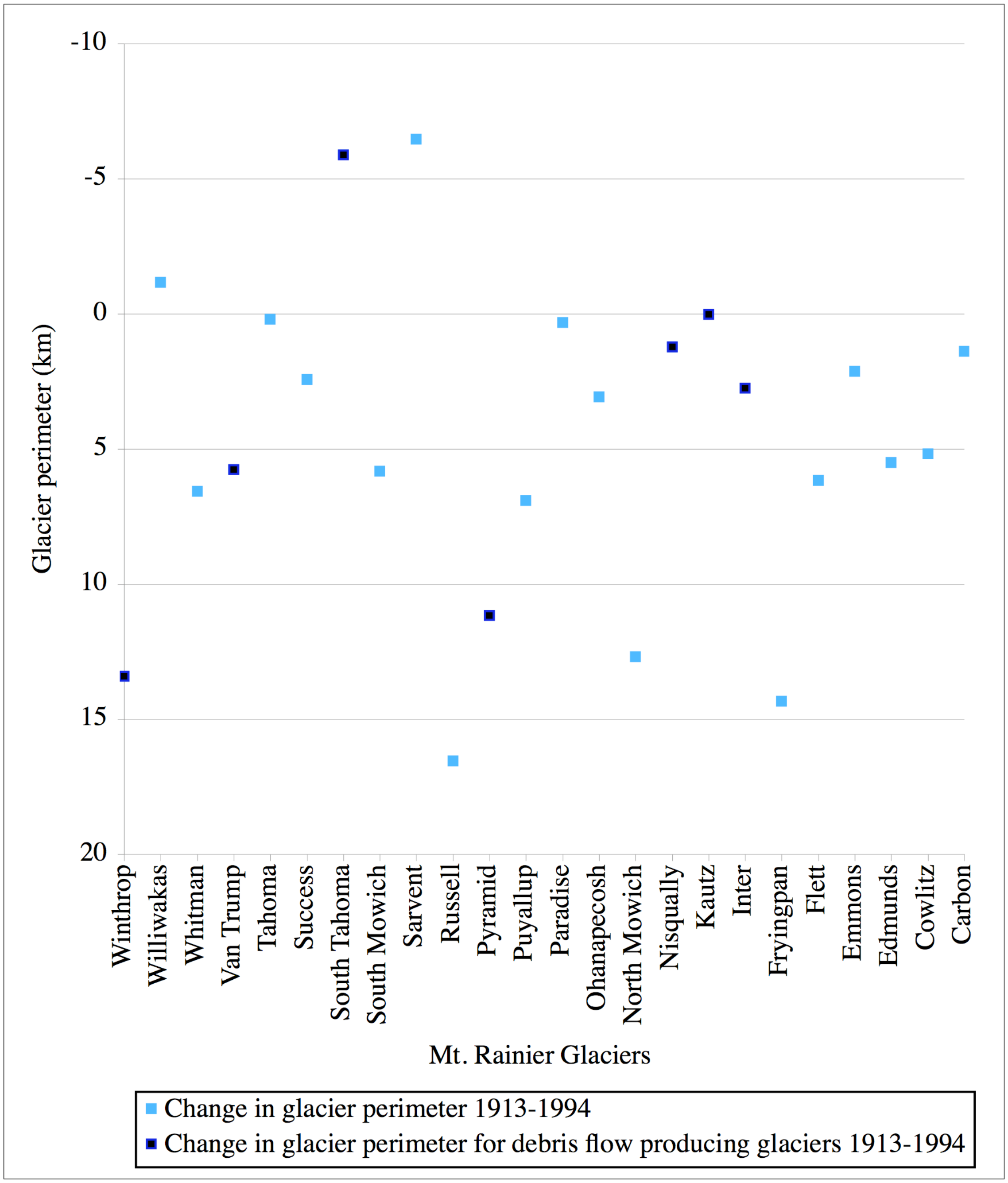

Figure 20. Change in glacier perimeter from 1913 to 1994 for all glaciers and debris flow producing glaciers (Nylen, 2004). Positive values indicate increases in glacier perimeter and possible fragmentation.

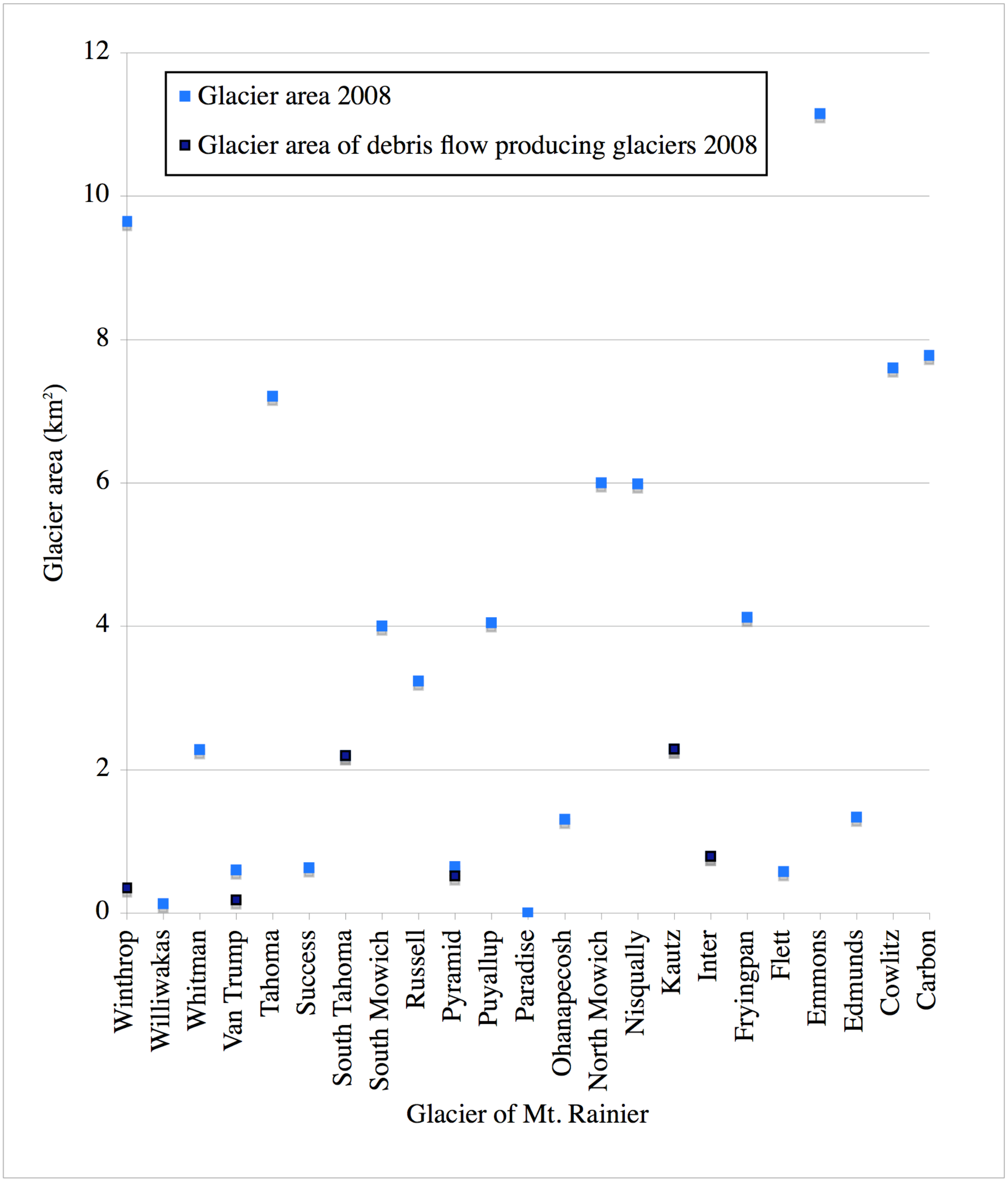

Figure 21. Size of all glaciers on Mt. Rainier and those associated with debris flow initiation in 2006.

Debris Cover

Limited data exist regarding the debris-covered area of glaciers. Debris cover can be obscured by snow cover in aerial photographs and few glacier mapping efforts have even included estimates of fractional debris cover (Nylen, 2004). Of the few glaciers where the extent of debris cover has been mapped or reconstructed, no relationship between debris flow initiation and fractional debris cover has been discerned (**Table 9**).

Table 10. Available data regarding fractional debris covered area of debris flow and non-debris flow producing glaciers (Nylen, 2004). Debris flow producing glaciers are highlighted.

	Fractional debris covered glacier area (%)		
Glacier	1913	1971	1994
Carbon	66	42	45
Cowlitz	10	15	24
Emmons	10	28	30
Nisqually	10	18	23
South Tahoma	13	23	21
Tahoma	16	15	17

Elevation

All initiation sites are located at elevations greater than 1937 m. Historically, debris flows have initiated predominantly at glaciers with termini located at lower elevations, such as those of South Tahoma Glaciers, Kautz, and Nisqually Glaciers (Walder and Driedger, 1994). Debris flows that occurred in 2001, 2003, 2005, and 2006 occurred at higher elevation glacier termini such as Pyramid and Van Trump Glaciers, as well as fragments of glaciers located at high elevation, such as Winthrop Glacier (**Fig. 22**).

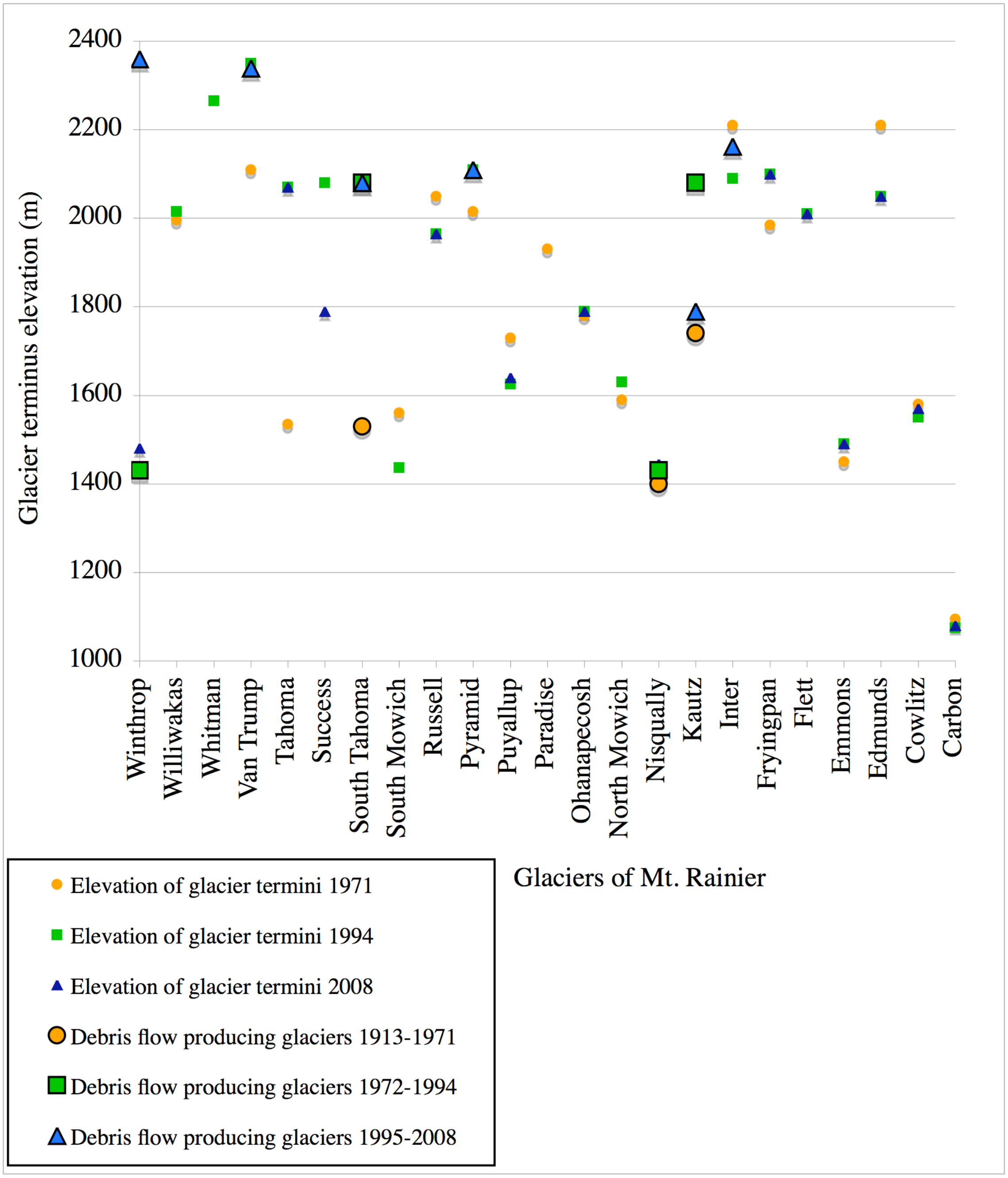

Figure 22. Elevations of glacier termini for the years 1913, 1971, 1994, and 2008. The elevation of glacier termini associated with debris flows during the periods 1913 to 1971, 1972 to 1994, and 1995 to 2008 are indicated with reference to the end of each interval considered: 1971, 1994, and 2008. All glacier termini elevations correspond to the main body of a glacier, but debris flows may initiate at glacier fragments located at a different elevation than that of the main body of the glaciers. This was the case for the 2006 debris flow from Winthrop Glacier. The elevation of debris flow producing glacier fragment is indicated in addition to the terminus of the main body of the glacier.

Orientation

Prior to 2001, only one debris flow was recorded in association with a north-facing glacier (Winthrop Glacier: August 9, 1987) and all other debris flows were associated with south facing glaciers (Walder and Driedger, 1994). In 2006, two debris flows were triggered in association with north-facing glaciers; Inter and Winthrop Glaciers. Analysis of the aspect of all known debris flow initiation sites, reveals that debris flow initiation sites have a variety of orientations although the majority of debris flows have historically originated at southwest trending glaciers and fewer debris flows have initiated at northeast trending glaciers **(Fig. 23)**.

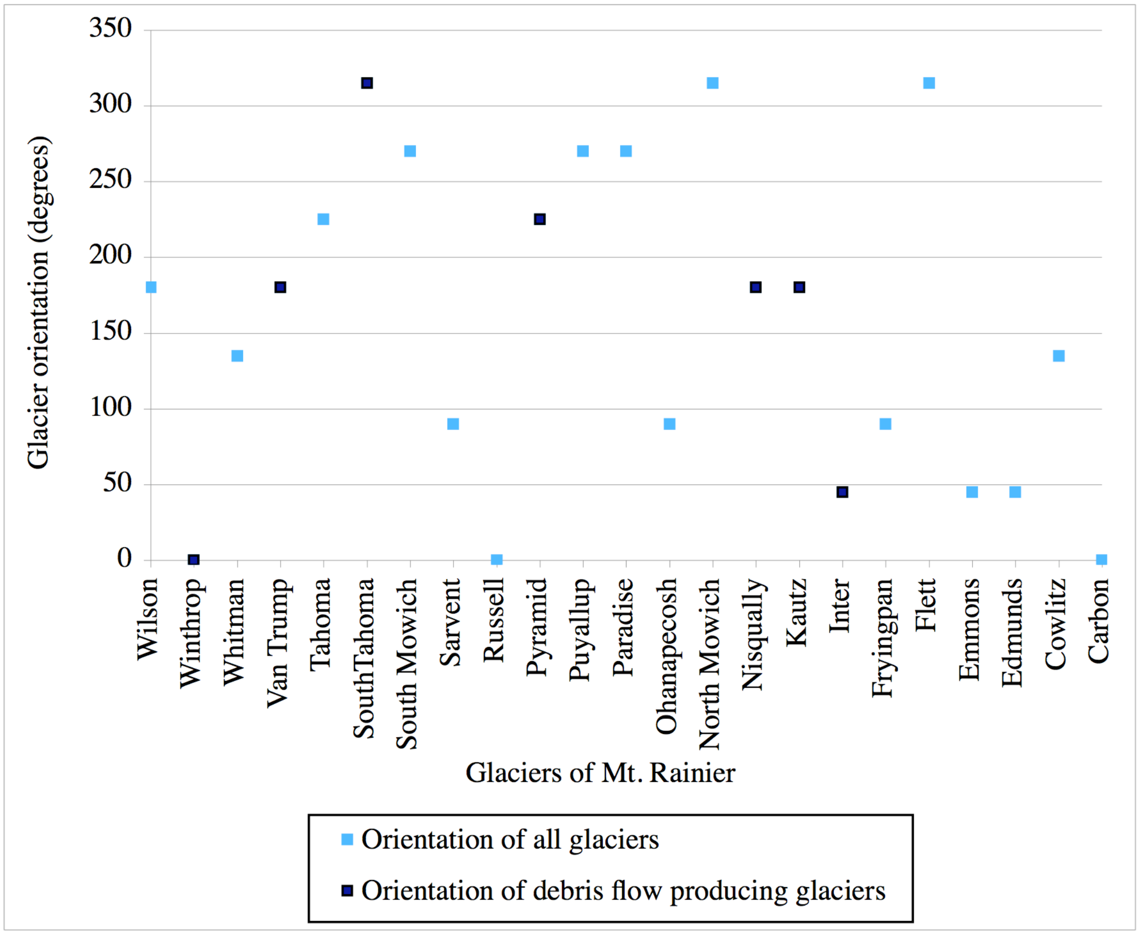

Figure 23. Orientation of glaciers associated with debris flows and the orientation of all Mt. Rainier glaciers.

Gradient

All debris flows, with the exception of the 2006 debris flow from Winthrop Glacier, initiated on slopes steeper than 20°. Average gradient for a 100 m radius circle surrounding each debris flow initiation site is 32°. The average debris flow channel gradient at initiation for the first approximately 9 m of the longitudinal profile of the debris flow track 39° (**Fig. 24)**. Both types of calculated gradients are important for debris flow initiation as channel gradient will aid sediment mobilization and the steepness of surrounding terrain will aid flow concentration. Nearly all proglacial areas exposed by recent retreat contain slopes sufficient for debris flow initiation **(Fig. 25)**. Glacier retreat during the period 1971 to 1994 exposed slopes steeper than retreat during either 1913 to 1971 or 1994 to 2008 **(Table 11).**

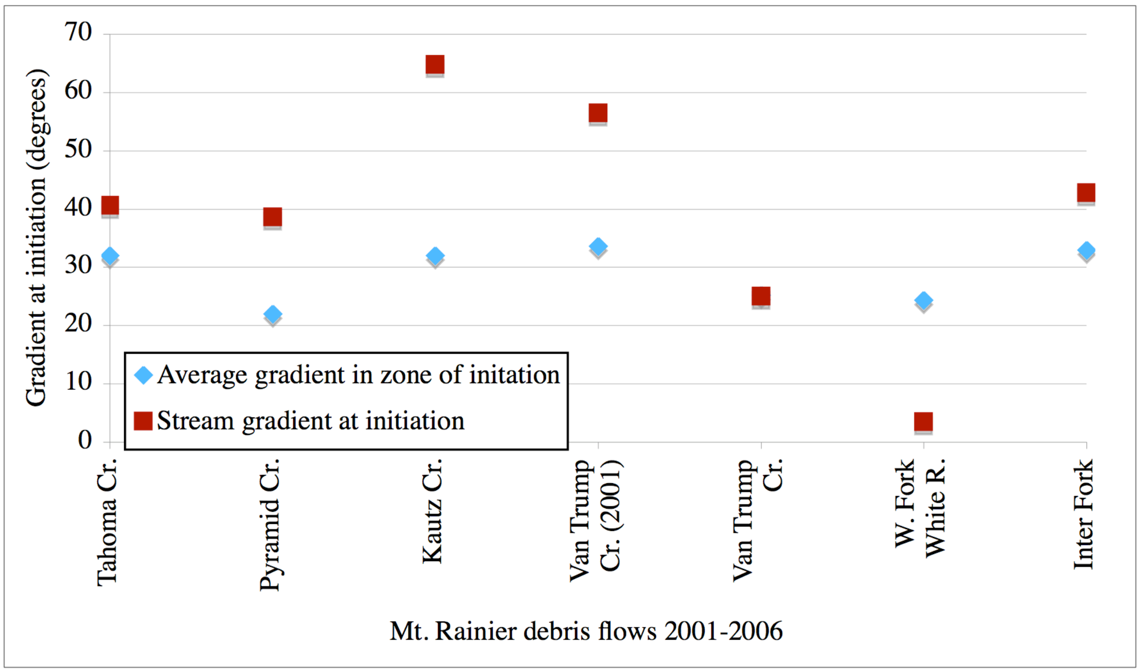

Figure 24. Average gradient (degrees) within a 100 m radius of each debris flow initiation site and the channel gradient of the debris flow track at initiation.

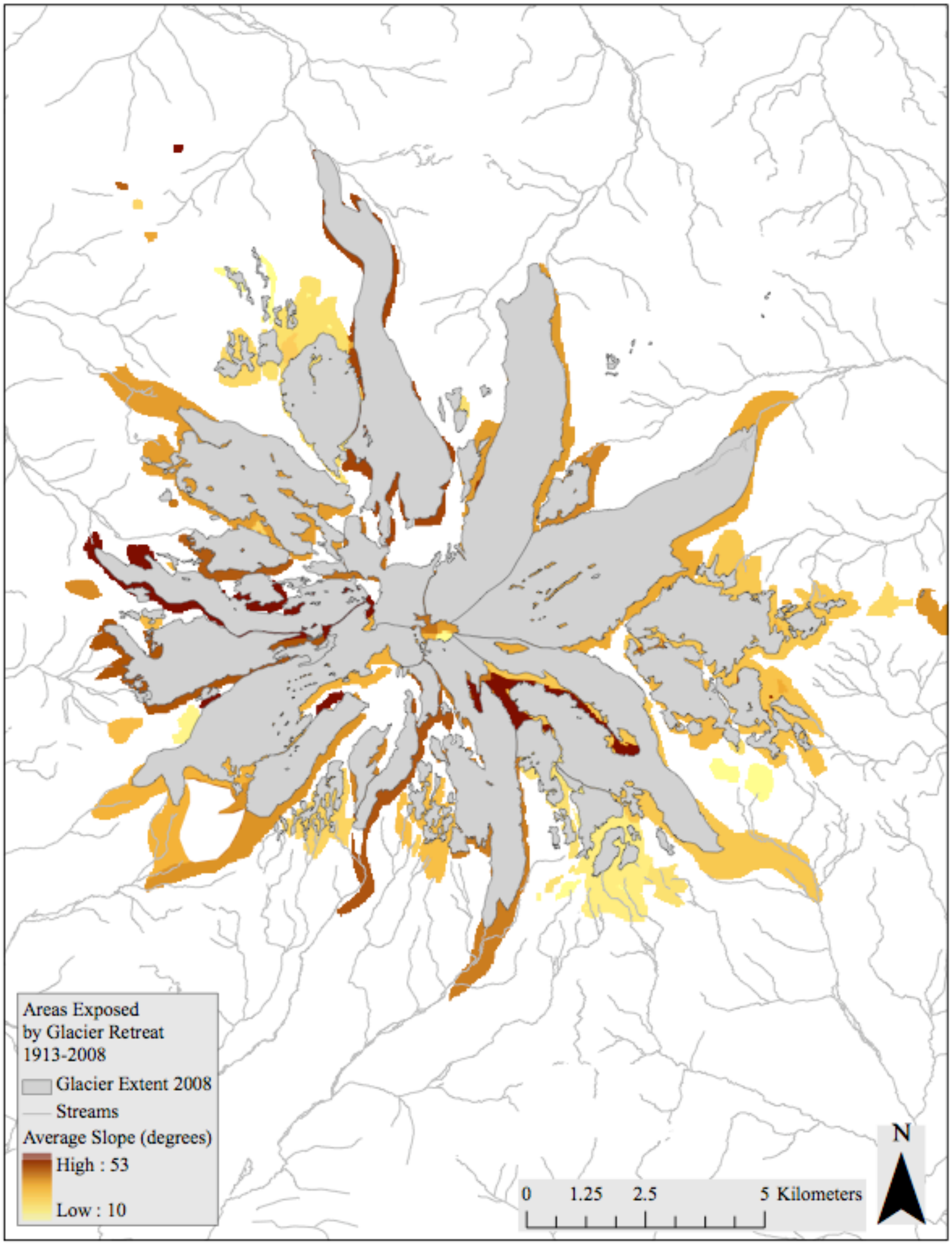

Figure 25. Average gradient in degrees of zones exposed by glacier retreat from 1913 to 2008 calculated from LiDAR.

Table 11. Slopes exposed by glacier retreat for the periods 1913 to 1971, 1971 to 1994, and 1994 to 2008.

	1913-1971	1971-1994	1994-2008
Area (m^2) exposed by glacier retreat with slopes:			
Values > 40	1043826	262764	125594
40 < Values > 30	8983888	3693280	2118098
30 < Values > 20	11078626	738716	2213925
20 < Values > 10	757776	1715	272252
Percent of total area exposed with slopes:			
Values > 40	4.77	5.59	2.66
40 < Values > 30	41.1	78.6	44.8
30 < Values > 20	50.7	15.7	46.8
20 < Values > 10	3.47	0.0365	5.76

Debris Flow Path Characteristics

All recent debris flows initiated in gullies fed by glacier meltwater and followed existing stream channels. Debris flows frequently transitioned from debris flow to flood-like behavior and ultimately deposited material and irreversibly transformed into hyperconcentrated flows or floods without formation of a distinct debris flow terminus or fan. For experiments involving poorly sorted saturated sediment values of run-out efficiency, or path length divided by descent height or the elevation difference between initiation and deposition (L/H), for debris flows with volumes smaller than 10^5 m^3 is 2 to 4 and values of L/H greater than 2 are indicative of channelized run-out (Iverson, 1997). For Mt. Rainier only debris flows in Van Trump Creek conform to expectations regarding run-out efficiency **(Fig. 26)**. Debris flows from Van Trump Creek are somewhat unique as multiple debris flows have deposited in a span of several hundred meters at the confluence of the Nisqually River and have formed a levee of sediment. Van Trump

Creek is not a braided river, but rather a single-thread stream that is confined by bedrock in reaches. All other recent debris flows from Mt. Rainier traversed multi-thread streams or braided rivers and deposited sediment seemingly in discontinuous pulses upstream of the confluence with a major river. Unexpectedly high values for run-out efficiency for debris flow paths other than Van Trump Creek may indicate that debris flow path lengths were overestimated. Evidence of deposition observed at the farthest downstream location was likely the result of debris flows transitioning into hyperconcentrated flow or flood phases and continuing to deposit sediment. Multiple debris flows have originated from initiation locations adjacent to South Tahoma, Pyramid, and Van Trump Glaciers and separate flows deposited material in the similar locations, suggesting that the downstream most extent of damage is predictable even if it is the result of hyperconcentrated flow rather than debris flow behavior at the downstream most locations.

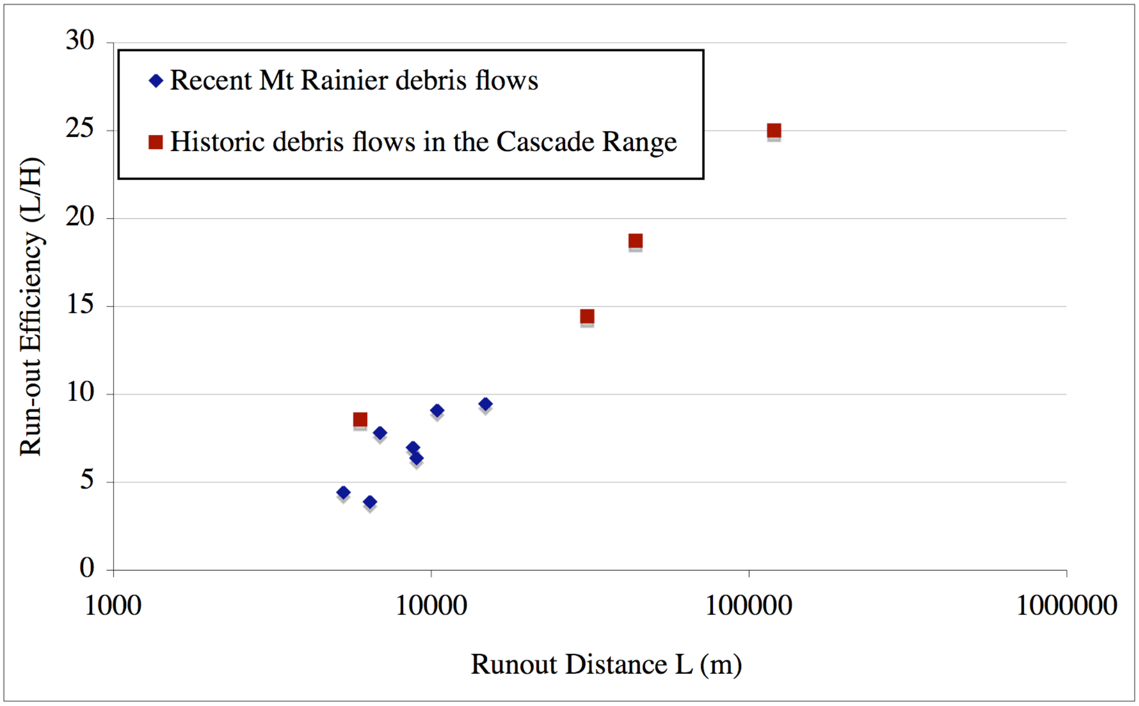

Figure 26. Initiation elevation and debris flow path length for Mt. Rainier debris flows other debris flows or lahars. Comparison data from the Cascade Range includes the Osceola mudflow from Mt. Rainier, Muddy River debris flow from Mt. Saint Helens, South Fork Toutle debris flow from Mt. Saint Helens, and Separation Creek debris flow from Three Sisters (Iverson, 1997). For Mt. Rainier, each unique debris flow path 2001 to 2008 is included as a single point, although multiple debris flows from South Tahoma, Pyramid, and Van Trump Glaciers are known to have initiated and deposited at similar locations.

As zones of debris flow behavior were defined in this study, the erosion, transition or transport, and deposition zones of debris flow path have average lengths of 2.0 km, 4.8 km, and 1.8 km and mean channel gradients of 26°, 12°, and 7°, respectively **(Fig. 27, 28, and 29).** Gradient associated with zones of debris flow behavior and transition points is shown in **Figure 30.** Channel width and valley floor width did not change appreciably in transition zones of debris flow behavior. Debris flow damage in the erosion zone is predominantly confined to the existing stream channel. In the transport and deposition zones, some debris flow paths deviate from the stream channel and the presence of trees in the appears to cause debris flow paths to bifurcate or transition into hyperconcentrated flows or floods by depositing material. The Pyramid and Kautz Creek debris flows deviate from the stream channels most noticeably due to the minimal topographic relief between the two stream channels **(See Appendix B)**. The introduction of a volume of water at a tributary junction may lead to changes in debris flow behavior. The majority of debris flow paths encounter three tributaries before transitioning from erosion to transport.

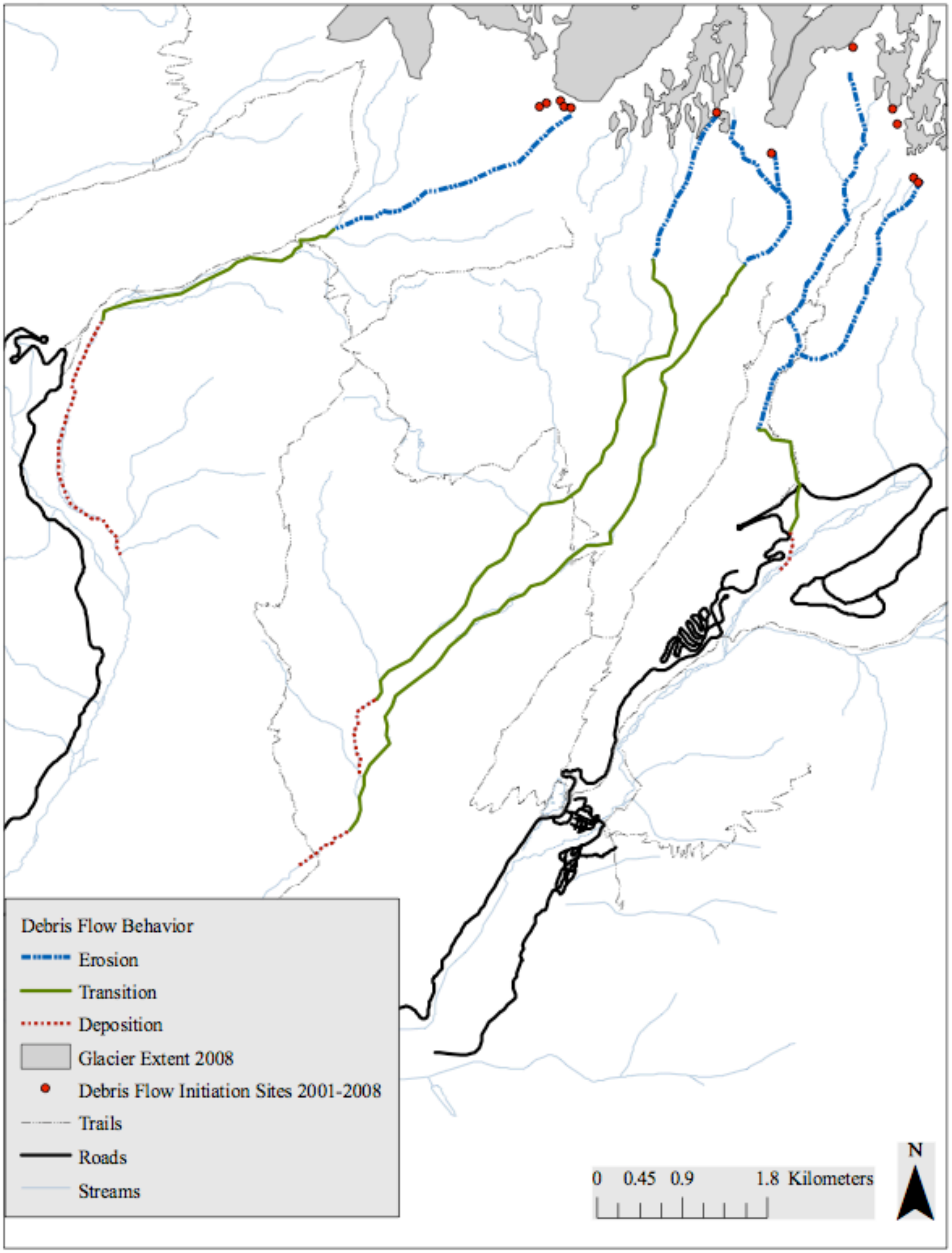

Figure 27. Recent debris flow paths from south-facing glaciers with zones of debris flow behavior and Mt. Rainier National Park.

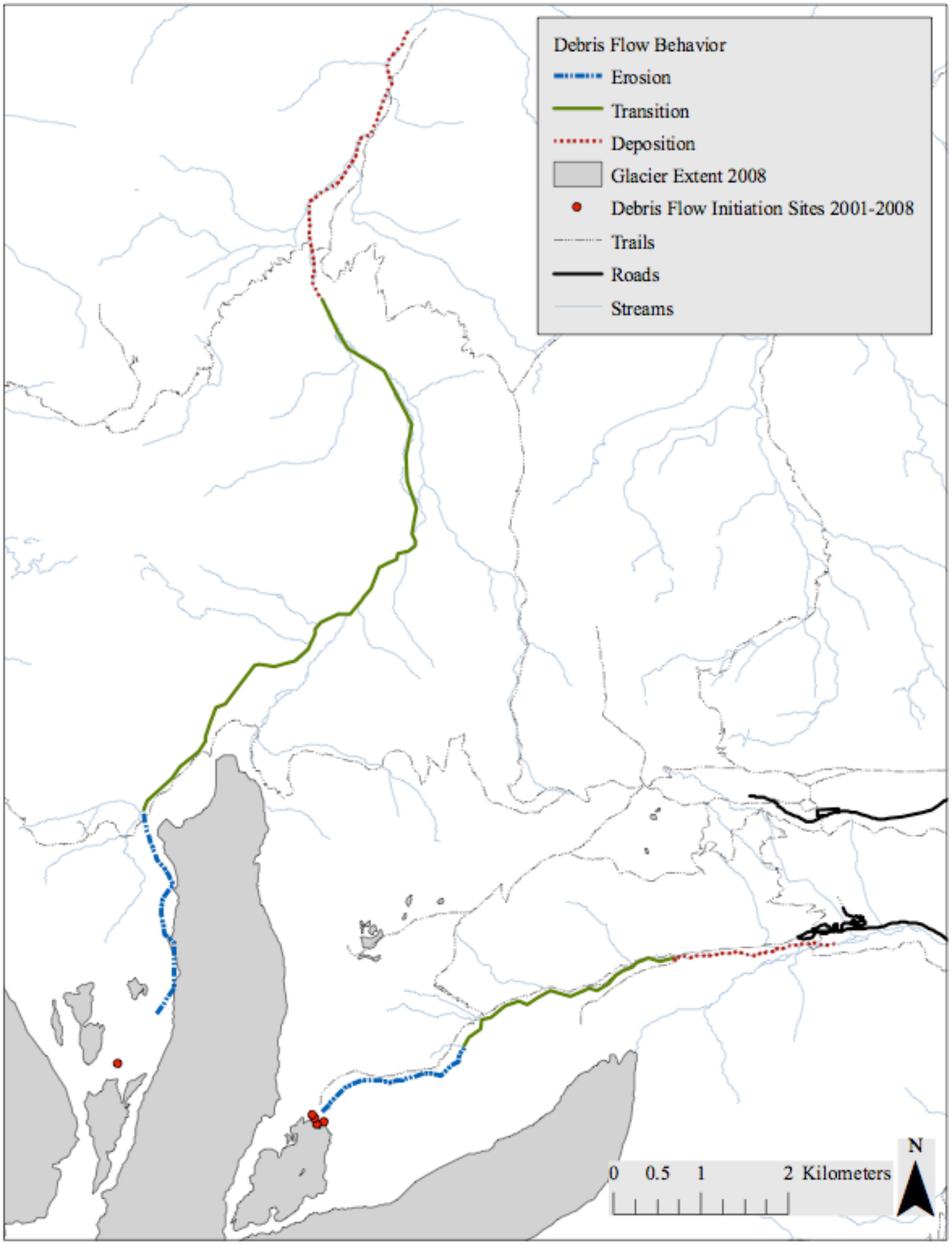

Figure 28. Recent debris flow paths from north-facing glaciers with zones of debris flow behavior and Mt. Rainier National Park.

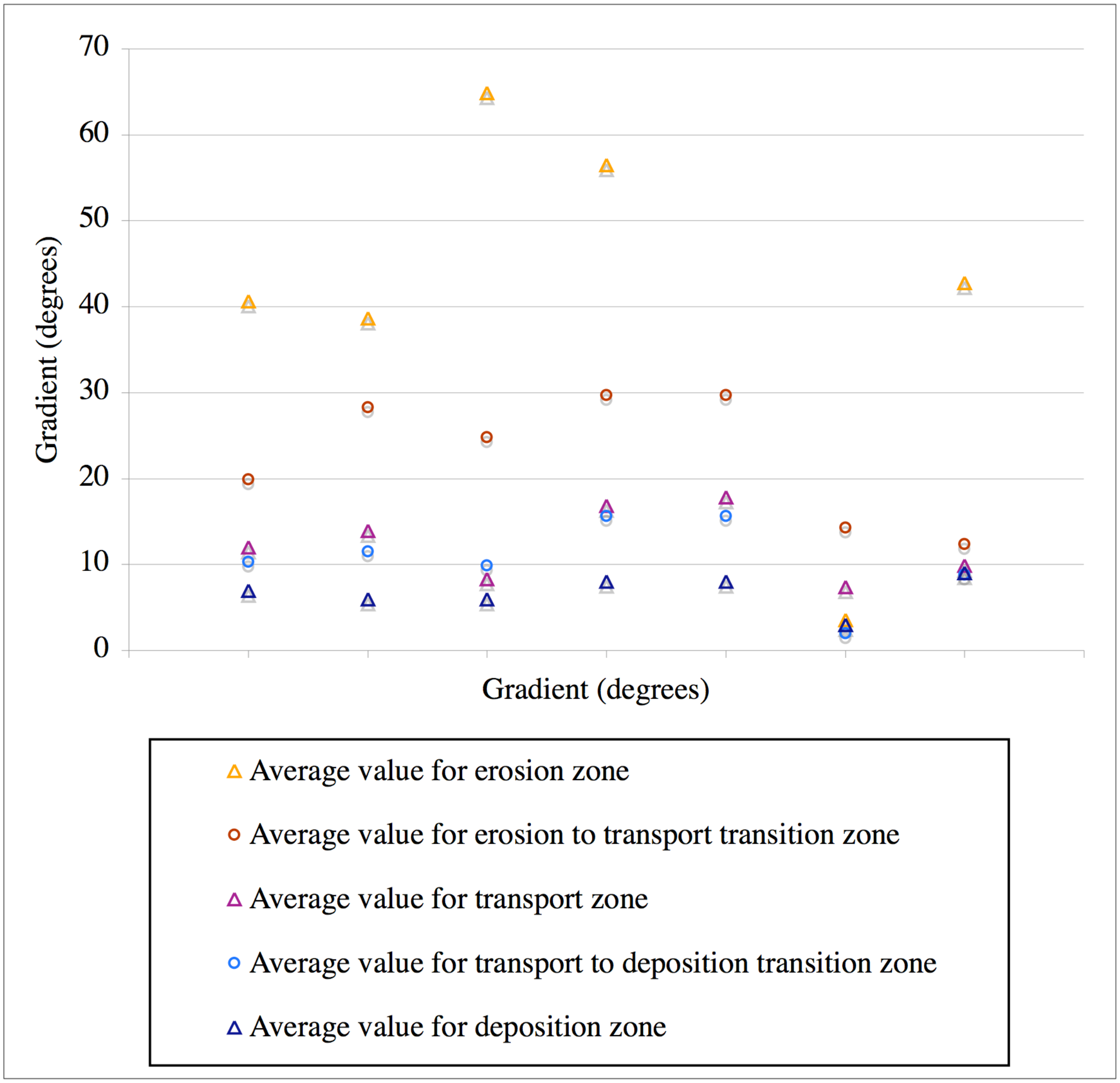

Figure 29. Gradient for zones and transitions in debris flow behavoir. From left to right, debris flow paths include Tahoma Creek, Pyramid Creek, Kautz Creek, Van Trump Creek in 2001, Van Trump Creek for the years 2003, 2005, and 2006, West Fork of the White River, and Inter Fork of the White River. Where insufficient evidence for the location of a zone or transition in debris flow behavior exists, data has been excluded.

Chapter 4 – Discussion

Debris Flow Initiation

Recent data on debris flow initiation suggest that debris flows initiate close to glacier margins in gullies or steep-walled, glacier meltwater channels that predate debris flow initiation. The location of future debris flow initiation is partially controlled by the retreat of the glacier boundaries. Presently, all glacier termini are located at elevations greater than 1940 m and nearly all proglacial areas exposed by glacier retreat are characterized by slopes sufficient for debris flow initiation. There is a seemingly limitless supply of un-vegetated, unconsolidated material remaining from Pleistocene and LIA glacier retreat. The most recent period of glacier retreat, 1994 to 2008, has not exposed particularly steeper gradients than other periods of retreat. Other metrics potentially related to the abundance of water sources, unconsolidated sediment, or steep slopes such the magnitude of glacier retreat, orientation, and debris covered area do not differentiate glaciers associated with debris flow initiation from the total population of glaciers.

I hypothesize that debris flows initiate close to glacier margins because glaciers provide a mechanism by which to concentrate water flow and deliver it quickly to adjacent unstable slopes. Glacier melt during the summer ablation season may ensure the exposure of relatively impermeable glacier ice at the toe of a glacier and the evolution of a channelized en- and sub-glacial drainage networks that act to increase the volume and velocity of meltwater and rainwater exiting the glacier (Fountain and Walder, 1998). At the end of the ablation season, the smooth bare ice rapidly transmits supraglacial meltwater or rainwater, either into crevasses and the en-glacial drainage network, or from the glacier surface into proglacial sediments (Fountain and Walder, 1998). Without a layer of firn, or old snow to retain and retard the flow of meltwater and rainwater, the response of englacial and subglacial networks below the ablation zone to meltwater variations and rainfall is rapid and peaked (Fountain and Walder, 1998). Where runoff from firn can be delayed days to weeks, runoff from ice is delayed only hours (Jansson et al., 2003). Cavities may be the dominant form of glacier drainage at the beginning of the ablation season as cavities can survive from one ablation season to the next due to sliding of the glacier (Walder and Driedger, 1994; Fountain and Walder, 1998). The glacier drainage system transforms from a linked-cavity network into a more channelized network at a rated determined by the retreat of the firn or seasonal snow line from the toe of the glacier (Fountain and Walder, 1998; Nienow et al., 1998). The cavity-linked system can become channelized as a result of water pressure variations from rapid ablation or heavy rainstorms (Walder and Driedger, 1994; Nienow and others, 1998). A single precipitation event or a series of small events can trigger changes in a drainage network (Nienow et al., 1998). A sudden increase in meltwater production due to unusually hot dry weather can also create changes in the glacier drainage network (Walder and Driedger, 1994). The en- and sub-glacial drainage networks at the end of the ablation season act to channelize water and effectively extend the stream network, resulting in rapid transmission of meltwater and or rainwater to the proglacial area.

Geomorphic Setting and Interpreted Initiation Mechanism of Debris Flow Initiation

Glacial meltwater, snowmelt, and rainwater exit the supra-, en-, or sub-glacial drainage networks of either massive or fragmented glaciers and enter proglacial areas characterized by two basic geomorphic settings depending on size and retreat characteristic of the upslope glacier. Both types are characterized by the presence of pre-existing gullies or meltwater channels **(Table 12)**. ***Type 1*** geomorphic setting contains gullies formed in unconsolidated material at the edge of small fragmented glaciers or perennial ice. Meltwater from glacier fragments drains into a single gully. ***Type 2*** geomorphic setting contains glaciers that have remained largely intact during retreat, or are composed primarily of a single large mass, and multiple gullies drain glacier meltwater and may contribute to debris flow initiation. Classification of a glacier as massive or fragmented can be based on the ratio of glacier area to perimeter. In 1994, massive glaciers, such as South Tahoma, Kautz, and Winthrop, had ratios of glacier area to perimeter greater than 200, whereas for fragmented glaciers, such as Pyramid and Van Trump, the ratio was less than 40.

Table 12. Geomorphic setting of debris flow initiation

Source Glacier	Glacier Morphology	Glacier Retreat	Initiation Location	Gully	Type
South Tahoma	Massive	Significant	Terminus	Multiple	Type 2
Pyramid	Fragmented	Significant	Fragment	Single	Type 1
Van Trump	Fragmented	Significant	Fragment	Single	Type 1
Kautz	Massive	Significant	Terminus	Single	Type 1
Inter	Massive	Minimal	Terminus	Multiple	Type 2
Winthrop	-	Minimal	Fragment	Single	Type 1

The cause of debris flow initiation during either dry or wet weather is interpreted as the result of a small surge of discharge from glacier meltwater, rainwater, or a combination of sources, that undercuts the steep-sided walls of the gully, causing slumping of volumes of sediment into the stream channel and the formation of a debris flow. The only direct observation of a Mt. Rainier debris flow shortly after initiation occurred on August 13, 2001 by USGS CVO scientists and described by Vallance et al. (2002). This flow began as the result of glacier meltwater emanating from the lateral margin of Kautz Glacier. Park Rangers at Mt. Rainier National Park observed discoloration in Van Trump Creek streamflow, or an early pulse of the debris flow, which allowed later helicopter reconnaissance by USGS CVO scientists J.W. Vallance, C.L. Driedger, W.E. Scott, and others on August 14 and 15, 2001. The meltwater diversion, estimated to be 1 m^3s^{-1}, caused slumping from the walls of a gully that originated in the left lateral moraine of Kautz Glacier. Slumping rapidly transformed the meltwater stream into a debris flow, which then entered Van Trump Park and caused rapid erosion of a new channel segment. The debris flow then entered Van Trump Creek, eventually depositing at the confluence of the Nisqually River. The observers wrote:

"On August 13, a meltwater stream on the east margin of Kautz Glacier began to spill muddy water into the Van Trump basin though a 2- to 3-m deep notch in the left-lateral moraine at the lower end of Wapowety Cleaver at an altitude of about 2682 m. Beginning about 9:00pm on August 14, the flow incised a channel through the 5 to 30 m thick ground moraine in Van Trump Park and formed the largest of a series of debris flows. Progressive slumping of the glacial deposits during the next few hours formed additional debris flows and created a steep-walled channel that was visible at first light on August 15." (Vallance et al., 2002)

Walder and Driedger (1994) concluded that the majority of debris flows from South Tahoma and Kautz Glaciers during the period 1985 to 1992 were the result of glacier outburst floods. Previous authors have also argued that debris flows from South Tahoma Glacier are the result of glacier outburst floods (Richardson, 1968; Driedger and Fountain, 1989). Evidence of glacier outburst floods includes the observation of a debris flow in Tahoma Creek on July 26, 1988 by USGS hydrologist C.H. Swift and the subsequent estimation of the hydrograph for the event (Walder and Driedger, 1994). It was concluded that normal stream flow could not have produced the observed volume of water as the observed hydrograph from the zone of debris flow conveyance was approximately equal to total daily summer streamflow. Small volume outburst floods are likely produced by many glaciers and outbursts have been observed that did not transform into a debris flows (Walder and Driedger, 1994). Estimates of maximum discharge for historical glacier outburst floods range from 1 to 300,000 m^3s^{-1} (cited in Roberts, 2005). Proglacial geomorphology and saturation due to groundwater flow or melt of stagnant ice likely determine whether a glacier meltwater surge can transform into a debris flow. Frozen ground may have promoted flow concentration and mobilization of debris above a frozen layer (Kneisel, 2007). Chiarle et al. (2007) notes the potential importance of melt of ground ice in slope instability and promotion of glacier floods that transform into debris flows. The geographic extent of stagnant buried glacier ice, ice lenses, or permafrost is not known for Mt. Rainier and can only be detected on site through the temperature at the bottom of winter snowpack or geoelectrical, electromagnetic, and seismic soundings (Chiarle et al., 2007).

Walder and Driedger (1994) reported many wet-weather debris flows as the result of rainfall and glacier outburst floods. Walder and Driedger have later have revised their conclusions (C. Driedger, personal communcation, 2008).

"Be advised that since the Walder-Driedger papers were written in the mid 1990s, we now recognize that glacial outbursts are not always the culprit. Collapse of steep-angled saturated sediment due to increased stream discharge is a common process in debris flow initiation--perhaps more common as an initiation process than debris flows." (C. Driedger, personal communication, 2008)

The inferred initiation mechanism for wet and dry weather debris flows is the same, slumping of sediment from steep-walled gullies, but during rainstorms additional mechanisms may contribute to flow concentration and mobilization of sediment. Debris flows from Mt. Rainier in 2003, 2005, and 2006 occurred from rainstorms when the mountain was largely snow-free (P. Kennard, personal communication, 2008; Parker, 2009). Floods from rainfall are greatest in late summer when snowpack is at a minimum, thermally induced runoff is the greatest, and channelized glacial drainage networks have developed (Collins, 1998). Snow-free ground responds rapidly to rainfall with respect to infiltration and transmission of water to stream channels (Collins, 1998; Chiarle et al., 2007). Rainfall on ice remaining at the end of the ablation season or ash mantled bare ground may produce channelization and sediment entrainment in rills or gullies contributing to debris flow initiation.

Error Analysis

Major sources of potential error in this study are derived from incomplete historic records of debris flow initiation and from interpretation of debris flows from 2003, 2005, and 2006 (P. Kennard, personal communication, 2008). Debris flow evidence from 2003 and 2005 was not formally documented by personnel at Mt. Rainier National Park and subsequent debris flows in 2006 overprinted or erased past evidence. The present study relies heavily on observations by Mt. Rainier National Park Geomorphologist P. Kennard. Interpretation of debris flow initiation site locations, transitions in downstream behavior, and deposition location from data analysis and field observations are major sources of possible error. This study also relies heavily on data pertaining to Mt. Rainier glaciers by Nylen (2004) that is derived from interpretation of historic maps.

The identification of debris flow initiation sites is a major source of uncertainty in this study. Initiation sites were located by tracing a channel with evidence of debris flow deposits upslope to the head of the channel. When several tributaries coalesced upstream of the main channel marked by debris flow deposits, it was not possible to determine which tributaries contributed to debris flow initiation and which did not. All possible contributing sites to debris flow initiation were analyzed in this study. All gullies were characterized by a steep headwall, except for that of Winthrop Glacier, which is located at the edge of a glacier lake. Points used to define initiation sites were placed at gully headwalls. Debris flow initiation sites for Van Trump and Kautz Creek debris flows are difficult to identify, as numerous gullies contribute to each stream channel (**Table 13**). As gullies do not appreciably change in size or shape after the occurrence of a debris flow, it is not possible to distinguish which gullies contributed to debris flows in 2003. 2005, 2006 in Van Trump Creek. The initiation site for debris flows in Pyramid Creek is easy to identify, while the initiation site for Kautz Creek is quite difficult to identify. A single gully at a fragment of Pyramid Glacier that enters Pyramid Creek is assumed to be the Pyramid Glacier initiation site. Nearby to this glacier fragment, on the opposite side of the drainage divide, is a gully that extends into Kautz Creek. Debris flows in Kautz Creek may originate at the gully near Pyramid Glacier or may originate in a gully located on the stagnant ice terminus of Kautz Glacier.

Table 13. Strength of evidence used to define initiation and deposition locations of recent debris flows from Mt. Rainier.

Year	Date	Debris Flow Channel	Initiation Location	Deposition Location
2006	4-6-Nov	Van Trump Cr.	Low	High
		Pyramid Cr.	High	Low
		W. Fork of the White R.	High	Low
		Inter Fork of the White R.	High	Low
		Tahoma Cr.	Moderate	Low
		Kautz Cr.	Low	High
2005	29-Sep	Pyramid Cr.	High	Low
		Tahoma Cr.	Moderate	Low
		Kautz Cr.	Low	High
		Van Trump	Low	High
2003	20-Oct	Van Trump Cr.	Low	High
2001	14-Aug	Van Trump Cr.	High	High

Identification of debris flow initiation sites has implications for the conclusions drawn in this study. Debris flows are assumed to have initiated at glacier ice, as the head of each gully was at glacier ice for all initiation sites with the exception of South Tahoma, Kautz, and Winthrop Glaciers where the head of the gully was at stagnant ice or a proglacial lake. Yet, the upslope reaches of debris flow tracks are characterized by erosion that is indistinguishable in the field and through aerial photo analysis as erosion due to debris flows or due to normal fluvial processes. Initiation sites have been marked at the upstream extent of this zone, but all areas along this zone may have contributed to debris flow initiation as subtle changes in gully width are visible on imagery. It is possible that debris flows initiated not at the gully head wall, but at another point downslope or in a zone extending from the gully head wall to the end of the steep-walled channel. In this work, the zone where debris flow initiation may have occurred in is described as the erosion zone of debris flow behavior. If debris flow initiation occurred along the zone defined by erosion, rather than at the head of this zone, then initiation did not occur at glacier ice. The upper reaches of all zones of erosion are in areas exposed by glacier retreat, but debris flow initiation site are no longer located in the area exposed by the most recent period of glacier retreat.

Another source of error pertains to interpretation of field evidence observed during reconnaissance in 2008. Division of debris flow paths into zones characterized by erosion, transport, deposition relies extensively on qualitative descriptions made during field reconnaissance. Evidence used to define debris flow paths, namely the presence of boulder levees and reverse grading, was not observed continuously in the transport and deposition zones of paths. Rather, debris flow channels contained evidence of alternation between erosion and deposition, as well as alternation between evidence of debris flows and hyperconcentrated flows. It is very difficult to make clear distinctions between debris flow behavior types, let alone the downstream extent of debris flow deposits, particularly in channels where multiple debris flows have occurred. Debris flows appeared to transition into hyperconcentrated flows or floods without the formation of a debris flow fan or significant deposition. Deposits of woody debris at the downstream extent of flow paths were largely absent. For the few flow paths where wood snouts were located, the debris may not be representative of the length of the debris flow as woody debris could have been rafted downstream by flooding rather than carried by the debris flow. This was the case for the longest debris flow path in 2006 or the West Fork of the White River debris flow from a fragment of Winthrop Glacier. The run-out efficiency (L/H) for all debris flow paths, except that of Van Trump Creek, was greater than expected. Iverson (1997) notes that the run-out efficiency for all debris flows less than 10^5 m^3 in volume is two to four. It likely that debris flow path lengths were overestimated due to the continuum of debris flow, hyperconcentrated flow, and flood behavior observed during field reconnaissance. The deposition locations for recent debris flows, particularly debris flows in West Fork of the White River, Pyramid Creek, Kautz Creek, and Tahoma Creek are difficult to identify. In the case of the West Fork of the White River debris flow, the entire path length was not able to be surveyed during reconnaissance in 2008. The location of the wood snout of the debris flow was reported from reconnaissance by P. Kennard (personal communication, 2008; see Appendix B). Debris flows in Pyramid and Kautz Creeks interact. Debris flows in Pyramid Creek deposit sporadically in Pyramid Creek, but may also coalesce with debris flows in Kautz Creek and increase the debris flow deposits in Kautz Creek (Appendix B). Tahoma Creek has had numerous debris flows and previous authors describe a zone of deposition rather than discrete locations (Walder and Driedger, 1994). The most recent debris flow deposit cannot be distinguished from past debris flow deposits even days or weeks afterwards, let alone two years afterwards (C. Driedger, personal communication, 2008). Zones of deposition defined in this study have utility for managers at Mt. Rainier National Park, even if they are in fact zones of hyperconcentrated flow rather than solely debris flow deposition. Considerable damage to park infrastructure such as roads and trails occurred in zones of deposition. The downstream extent of deposition in a particular channel, whether it is interpreted as debris flow or hyperconcentrated flow deposits, is remarkably similar for multiple events.

Historical glacier coverages as well as the 2008 glacier coverage used in this study are not exact. Please see Nylen (2004) for a full description of the error inherent in field surveys and aerial photo analysis used to create the maps on which his analyses are based. Error in interpretation of aerial photos and LiDAR data, particularly difficulties in distinguishing snow covered glacier ice from seasonal snow, likely resulted in an overestimation of the 2008 glacier coverage. The 2008 glacier coverage can only be used for certain analyses, such as terminus position and elevation, and considerable additional work would be needed to replicate all of Nylen's analyses for 2008. Lack of correspondence between various glacier metrics and debris flow initiation may be the result of error present in glacier data, the infrequency of debris flow initiation, incomplete debris flow initiation data, or simply because it may not be possible to accurately compare debris flow initiation to the few dates for which glacier data is available. For example, to compare glacier terminus elevation in 1971, 1994, and 2008 with debris flow initiation it is necessary to compare the terminus elevation of glaciers that had debris flows during the periods of 1913 to 1971, 1972 to 1994, and 1995 to 2008 to the terminus elevation of glaciers that did not produce debris flows. A range of debris flow initiation dates must be considered in reference to each single date of glacier coverage because otherwise it would not be possible to make a comparison between glaciers associated with debris flows and those not associated with debris flows. Or even more specifically, only one debris flow occurred in 1971, but during the period from 1913 to 1971 14 debris flows occurred in association with three different glaciers. The range of values for glacier metrics for debris flow producing glaciers minimizes the importance of errors related to the creation of glacier data for comparison of glaciers with and without a history of debris flow initiation. Errors in the calculation of individual glacier metrics are overshadowed by overlapping range of values for glaciers associated with debris flows and glaciers not associated with debris flows.

Climate Change and Debris Flow Initiation on Mt. Rainier

Debris flow timing, geography, and initiation mechanisms may be impacted by hydrologic patterns in PNW altered by climate change. The PNW has experienced 0.83° warming in the 20th Century and it is expected that future warming will continue at a rate of 0.27° per decade (Mote, 2003). Cool season precipitation is expected to be higher, with increased variability and persistence (Mote, 2003; Stewart et al., 2005; Hamlet and Lettenmaier, 2007;). Snowmelt across the PNW is occurring earlier in the spring (Stewart et al., 2005). Observed and predicted climate change in the PNW region have not yet been confirmed and quantified for Mt. Rainier National Park. At 1646 m, the Paradise Ranger Station meteorological station on Mt. Rainier during the period 1954 to 1994 saw no increase in summer temperature and a decline in winter snowfall of 5.1 cm per year (Nylen, 2004). It is unknown how these trends related to elsewhere on Mt. Rainier, particularly the rain shadow on the eastern side. Available data regarding extreme precipitation or stream discharge do not show significant trends toward increasing values. Peak discharge for water years 1943 to 2008 for the closest USGS stream gage to Mt. Rainier, Nisqually River Near National, Washington (Gage Number 12082500), shows a slight increase in peak discharge, but the trend is not statistically significant with an r-squared value of 0.1 (USGS, NWIS, 2009). Monthly maximum storm depth data is only available for the Longmire meteorological station (Station Number 454764) for the period 1978 to 1999 and much of the data during that interval is missing (NOAA, NCDC, 2009).

There is a slight trend of increasing maximum storm depth, but the trend not statistically significant with an r-squared value of 0.03 (NOAA, NCDC, 2009). Preliminary analysis of USGS gage Nisqually River, Mineral Creek near Mineral, Washington (Gage Number 12083000) indicates that spring melt during the period 1997 to 2006 occurred > 20 days earlier and was approximately 2 m^3s^{-1} greater during the period 1948 to 1957 (E. Copeland, unpublished data). The impacts of climate change within Mt. Rainier National Park are clearly visible, but the altered patterns of temperature and precipitation that are directly responsible are unclear. For example, tree recruitment in subalpine meadows has occurred continuously since 1930 on the west side of Mt. Rainier and to a more limited extent on the east side (Rochefort and Peterson, 1996). Tree establishment is attributed to a combination of snow accumulation and summertime temperature and precipitation (Rochefort and Peterson, 1996). Additional work is needed to translate how regional climate change is impacting recent trends in the timing and magnitude of temperature and moisture fluxes at Mt. Rainier. Moreover, increases in regional temperatures and retreat of glaciers on Mt. Rainer are ongoing since the end of the LIA. Climate change may have impacted geomorphic processes continuously since the end of the LIA or it may have been more influential in the past and not the present. The coupling between climate change geomorphic and response is obscure and will remain obscure until the impacts of climate change at Mt. Rainier can be quantified and shown to be of a severity not experienced since the end of the LIA.

Ongoing glacier retreat on Mt. Rainier may produce more debris flow initiation sites as initiation is associated with predominantly small glaciers and glacier fragments or perennial ice. As debris flows initiate near glacier margins, future debris flow initiation sites will be located at higher elevations and possibly steeper gradients as glaciers retreat upslope. Higher annual temperatures may lead to changes in glacier dynamics resulting in debris flows from glaciers that have not historically produced debris flows, or simply more dry-weather debris flows as greater volumes of en- or sub-glacier water develop and fail. Dry weather glacier outburst floods that result in debris flows are only produced by a small subset of Mt. Rainier glaciers, which are the more massive ones such as South Tahoma, Kautz, and Nisqually Glaciers. These glaciers are contained by steep-walled, unvegetated moraines and their retreat over tiered bedrock has deposited debris covered stagnant ice (Walder and Driedger, 1994). The small, fragmented glaciers that have recently initiated debris flows for the first time, including Van Trump and Pyramid, are not surrounded by steep canyon-like lateral moraines. Past evidence suggests that if additional small, fragmented glaciers are to initiate debris flows, it is unlikely that they will occur during dry-weather as the result of glacier outburst floods. Small, fragmented glacier may lack sufficient en- or sub-glacial storage for a pulse of glacier meltwater to initiate a debris flow. Glacier retreat and a possible reduction of seasonally frozen ground may lead to exposure of unconsolidated unstable sediment and slope instability. Changing rainstorm characteristics may result in more frequent debris flow triggering events or potentially changes in initiation site geography. Parker (2009) found that debris flow producing storms for Mt. Rainier and Mt. Hood are characterized by high freezing levels altitude and little antecedent snow-water equivalent (SWE) suggesting that precipitation was delivered to bare ground at high elevations as rain rather than snow. All Mt. Rainier debris flows during the period 2001 to 2006 initiated above 1800 m and climate predictions for the PNW suggest that the combined effect of both increased precipitation and temperature will result in decreased snow pack below 1800 m (Mote, 2003). Increased precipitation in the form of snow at elevations prone to debris flows, may counter balance the effects of warmer temperatures on glacier retreat and exposure of unstable sediment. Warmer temperatures will also result in drying of the soil column (Mote, 2003). Decreased soil moisture might prevent creation of saturated conditions needed for debris flow initiation even as melt of glaciers and ground ice promotes saturation. In whatever ways climate change influences debris flow initiation, the downstream hazards associated with debris flows can be mitigated through application of knowledge of past debris flow path characteristics. The lengths of debris flow paths and the location of debris flow deposits are remarkably similar from year to year, suggesting these characteristics are controlled primarily by channel geomorphology. For example, debris flows in Van Trump Creek whether from a glacier outburst from a massive glacier or from rainfall from a fragmented glacier deposit in the same channel reach.

The present study cannot address whether recent climate changes have resulted in changes in debris flow frequency, as ancillary data such as dendrochronology would be needed to reconstruct the complete debris flow history of Mt. Rainier. It is very likely that small magnitude debris flows that failed to damage infrastructure went unnoticed or unrecorded and that apparent changes in initiation geography is indicative of renewed interest in debris flow hazards, rather than true changes. Two storms during the period 2001 to 2006 are responsible for all but two of the twelve debris flows. These high magnitude events focused attention on debris flows from Mt. Rainier and other Cascade Range volcanoes and led to inquiries regarding changing debris flow frequency. Flood frequency analysis using a Log-Pearson Type III Distribution and the nearest USGS stream gage to Mt. Rainier National Park, Nisqually River Near National, Washington

(Gage Number 12082500), shows that the 100-year flood for the 344 km^2 basin is 622 m^3s^{-1} (USGS, NWIS, 2009). The November 4 to 6, 2006 storm produced six debris flows on Mt. Rainier and 617 m^3s^{-1} discharge at the USGS stream gage, or the maximum discharge recorded during the 2006 water year and also for the available period of record, water years 1943 to 2008. For reference, in the Swiss Alps, the summers of 1987 and 2003 were characterized by rainstorms that triggered a seemingly remarkable number of debris flows, but further analysis using dendrochronology revealed that similar events had occurred historically (Stoffel et al., 2005). For Mt. Rainier, apparent changes in the frequency or seasonal timing of debris flows during the two periods for which a complete accounting of debris flow activity is assumed are inconclusive. Eighteen debris flows occurred from 1985 to 1992 with an average of 354 days between events and debris flows occurred on four unique dates 2001 to 2006 with an average of 309 days between events. The average day of year of the nine wet-weather debris flows that occurred during 9 storms from 1985 to 1992 is September 29th or 272 whereas the average day of year of the 11 debris flows that were the result of three storms in 2003, 2005, and 2006 is October 18th or 291. The average day of year of the 8 dry-weather debris flows that occurred 1985 to 1992 was August 18th or 230 and the single dry-weather debris flow that occurred in 2001 is August 14th or 226.

Climate Change and Debris Flow Initiation Globally

Analysis of changes in debris flow timing, geography, and triggering mechanisms are most often addressed using dendrochonology, as historic records are typically incomplete and perceived increases in debris flow frequency are often the result of changes in record keeping or the construction of infrastructure in debris flow prone areas (Stoffel et al., 2005). Dendrochonology is an invaluable tool, yet is limited spatially and temporally in application. Dendrochronology uses growth disturbances recorded in tree-rings as evidence for various types of damage associated with debris flows. Growth disturbances can be reaction or compression wood from the tilting of the stem, growth reductions or increases from destruction of the root mass, partial burial, decapitation or elimination of nearby trees, and scars (Stoffel and Beniston, 2006). Geomorphic mapping of a site is used to ensure that growth disturbances from snow avalanches or rockfalls are not confused as evidence of debris flows. Debris flow occurrence can only be reconstructed several hundred years but median tree-age is often a major limiting factor in reconstructing debris flow frequency. Only debris flows that exit stream channels and damage riparian vegetation can be dated, therefore the geomorphic history of the debris flow prone channel is of great importance. Channel incision reduces the potential for future dendrochronological evidence to be recorded (Bollschweiller, 2008). Small debris flows may follow existing stream channels or former debris flow tracks and cause no damage to nearby trees (Stoffel et al., 2005). Dendrochronological evidence of small debris flows may be subsequently destroyed or over-printed by larger debris flows.

Dendrochronology for the purpose of reconstructing debris flow chronology with respect to climate change has not been conducted in the Cascade Range. Osterkamp et al. (1986) used dendrochronology on Mt. Shasta, but raised the possibility of increasing debris flow frequency on as a result of patterns of relatively young (< 300 years) deposits and evidence of rapid incision of stream channels. Hupp (1984) predominantly dated trees growing on or near debris flow terraces on Mt. Shasta and concluded that dendrochronology matched existing historical records, but Pierson (2006) notes that the time needed for colonization, germination, and growth of the tree on a debris flow terrace varies substantially and cannot be used to date terrace formation precisely. Far more dendrogeomorphological studies have been conducted in the European Alps, but changes in debris flow frequency are either inconclusive or point to decreasing frequency (Stunk, 1992; van Steijn, 1996; Blijenberg, 1998; Jomelli et al., 2004; Stoffel, 2005). Numerous authors have found that debris flow frequency was high in the 1980s in glaciated and deglaciated regions, but debris flow frequency had not increased (van Steijn, 1996; Blijenberg, 1998; Stoffel, 2005; Stoffel and Beniston, 2006; Pelfini and Santilli, 2008; Stoffel and Bollschweiler, 2008). Stoffel et al. (2005) used tree-ring analysis in the Valais region of the Swiss Alps to reconstruct past debris flow activity and found that the apparent above average number of periglacial debris flows 1987 to present was due to incomplete historical observations. Debris flows occurred more frequently during the 19th century, following the LIA maximum, than present. Stoffel (2005) concluded from a population of 53 recorded debris flows dating from 1605 that the seasonality of debris flows had shifted towards the fall. From the 19th century to 1947, all debris flows occurred June to August, but during the period 1948 to 2002, all debris flows occurred August to September and the shift in debris flow seasonality was associated with an increase in extreme precipitation capable triggering debris flows during the same months (Rebetez et al., 1997). Chiarle et al. (2007) note that in the Italian, Swiss, and French Alps the majority of debris flows are triggered by heavy, prolonged periods of rainfall that occurr in late summer, while fewer debris flows are caused by brief, localized rainstorms or drainage of ice-marginal lakes in early summer. Future decreases in summer precipitation and increases in spring and fall precipitation are predicted for the Swiss Alps and will likely further decrease the frequency of debris flow initiation (Stoffel and Beniston, 2006). In the French Alps, there have been observed increases in extreme summer rainfall since the 1980s and a decrease in the number of freezing days (Jomelli et al., 2004). Observed climate trends may have led to initiation sites shifting to higher elevations, climate trends do not necessarily explain why debris flow frequency has elevations, however climate trends do not explain why debris flow frequency has decreased from 1950 to 2000 (Jomelli et al., 2004). Jomelli et al. (2004) note that debris flows occurring at elevations below 2200 m and less than 400 m in length decreased where there has been no trend for debris flows initiating above 2200 m. The coupling between climate and debris flows is by no means simple.

Proposed Research for Mt. Rainier

Additional data analysis, field monitoring, and potentially climate modeling is needed to narrow the scope of potential links between changing climate and geomorphic hazards. Nylen (2004) reports that from 1954 to 1994 there was a decline in snowpack and no trend of increasing summer temperatures at Paradise Ranger Station, but it is unknown how these findings relate to elsewhere on the mountain, particularly the rain shadow on the eastern side. Moreover, is it unknown how the characteristics of precipitation producing wintertime or summertime storms, such as frequency and magnitude, have varied over time. Changes in the onset of spring snowmelt or fall snow accumulation are unknown. Trends in the frequency, duration, and timing of extreme temperature, precipitation, and streamflow should be analyzed from meteorological and stream flow gaging stations surrounding Mt. Rainier to quantify the magnitude of changes. Data collection on Mt. Rainier will also be needed to understand how or if local conditions relate to nearby stations. Distribution and data analysis of small temperature sensors on Mt. Rainier is currently being conducted by J. Lundquist of the University of Washington. Data from these temperature sensors may elucidate how the breath-taking topography of Mt. Rainier shapes local patterns of temperature and precipitation. Pairs of temperature sensors placed in the tree-canopy and in the soil duff also reveal when snowmelt occurred at a particular location. Trends in the timing of snowmelt or accumulation could also be revealed through longitudinal analysis of snow and glacier covered area in Landsat images from a particular calendar date. Late summer images are currently being used by students of A. Nolin at Oregon State University to address changes in glacier area, but future research may include images from April 1 when snow-water equivalent measurements are typically taken. The analyses described will quantify how climate change is impacting Mt. Rainier and will help constrain how debris flow initiation may change in the future.

There is evidence that some debris flow producing storms are not particularly large. The smallest magnitude storm that initiated a debris flow during the period 2001 to 2006 has a two-year recurrence interval according to monthly maximum storm depth data available for the Longmire meteorological station (Station Number 454764) for the period 1978 to 1999 (NOAA, NCDC, 2009). Additional research regarding the geomorphic settings that facilitate sediment mobilization after small inputs of rainfall is necessary. The scope research also needs to be broadened to include geomorphic hazards such as hyperconcentrated flows and floods that also mobilize and transport large volumes of sediment and likely occur more frequently than debris flows. The November 2006 storm triggered debris flows in only six channels yet damage to infrastructure in Mt. Rainier National Park was widespread, suggesting that debris flows were not the primary cause of damage parkwide (P. Kennard, personal communication, 2008). Beason (2007) found that the major rivers that drain Mt. Rainier are aggrading and few of these rivers are fed by streams that have experienced debris flows. His work suggests that debris flows are not solely responsible for aggradation. Large floods disproportionately mobilize sediment stored in channels (Major et al., 2000). Yet the largest flood of record for the Nisqually River resulted in aggradation (Beason, 2007). Channels in valley fill, like the braided rivers of Mt. Rainier, are expected to undergo periods of incision, aggradation, and widening following their establishment, but widening is the dominant process (Major et al., 2000 cites Meyer and Martinson, 1989; Simon, 1999). Sediment yield is dependent on stream discharges that result in bank collapse as well as other factors that contribute to bank instability (Major et al., 2000). Debris flow initiation at Mt. Rainier is also dependent on factors that contribute to bank instability, such as melting ice-cored, over-steepened moraines and debris covered masses of stagnant ice deposited during periods of glacier thinning and retreat over tiered bedrock (C. Driedger, personal communication, 2008). Future work should address mapping and quantification of buried ice and over-steepened embankments to understand possible relationships between slope instability, debris flows, and channel aggradation. Distribution of small temperature sensors on Mt. Rainier would indicate whether permafrost or buried ice exists at particular locations (Chiarle et al., 2007). Rates of slope failure might be quantified through mapping of prone slopes using LiDAR data and insertion of erosion stakes at selected locations. Research to address climate impacts at Mt. Rainier, such as analysis of the timing, magnitude, duration, and frequency of high stream flows, will also address if the conditions that facilitate stream bank collapse are changing.

Chapter 5 – Conclusions

Three new stream channels on Mt. Rainier have been impacted by debris flows since 2001 and rainstorms in 2005 and 2006 are the first known events to have triggered more than one debris flows. Preliminary evidence suggests that debris flow characteristics such as the timing of initiation or the geography of initiation sites may have altered in recent years, but these claims cannot be substantiated due to limited historical records. Individual debris flows from Mt. Rainier were often not recorded at all or typically recorded in association with a particular glacier during a given year, but not with a specific date. Fewer debris flows were recorded with a description of the initiation location or a specific date of initiation. Knowledge of past debris flows is the result of compilation of records and extensive field reconnaissance from 1985 to 1994 by and J. Walder and C. Driedger (1993; 1994). Debris flow occur infrequently and some debris flow paths are quite difficult to access, therefore, Walder and Driedger focused their study on debris flows from South Tahoma Glacier into Tahoma Creek (Walder and Driedger, 1994). Debris flows from Kautz, Nisqually, and Winthrop Glaciers were described only minimally (Walder and Driedger, 1994). The 2001 Van Trump Creek debris flow from Kautz Glacier is the only debris flow path, other than that of Tahoma Creek, for which the timing of initiation is known, the initiation site location has been defined, an initiation mechanism has been inferred, geomorphic change along the flow path has been described, and an approximate deposition location has been defined (Vallance et al., 2002). This study represents the first time that a population of debris flows from Mt. Rainier have been described in detail.

The majority of debris flows from 2001 to 2006 initiate near the margins of small bodies of glacier ice or permanent ice, while the minority initiate on stagnant ice proximal to an active glacier terminus or at the margin of a proglacial lake. Glaciers and glacier fragments associated with debris flows are all less than 2.3 km^2 in size with a median area of 0.7 km^2. Debris flows from 2001 to 2006 initiated in steep walled gullies in material exposed or deposited by glacier retreat. Gullies are characterized by headwalls located at bodies of ice or snow. While numerous gullies that are not associated with debris flow initiation exist downstream of glacier fragments, heads of gullies associated with debris flows are located at statistically significantly higher elevations. Gully heads for debris flow initiation sites are all at an elevation of 1937 m or above and the average elevation of gully heads is 2181 m. Channel gradients associated with debris flows vary considerably and do not differ significantly from gradients associated with gullies without a history of debris flow initiation. Debris flow behavior transitioned from erosion to transport and ultimately deposited in-channel without the formation of a fan at gradients of less than 10°. The downstream extent of deposits in a particular channel are at similar locations regardless of the debris flow triggering mechanism or the size or retreat chronology of the source glacier.

The geomorphic impacts of debris flows are difficult to distinguish from other processes, either in the field or from analysis of aerial photos. Geomorphic reconnaissance and acquisition of aerial photographs or other data to address geomorphic change must occur when ground is snow-free. The season during which this work can be done is short, as the upper slopes of Mt. Rainier are snow cover for most of the year. Without field reconnaissance immediately after a debris flow, multiple seasons of field reconnaissance, or LiDAR data captured before and after a debris flow, debris flow characteristics reported in this study should be used to constrain future research rather than predict future debris flow initiation.

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Appendix A

Table 1. Coordinates of gullies in NAD 1983 UTM Zone 10 North.

Possible Debris Flow Producing Gullies		
ID	X	Y
Inter Glacier 2006	597717	5192979
Kautz Glacier into Van Trump Cr. 2001	593717	5186106
Kautz Glacier stagnant ice 2005, 2006	592871	5185046
Pyramid Glacier 2005, 2006	592284	5185477
Pyramid Glacier into Kautz Cr. 2005, 2006	592446	5185571
South Tahoma Glacier (West to East 1) 2005, 2006	590403	5185538
South Tahoma Glacier (West to East 2) 2005, 2006	590478	5185532
Van Trump Glacier (West to East 1) 2003, 2005, 2006	593948	5185600
Van Trump Glacier (West to East 2) 2003, 2005, 2006	594148	5185514
Van Trump Glacier (West to East 3) 2003, 2005, 2006	594095	5185064
Van Trump Glacier (West to East 4) 2003, 2005, 2006	594156	5184620
Van Trump Glacier (West to East 5) 2003, 2005, 2006	594395	5184680
Winthrop Glacier 2006	595370	5193680
Gullies Not Known to Have Produced Debris Flows		
ID	X	Y
1	594876	5184662
2	596313	5183882
3	598001	5184478
4	600649	5185105
5	600992	5185654
6	602444	5187649
7	602777	5188600
8	587421	5191186
9	597755	5184044
10	599606	5183970
11	602062	5186301
12	600631	5186271
13	600818	5190747
14	597307	5193856
15	588561	5191201
16	588214	5186365
17	589094	5185863
18	595752	5183437
19	596396	5184161
20	601114	5185812
21	603290	5188922
22	603165	5188562
23	602385	5190126
24	589149	5194162
25	588234	5192395
26	587540	5189513

Appendix B

Debris Flow Synopses 2001 to 2006

Debris Flows from South Tahoma Glacier

South Tahoma Glacier was one of the first glaciers on Mt. Rainier to undergo rapid change. Walder and Driedger (1994) report that aerial photographs from the 1930s show that South Tahoma and Tahoma Glaciers were once a single body of ice. In 1967, a supraglacial meltwater channel incised through glacier ice until it reached bedrock and separated the glacier into two pieces (Walder and Driedger, 1994). The glacier continued to retreat and thin significantly until high snowfall during the 1960s caused the glacier to advance in the late 1970s and early 1980s (Walder and Driedger, 1994).

Eight recorded debris flows occurred from 1967 to summer 1971 and incised the bedrock walled reach near the glacier terminus 5 to 7 m (Walder and Driedger, 1994). From fall 1971 to 1986 two additional debris flows occurred that resulted in little geomorphic change. The Walder and Driedger study began in 1985, and beginning with a debris flow on October 26, 1986, there were 15 recorded debris flows before the conclusion of the study. Debris flows during this period removed significant sediment. Two debris flows in September 1992 caused a bedrock nickpoint to migrate 30 to 40 m upstream and incised a channel into bedrock 15 to 20 m deep near river km 10.6 (Walder and Driedger, 1994). Debris flows occurred during both dry and wet weather and were attributed to glacier outburst floods, as well as flowslides (October 16, 1988) and slumping of saturated sediment from the melt of buried, stagnant ice (October 11, 1990). Scott (1992) and Walder and Driedger (1994) observed glacier ice in some debris flow deposits in 1986, 1987, and 1988 that could have been the result of either changes in the glacier terminus associated with a glacier outburst flood or the result of slope failure associated with buried stagnant ice. Landslide or debris flow damming of Tahoma Creek was not observed (Walder and Driedger, 1994).

No records of debris flows in Tahoma Creek were kept during the period 1993 to 2001. The initiation of the 2003 debris flow was inferred from a large slope failure at the downstream left moraine of South Tahoma glacier observed September 12, 2003 (P. Kennard, personal communication, 2008). The slope failure was estimated to be over 250 m in length during fieldwork conducted during the summer of 2008. It is likely that the slope failure was the result of failure of an oversteepened, unconsolidated slope that was undercut at the toe by long-term fluvial incision, a pulse of glacier meltwater, or the passage of a debris flow. The slope failure may have reinforced an existing debris flow that initiated at the glacier terminus (P. Kennard, personal communication, 2008). Photos of the downstream reaches of Tahoma Creek indicating debris flow damage were taken two days after the slope failure was observed and are available from P. Kennard (personal communication, 2009). Walder and Driedger (1994) described slope failures and in-channel recharge of sediment in Tahoma Creek by similar mechanisms, but did not believe that the sediment of the lateral moraines of Tahoma Creek contained sufficient moisture for a slope failure to transform into a debris flow in-channel.

Debris flows in Tahoma Creek in 2005 and 2006 were confirmed by the deposition of large woody debris and boulders near the Westside Road (P. Kennard, personal communication, 2008). The September 29, 2005 debris flow traveled Tahoma Creek into Fish Creek and aggraded a large armored culvert known to National Park

Service personnel as Texas Crossing (P. Kennard, personal communication, 2008). During flooding associated with the debris flow the entire volume of Tahoma Creek appeared flow into Fish Creek (P. Kennard, personal communication, 2008). A wood snout was located near the culvert that transmits Fish Creek under the Westside Road, which was washed out during the storm of 2006 and has since been repaired (P. Kennard, personal communication, 2008). The occurrence of the 2006 debris flow is confirmed by the deposition of boulders on the Westside Road, parallel to Tahoma Creek, between river km 8 and 7. The 2006 debris flow further aggraded Texas Crossing and in 2008 nearly 1 m of sediment covered the stream culvert (P. Kennard, personal communication, 2008). There is also photo evidence that several large trees comprising a logjam were removed in the 2006 event (P. Kennard, personal communication, 2008). The Westside road, which runs approximately parallel to Tahoma Creek from Nisqually-Longmire entrance road (Hwy 706) to river km 7 was first threatened by Tahoma Creek in the 1980s. Subsequent washouts along the road have caused frequent closures in the past twenty years. Between river km 8 and 6 the road has been washed out in at least three locations.

Figure 1. Debris photographed July 25, 2006 and subsequently removed by November 2006 debris flow in Tahoma Creek (P. Kennard, personnel communication, 2008). Boulders deposited on Westside Road are also evidence of the 2006 debris flow.

Debris Flows from Pyramid Glacier

Pyramid Glacier is a highly fragmented collection of glaciers and permanent snowfields. The first debris flow from Pyramid Glacier occurred in 2005. A gully immediately below a fragment of the glacier acted as an initiation site for two debris flows; one of which eventually traveled Kautz Creek and the other of which followed a tributary of Pyramid Creek (P. Kennard, personal communication, 2008). This gully is also likely the source of the 2006 debris flow that traveled Pyramid Creek.

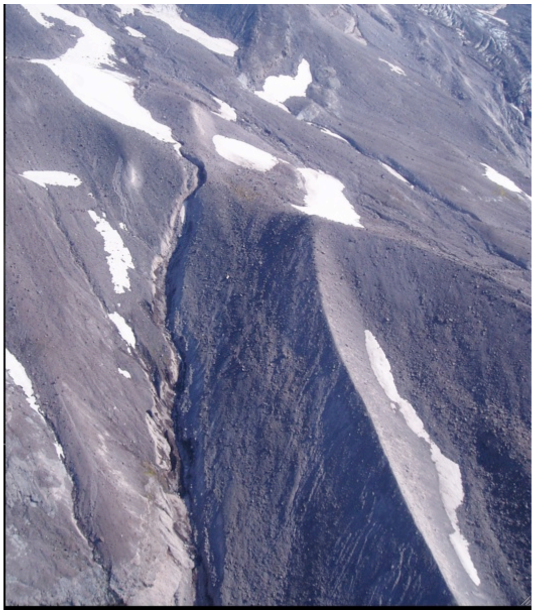

Figure 2. Pyramid Glacier fragment and initiation site for 2005 and 2006 debris flows.

Debris flows from Pyramid Glacier into Pyramid Creek alternately erode and deposit sediment from the waterfall on Pearl Creek to the mapped confluence of Pyramid Creek with Kautz Creek (river km 6 to 0). There is evidence that the debris flow repeatedly transitioned from a watery flood to a debris flow and deposited cobble size material without causing the mortality of mature trees. Diversions of Pyramid Creek intersect Kautz Creek at numerous locations (river km 6, 4, and elsewhere). Multiple wood snouts are located between river km 1 and the mapped confluence of Pyramid and Kautz Creeks. The former Pyramid Creek backcountry campsite near the Wonderland Trail was damaged by the 2005 debris flow. The campsite was repaired and reopened by summer 2006. The 2006 debris flow subsequently followed a similar path to the 2005 debris flow and forced the relocation of the campsite farther from Pyramid Creek.

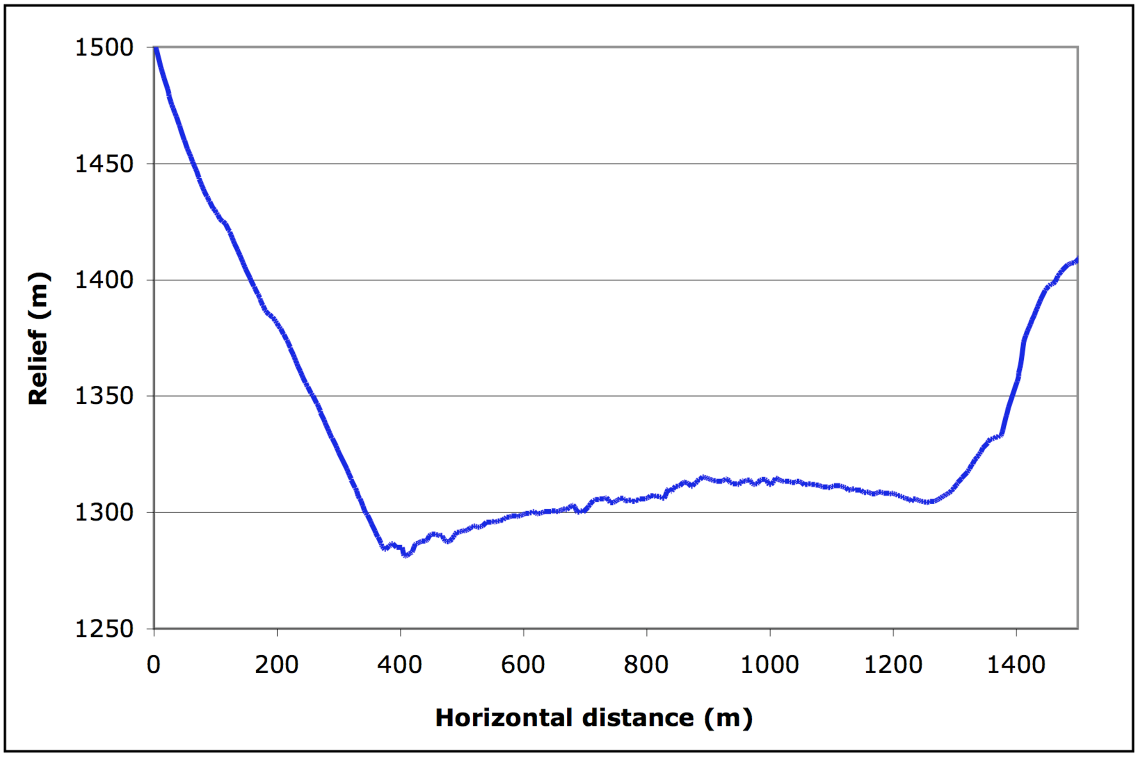

Figure 3. Cross-section from LiDAR where the confluence of Pearl Creek and an unnamed tributary of Pyramid Creek is located at approximately 400 m (horizontal distance) and Kautz Creek is located at approximately 1300 m.

Debris Flows from Kautz Glacier

Kautz Glacier was the source of the largest non-volcanic debris flow in the history of the Mt. Rainier National Park. Four pulses of debris flows on October 2 and 3, 1947 were triggered by heavy rain and a possible glacial outburst flood. The Nisqually-Longmire Road, 9 km from the glacier terminus, was buried by 9 m of sediment (Walder and Driedger, 1993). In total, it is estimated that the 1947 debris flow deposited 40 million m^3 of material. Far smaller debris flows were recorded in 1961, 1985, and 1986 (Walder and Driedger, 1994). The most recent debris flows in Kautz Creek occurred in 2005 and 2006. The 2005 flow initiated in a meltwater gully originating at a fragment of

Pyramid Glacier and subsequently traveled into Kautz Creek (P. Kennard personal communication, 2008). The 2006 Kautz Creek debris flow, like the 2005, may have started at Pyramid Glacier and then traveled into Kautz Creek or it may have originated at the stagnant terminus of Kautz Glacier where a gully is cut into the surface of the debris covered ice.

The 1947 Kautz Creek debris flow helped to create a broad plain on which both Kautz Creek and Pyramid Creek migrate laterally. There is evidence of interaction of debris flows from Pyramid and Kautz Glacier downstream of the canyon-like Pleistocene-age lateral moraines of Kautz Glacier and the waterfalls on the tributaries that form Pyramid Creek. At this location Kautz and Pyramid Creeks are less than 500 m apart. Dry stream channels have been cut between the two creeks and an area of old growth trees have been inundated with cobble-sized material. Diversions of Pyramid Creek merge with Kautz Creek several more times upstream of the mapped confluence. Both the 2005 and 2006 debris flows deposited in Kautz Creek in a similar span. The 2006 debris flow overrode the 2005 deposit (P. Kennard, personal communication, 2008). Wood snout-like deposits are present 1.5 to 1.4 km upstream of the Nisqually-Longmire Road. The snouts of both debris flows deposited at an elevation of 750 m on a 4° to 6° gradient and initially could be distinguished based on the degree the wood had been bleached by the sun (P. Kennard, personal communication, 2008). During fieldwork in 2008, wood snouts were indistinguishable from one another. The 2006 Kautz Creek debris flow was associated with a channel avulsion approximately 1.5 km upstream from the Nisqually-Longmire park entrance road. Airphoto analysis by National Park Service personnel, however, revealed that trees along the avulsion died prior to the 2006 debris flow, indicating that there was extensive water flow along the new channel prior to the 2006 storm (P. Kennard, personal communication, 2008).

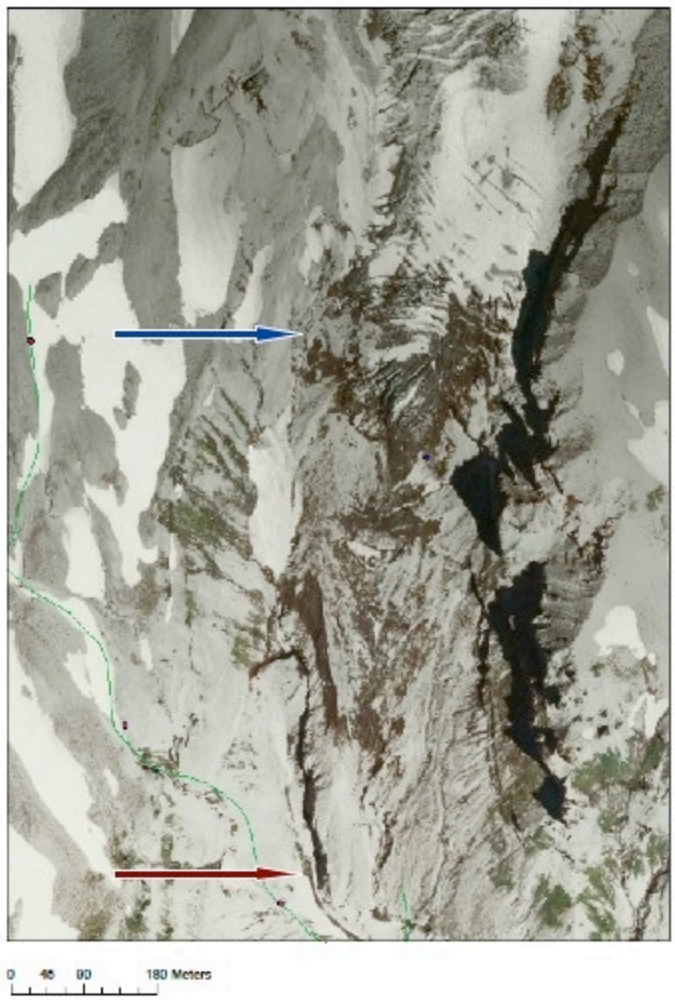

Figure 4. Kautz Glacier active (blue arrow) and stagnant (red arrow) termini. A gully is incisized into the debris covered stagnant ice.

Debris Flows from Van Trump Glacier

Van Trump Glacier is a collection of glacier fragments. The first debris flow in Van Trump Creek occurred in 2001 while the first debris flow from Van Trump Glacier initiated in 2003. The event is widely known in the communities surrounding Mt Rainier

National Park, as it was initially reported by local media as a life-threatening lahar (P. Kennard, personal communication, 2008). On August 14 and 15, 2001 diversion of Kautz Glacier meltwater incised a steep-walled gully and eventually entered Van Trump Creek as several debris flow pulses (Vallance et al., 2002). The debris flow initiated at nearly 3350 m, caused catastrophic gullying, and ultimately mobilized 2.5 million cubic meters of sediment (Vallance et al., 2002). The first pulse of the debris flow was observed downstream by National Park Service personnel as a change in stream color and stage. A later debris flow pulse, including the passage of the debris flow over Comet Falls, was observed and video recorded by USGS CVO scientists during helicopter reconnaissance. Three additional debris flows have occurred since 2001 all of which are believed to have followed a tributary of Van Trump Creek located to the east of the unnamed tributary of Van Trump Creek the 2001 debris flow followed. The 2003 debris flow was studied by an undergraduate student from England, Kate Donovan, and is believed to have been triggered by a combination of rockfall and precipitation (P. Kennard, personal communication, 2008). P. Kennard reported seeing boulders that appeared to have slid across a snowfield during field reconnaissance (personal communication, 2008).

Debris flows in 2005 and 2006 caused Van Trump Creek to flow over the Nisqually-Longmire entrance road at a location known as Van Trump Curve. Several large boulders were deposited and existing boulders were removed during the debris flow (P. Kennard, personal communication, 2008). Debris flows in 2001, 2003, 2005, and 2006 deposited downstream of river km 1 and the majority of the deposition occurred immediately at the confluence of Van Trump Creek and the Nisqually River.

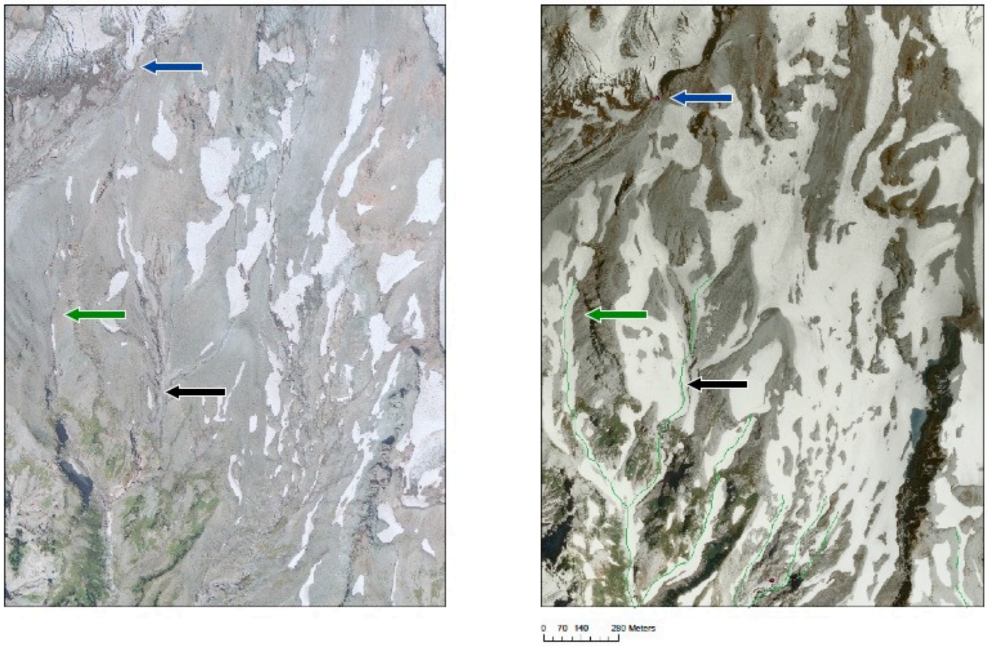

Figure 5. Debris flows in Van Trump Creek originated at Kautz Glacier in 2001 (blue arrow) and followed an unnamed tributary over Comet Falls (green arrow) into Van Trump Creek and originated at fragments of Van Trump Glacier in 2003, 2005, and 2006 in the headwaters of Van Trump Creek (black arrow). The 2006 NAIP orthophoto (right) is largely snow-covered, but provides spatial reference for the unorthorectified 2007 aerial photo (left).

Debris Flows from Inter Glacier

Inter Fork of the White River below Inter Glacier produced the first recorded debris flow in 2006. The meltwater fed channel located far east of the Inter Glacier terminus is believed to have triggered the debris flow based on apparent displacement of boulders and deposition of sediment on top of large boulders, possibly caused by material being thrown up and out of the debris flow (P. Kennard, personal communication, 2008). Small sections of bedrock are exposed in each of the gullies and P. Kennard reported stagnant ice or ground ice visible in the far downstream right gully during field reconnaissance in the spring of 2006 (personal communication, 2008).

There is abundant evidence of debris movement from the valley walls near where the meltwater channels merge at the moraine on the downstream left of the valley. A side channel located where the Glacier Basin Trail intersects the Inter Fork of the White River appears to have contributed to the debris flow, as fresh boulders are located at the banks of the channel. The magnitude of the 2006 debris flow on the Inter Fork of the White River was quite large, but upstream damage is uneven. At river km 2 a rockslide on the downstream left valley wall badly damaged the Glacier Basin Trail. At few hundred meters downstream, riparian vegetation is does not appear to be scoured, flattened, stripped or otherwise damaged. At river km 1 the Glacier Basin Trail is inundated with debris some 2 to 3 m thick and the downstream right back, which is the Emmons Glacier moraine, has been severely undercut and eroded, destroying the Emmons Moraine Trail. These findings indicate that the debris flow was recharged by incision of valley walls. Fluvial incision of the Glacier Basin Trail continues to the trailhead located at the White River Campground. The Inter Fork joins the White River without evidence of a wood snout or debris flow terminus. It is assumed that the debris flow deposited or transitioned into a hyperconcentrated flow or flood near or at the confluence of the Inter Fork with the White River.

Debris Flows from Winthrop Glacier

The only recorded debris flow on the West Fork of the White River below Winthrop Glacier prior to 2006 storm was in 1987 (Walder and Driedger, 1994). The 2006 debris flow initiated from a remnant located to the west of the present glacier. Melt from the glacier remnant has created a small lake that terminates at two steep walled gullies connect the lake to the west margin of the main body of Winthrop Glacier. The 2006 debris flow cut through the west lateral moraine at a location 0.9 km upslope of the terminus of the glacier. The wood snout of the debris flow was observed north of Pigeon Peak and near the park boundary during field reconnaissance by P. Kennard, S. Beason, C, Driedger and others (P. Kennard, personal communication, 2008). Analysis of aerial photos and other data suggests that deposition occurred at an elevation 963 m and a gradient of 2.9°.

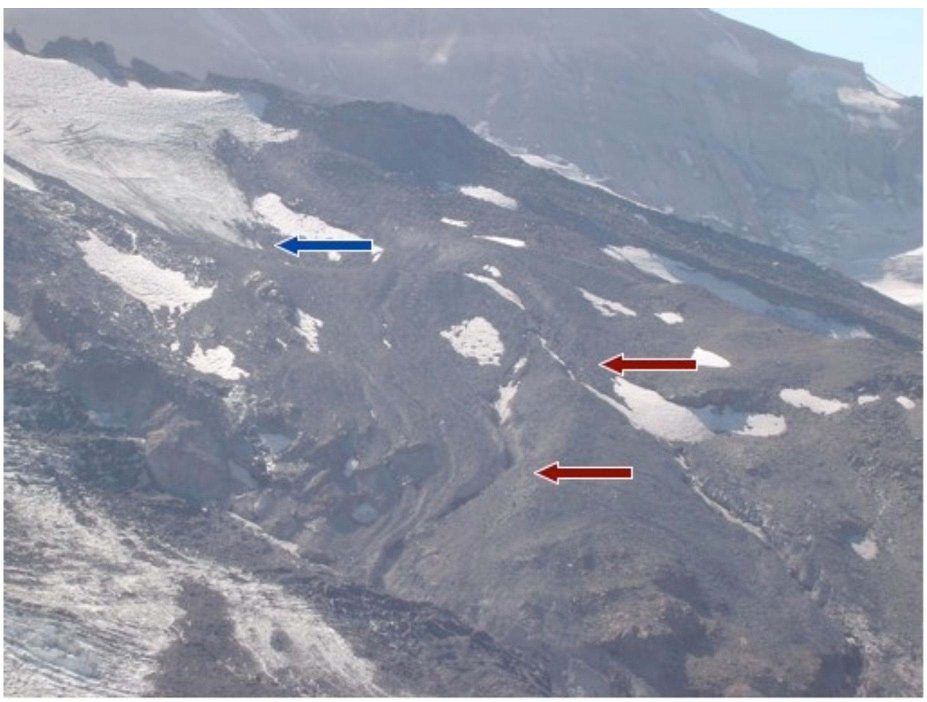

Figure 6. Oblique view of Winthrop Glacier debris flow initiation site showing debris flow initiation site at the glacier lake (blue arrow) and the two main gullies the debris flow followed from initiation to the lateral side of Winthrop Glacier what is visible in bottom left corner of the photo.