

Monitoring and modeling ice-rock avalanches from ice-capped volcanoes: A case study of frequent large avalanches on Iliamna Volcano, Alaska

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Abstract

Iliamna is an andesitic stratovolcano of the Aleutian arc with regular gas and steam emissions and mantled by several large glaciers. Iliamna Volcano exhibits an unusual combination of frequent and large ice-rock avalanches in the order of $1 \times 10^6 \text{ m}^3$ to $3 \times 10^7 \text{ m}^3$ with recent return periods of 2–4 years. We have reconstructed an avalanche event record for the past 45 years that indicates Iliamna avalanches occur at higher frequency at a given magnitude than other mass failures in volcanic and alpine environments. Iliamna Volcano is thus an ideal site to study such mass failures and its relation to volcanic activity.

In this study, we present different methods that fit into a concept of (1) long-term monitoring, (2) early warning, and (3) event documentation and analysis of ice-rock avalanches on ice-capped active volcanoes. Long-term monitoring methods include seismic signal analysis, and space- and airborne observations. Landsat and ASTER satellite data was used to study the extent of hydrothermally altered rocks and surface thermal anomalies at the summit region of Iliamna. Subpixel heat source calculation for the summit regions where avalanches initiate yielded temperatures of 307 to 613 K assuming heat source areas of 1000 to 25 m², respectively, indicating strong convective heat flux processes. Such heat flow causes ice melting conditions and is thus likely to reduce the strength at the base of the glacier.

We furthermore demonstrate typical seismic records of Iliamna avalanches with rarely observed precursory signals up to two hours prior to failure, and show how such signals could be used for a multi-stage avalanche warning system in the future. For event analysis and documentation, space- and airborne observations and seismic records in combination with SRTM and ASTER derived terrain data allowed us to reconstruct avalanche dynamics and to identify remarkably similar failure and propagation mechanisms of Iliamna avalanches for the past 45 years. Simple avalanche flow modeling was able to reasonably replicate Iliamna avalanches and can thus be applied for hazard assessments. Hazards at Iliamna Volcano are low due to its remote location; however, we emphasize the transfer potential of the methods presented here to other ice-capped volcanoes with much higher hazards such as those in the Cascades or the Andes.

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1. Introduction

Active ice-capped volcanoes can pose severe hazards to nearby populated areas and have repeatedly triggered disasters, most of which are unrelated to eruptive activity, but some not. By far the largest historical catastrophe associated with an ice-capped volcano occurred on Nevado del Ruiz, Colombia, in 1985. Pyroclastic density currents interacting with snow and ice, and ice-rock avalanches, transformed into lahars that killed more than 20,000 people in downstream areas (Pierson et al., 1990; Thouret, 1990). On many other ice-capped volcanoes documented historical and prehistoric events would have devastating consequences under present-day population and development. Examples can be found in Colombia south of Nevado del Ruiz (Huggel et al., 2007), in Ecuador, Peru (Delaite et al., 2005), Mexico (Julio Miranda et al., *in press*), the Cascades (e.g. Mount Rainier; Hoblitt et al., 1998; Reid et al., 2001) and elsewhere. Despite the extent of hazard, our understanding of mass failures on ice-capped volcanoes is incomplete. This is largely due to the low frequency of such phenomena. Monitoring activities are therefore important measures for early detection and prevention of related hazards.

Iliamna Volcano in Alaska is an ideal field laboratory for the study of failure and dynamics of ice-rock avalanches (Caplan-Auerbach et al., 2004; Caplan-Auerbach and Huggel, 2007). This extensively glaciated volcano exhibits an unusual combination of highly frequent and large ice-rock avalanches (note that in this study we use the term “avalanche” to mean ice or ice-rock avalanches, as snow avalanches are not considered). We present here an extended record of historical ice-rock avalanches back to 1960. During the subsequent twenty years several large avalanches occurred, and as monitoring activities on Iliamna Volcano were strengthened in the late 1980's and early 1990's by the Alaska Volcano Observatory (AVO), evidence of more frequent avalanches with magnitudes in the order of 10^6 to 10^7 m³ has been identified (Caplan-Auerbach and Huggel, 2007). Due to the remote location of Iliamna Volcano, smaller avalanches during the past 15 years, and larger ones prior to ~1990 have likely gone unnoticed. Iliamna Volcano has also been a site of repeated mass failure in earlier historical and prehistoric times. Waythomas et al. (2000) dated a series of debris avalanche and lahar deposits from the last few hundred years, some of which were related to flank collapse or smaller slope failures.

Iliamna Volcano is located 225 km southwest of Anchorage and far from population centers. The risks associated with avalanching are thus relatively small. In this study we want to provide an overview of monitoring

and modeling methods of ice-rock avalanches in volcanic terrain, with particular emphasis on locations with difficult access. The methods we are presenting can be categorized as (1) long-term monitoring, (2) early warning, and (3) event reconstruction and analysis. These methods include seismic signal analysis, airborne and spaceborne observations using Landsat and ASTER visible to thermal spectral information, spaceborne data-derived digital terrain data (SRTM and ASTER), and GIS-based avalanche flow modeling. However, we cannot provide a complete overview of existing and feasible state-of-the-art methods. Rather, we try to highlight the potential of selected monitoring and modeling methods and emphasize how different monitoring and modeling techniques can be integrated to improve our understanding of ice-rock avalanche generation and propagation mechanisms at volcanoes and provide tools for corresponding hazard assessment.

Due to the much larger hazards found at similar ice-capped volcanoes in more populous regions, we underline the transfer potential of these methods. This is particularly true for the analysis of seismic signals that may be used for ice avalanche warning, and is based on characteristic precursory signals associated with the failure of ice avalanches (Weaver and Malone, 1979; Caplan-Auerbach et al., 2004; Caplan-Auerbach and Huggel, 2007). While the methodology is not yet sufficiently advanced to be applied in an operational setting, we outline the related development potential for the future. We begin this study with an updated and extended description of recent Iliamna avalanches.

2. Iliamna avalanches

2.1. Iliamna Volcano

Iliamna is an andesitic stratovolcano in the Cook Inlet region of Alaska (Fig. 1). With an elevation of 3053 m asl it is one of the highest volcanoes in the Aleutian arc. The volcanic edifice has developed over older, high relief plutonic rocks of Jurassic age (Detterman and Reed, 1980). The volcano consists primarily of a stratified assemblage of andesite lava flows, and minor lahar, pyroclastic flow and debris-avalanche deposits. A zone of sulfurous fumaroles with frequent steam emission on the east face of the summit is a prominent feature.

Iliamna is extensively glaciated with several glaciers descending from the summit region. Tuxedni Glacier to the north, Lateral Glacier to the northeast, Red Glacier to the east and Umbrella Glacier to the west are the most important ones having a total volume of ~15 km³, with ~1 km³ of ice on the uppermost 1000 m of the edifice,

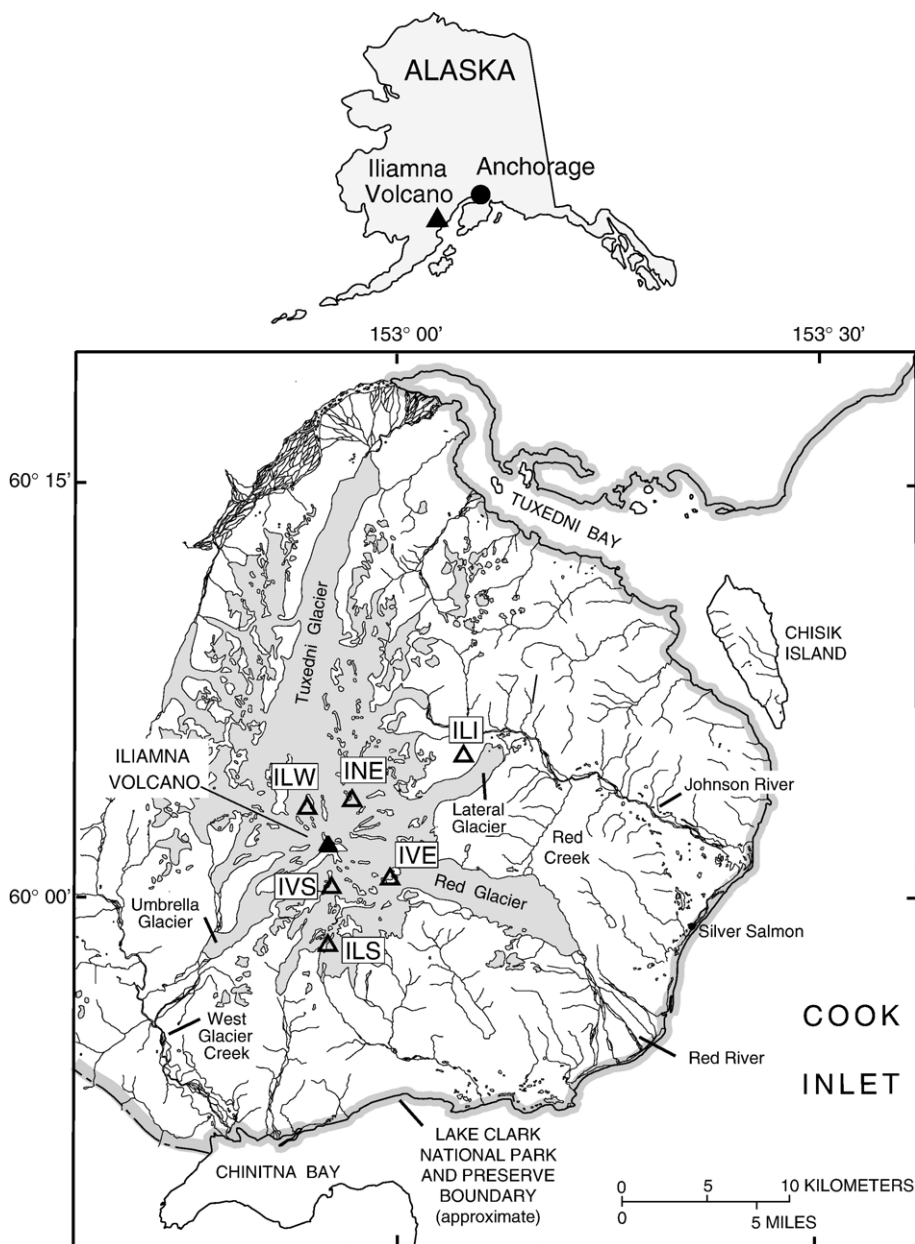


Fig. 1. Map showing Iliamna Volcano, its glacier and hydrologic system, and seismic network operated by the Alaska Volcano Observatory (the location of seismic stations is indicated by open triangles, glaciers are shown in grey).

and a maximum measured ice thickness of almost 400 m on Tuxedni Glacier (Trabant, 1999). Iliamna's flanks are deeply dissected by avalanches and the effects of glaciation. In particular the east and west flanks have large ($\sim 0.5 \text{ km}^3$) amphitheater-like scarps. These features may be glacial cirques, or they may have resulted from Holocene sector collapses, as they truncate young lava flows (Waythomas et al., 2000).

Major explosive eruptions of Iliamna are dated from 7000 and 4000 yr B.P. whereas little is known about the

eruptive history prior to about 7000 yr B.P. (Waythomas and Miller, 1999). Volcanic deposits of eruptions under a repeatedly thick ice cover during the Quaternary period may have been removed by glacial erosion. Granitic rocks exposed along Iliamna's flanks are heavily altered by hydrothermal activity and significantly weakened and friable, particularly in the scarps around the summit region that roughly coincide with fumarolic activity (Waythomas et al., 2000). Lahar deposits from the last 4000 yr are common around the

volcano. Lahars were typically generated by interaction of pyroclastic flows with snow and ice, and some of them appear to have evolved from flank collapses containing an abundance of hydrothermally altered rock debris (Waythomas and Miller, 1999).

2.2. Prehistoric, historical and recent ice-rock avalanches

Debris-avalanche deposits of prehistoric age (more than 200 yr old in Alaska) have been found on Lateral, Red and Umbrella Glacier (Waythomas et al., 2000). On Lateral Glacier, deposits of altered rock similar to the young avalanche deposits were identified within but not beyond the maximum Holocene glacier extent. An avalanche deposit of prehistoric age on Red Glacier covers an area of 20 km² with an estimated volume of 40 million m³ (Waythomas et al., 2000). On Umbrella Glacier a debris-avalanche deposit covers an area of about 1 km² along the northwest side of the glacier with an estimated volume of 15 million m³. Avalanche deposits are mostly unvegetated; where lichen growth can be observed, deposit age is suggested to be about 100 to 500 yr BP (Waythomas et al., 2000). Deposits are generally unsorted accumulations of boulder and cobble gravel; the matrix sediment consists of very poorly

sorted material with a mean grain size ranging from pebble to sand. Fine sediment (silt and clay) is present only in limited amounts. Large boulders and blocks are observable only on Red Glacier. Based on the observations of the more recent Iliamna avalanches and thin and featureless morphology of the deposits, it is likely that historical and prehistoric avalanches contained significant amounts of ice and snow. Actual avalanche volumes may thus have been considerably larger than estimated.

The earliest modern Iliamna avalanches that could be reconstructed based on overflights and aerial imagery made shortly after the events (Alean, 1984; A. Post, personal communication, 2006) took place in 1960, 1978, August 1980 and July 1983 (Figs. 2 and 3, Table 1). These were primarily ice avalanches with varying amounts of rock involved, and all descended down Red Glacier. The initiation zone was located on the southern side of the summit at the head of Red Glacier and the avalanche path was consistent with that of the more recent events in 1994, 1997, 2000 and 2003, described below. The 1980 event was the largest, with an estimated total volume of 28 million m³ and a failure volume of 10.8 million m³, and thus with significant entrainment of ice, snow and rock along the flow path. The extension of the failure zone was 760 m wide and 1000 m long with a maximum failure thickness of 38 m

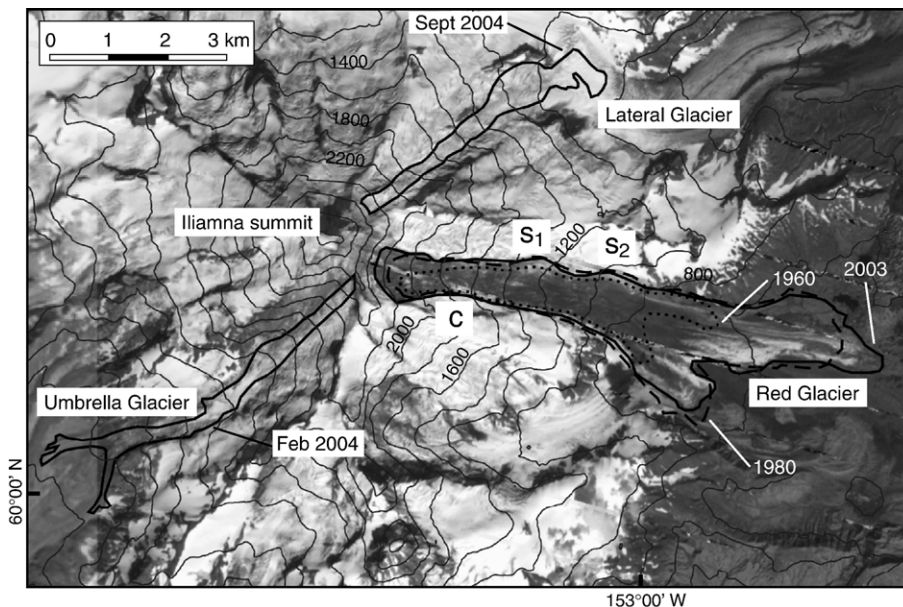


Fig. 2. Mapped extent of recent avalanches on Red, Umbrella and Lateral Glacier. For Umbrella and Lateral Glacier, the February 9, 2004, and September 10, 2004 avalanches, respectively, are indicated while for Red Glacier the extent of the 1960, 1980 and 2003 avalanches is shown. The similarity of flow paths between different avalanches on Red Glacier can be clearly identified. Background image is a Landsat-7 ETM+ panchromatic image from August 9, 2003. *s*₁ and *s*₂ indicate superelevation-like lateral flow lobes, and *c* refers to a wedge-like glacier segment generally not affected by avalanches (cf. section Avalanche modeling and dynamics).

(Alean, 1984). The 1978 avalanche was similar to the 1980 avalanche but the volume was 30 to 50% smaller while the volume of the 1960 event was 80 to 90% smaller and the runout length about 70% shorter. The avalanche observed in 1983 was a minor event with a volume of about 10^5 m^3 . Based on analysis of historical photographs and earlier studies (Alean, 1984), all four avalanches from 1960 to 1983 are likely to have started on intraglacial sliding planes.

Since the mid-1990's, intensification of the monitoring activities at Iliamna Volcano has permitted a more detailed detection of avalanches. In particular, the deployment of a real-time seismic network in the late 1980's provides a remote means of detecting avalanches in lieu of visual observations. Seismic signals were recorded in association with avalanches on Red Glacier, on June 30, 1994, May 19, 1997, August 8, 2000, and July 25, 2003. Avalanches occurring on Umbrella

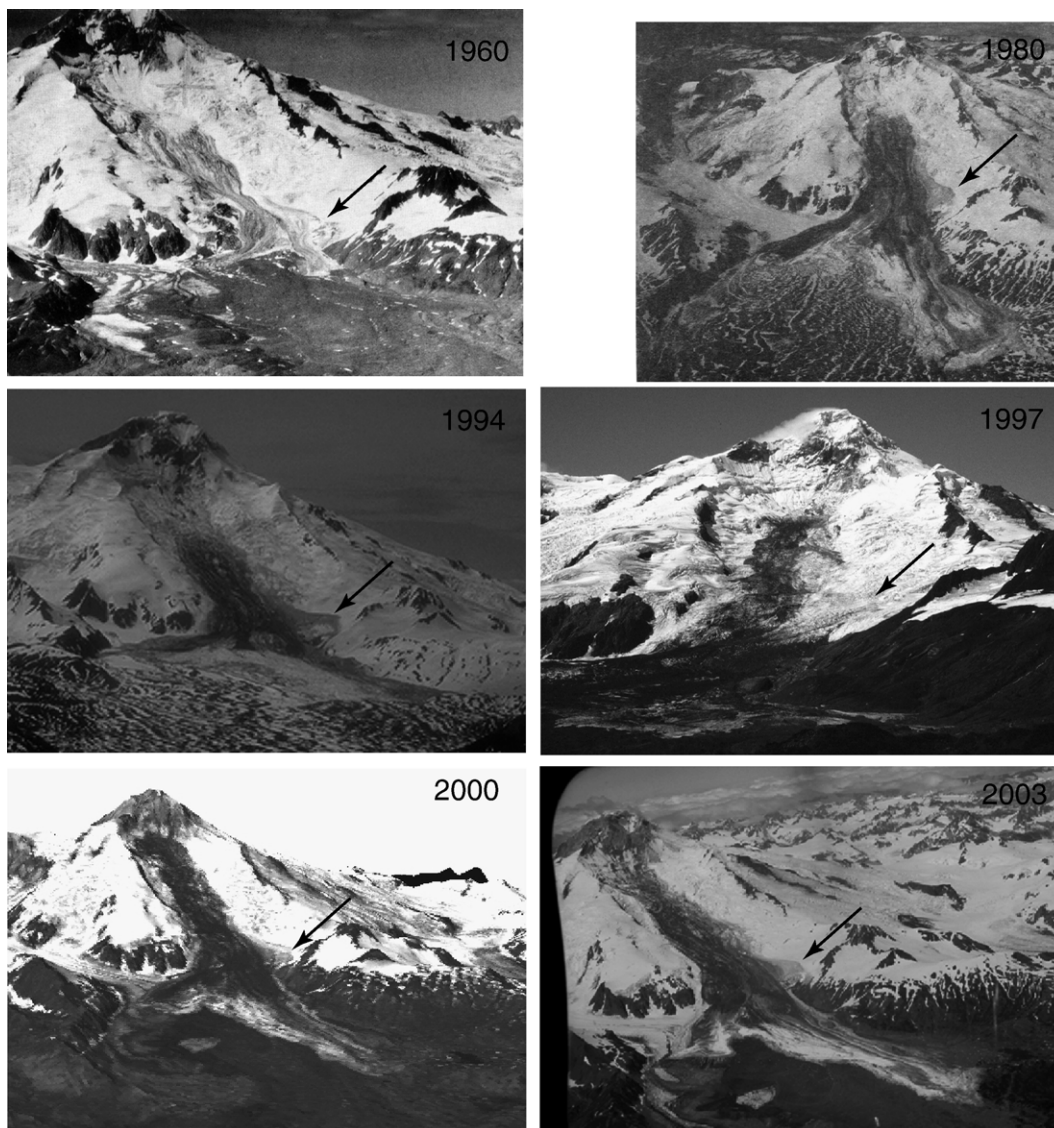


Fig. 3. A photographic comparison of Red Glacier avalanches from 1960 to 2003. The similarity of flow paths and runout distance among the different avalanches is remarkable. The arrows indicate a flow lobe that is present in all avalanche events. Note also the very similar runout of the 1980, 1994, 2000 and 2003 avalanches (August 24, 1960, and August 25, 1980 images by L. Mayo, July 1, 1994 image by U.S. Geological Survey, August 18, 1997 image by C. Waythomas, and August 1, 2003 image by R. Wessels. The 2000 image is an artificially generated view using a Landsat ETM+ image from August 16, 2000, and a SRTM DEM).

Table 1

Characteristics of Iliamna ice–rock avalanches during the past 45 years (data from the 1978, 1980 and 1983 avalanches from Alean, 1984)

Avalanche	Failure elevation (upper end) (m a.s.l.)	Drop height H (m)	Runout length L (m)	Failure width (m)	H/L	Volume (10 ⁶ m ³)	Failure slope	Velocity (m/s)
1960 Red Glacier	2100	1400	5500		0.25	3–6		
1978 Red Glacier	~2300	~1770	~7700		~0.23	14–20		
1980 Red Glacier	2160	1650	7800	760	0.21	28		
1983 Red Glacier	2300					~0.5		
1994 Red Glacier	2200	1750	10,000		0.18	16.5	41°	22–46
1994 Red Glacier tributary	1900	1006	3400		0.29	2.3		
June 30, 1994 Umbrella Glacier	2400	1366	3000		0.45	0.97	37°–40°	
May 19, 1997 Red Glacier	2200	1640	7700		0.21	14	38°–40°	22–51
August 8, 2000 Red Glacier	2300	1800	8900	660	0.20	11–18	35°–39°	60–75
July 25, 2003 Red Glacier	2250	1760	8550	730	0.21	12–20	41°	37–46
February 9, 2004 Umbrella Glacier	2400	1700	6200		0.27	2.5–5	37°	35–70
September 8, 2004 Umbrella Glacier	2550	880	1800		0.49	0.1–0.15	45°–50°	40–56
September 10, 2004 Lateral Glacier	2560	1740	5160		0.34	4–6	40°	29–65

Glacier on February 9, 2004 and September 8, 2004; and on Lateral Glacier on September 10, 2004 generated similar seismic signals. The coincident seismic signals provided a means by which the timing of these events could be precisely determined.

The 1994, 1997, 2000 and 2003 avalanches all detached from Iliamna's eastern flank at the head of Red Glacier at an elevation between 2200 and 2250 m asl. (Fig. 4, Table 1). In all cases, bedrock was exposed at the failure zone but it is unclear whether the initial failure occurred in rock or ice or at the ice-rock interface. In all three events, significant amounts of ice and rock were involved. Avalanche volume estimates range from 14.5 million m³ for the 1997 avalanche to 16.5 million m³ for the 1994, 11–18 million m³ for the 2000 and 12–20 million m³ for the 2003 avalanche (Waythomas et al., 2000; Caplan-Auerbach and Huggel, 2007, this study). Avalanche runout lengths varied from 7.7 km to 10 km. The failure volume of the 2003 avalanche was estimated at 6 million m³ indicating that a large volume of snow and ice was entrained along the avalanche trajectory. Observations suggest that snow and ice were the dominant components of the avalanche. In-situ examination of avalanche deposits could only be performed for the 1997 avalanche and found a ~50% content of snow and ice (Waythomas et al., 2000), however a similar avalanche on Mt. Adams, Oregon was also found to be composed primarily of snow and ice (R. Iverson, personal communication, 2006). The analysis of the Red Glacier avalanches thus suggests that the past 45 years of these mass movements have followed a characteristic sequence in terms of failure, rock entrainment, avalanche dynamics and deposition.

Avalanches on Umbrella Glacier were seismically recorded on February 9 and September 8, 2004 (Fig. 2). Both avalanches originated above Umbrella glacier on

Iliamna's southwest flank in a zone of hydrothermally altered rock covered by ice. Failure was down to bedrock, with an ice thickness of about 5 to 20 m at ~2400 and 2550 m asl, respectively, for the February and September avalanches. Reconstruction of the February avalanche using high-resolution satellite imagery taken within days after the event yielded an estimated volume of 2.5 to 5 million m³ with constant snow and ice erosion and deposition along the 6.6 km long flow path. The failure of the September avalanche was likely related to the debutressed glacial head wall after the February avalanche (Caplan-Auerbach and Huggel, 2007).

Just two days after the September 8, 2004 event, another major avalanche occurred on a tributary of Lateral Glacier originating from the northeastern flank of Iliamna Volcano at an elevation of ~2500 m asl (Fig. 2). Overflights shortly after the event clearly showed that the failure was down to the bedrock beneath the glacier. The failure is an excellent, but rarely observed example of a slab failure, also referred to as ramp failure, typically related to a reduction in strength at the base of the glacier (Haefeli, 1966; Huggel et al., 2004). The initial failure volume is estimated at 2 to 3 million m³, with 5 to 30 m thick glacier ice involved, which then bulked to 4 to 6 million m³, involving snow, ice and rock along the flow path. (Caplan-Auerbach et al., 2004; Caplan-Auerbach and Huggel, 2007).

Table 1 summarizes the dimensions of all avalanches documented so far. The frequency and magnitude of Red Glacier avalanches, in particular, with avalanches in the order of 10–20 million m³ every 3–4 years for the past 13 years is extraordinary and possibly unique worldwide. To put Iliamna avalanches into a wider perspective, we compared them with magnitude-

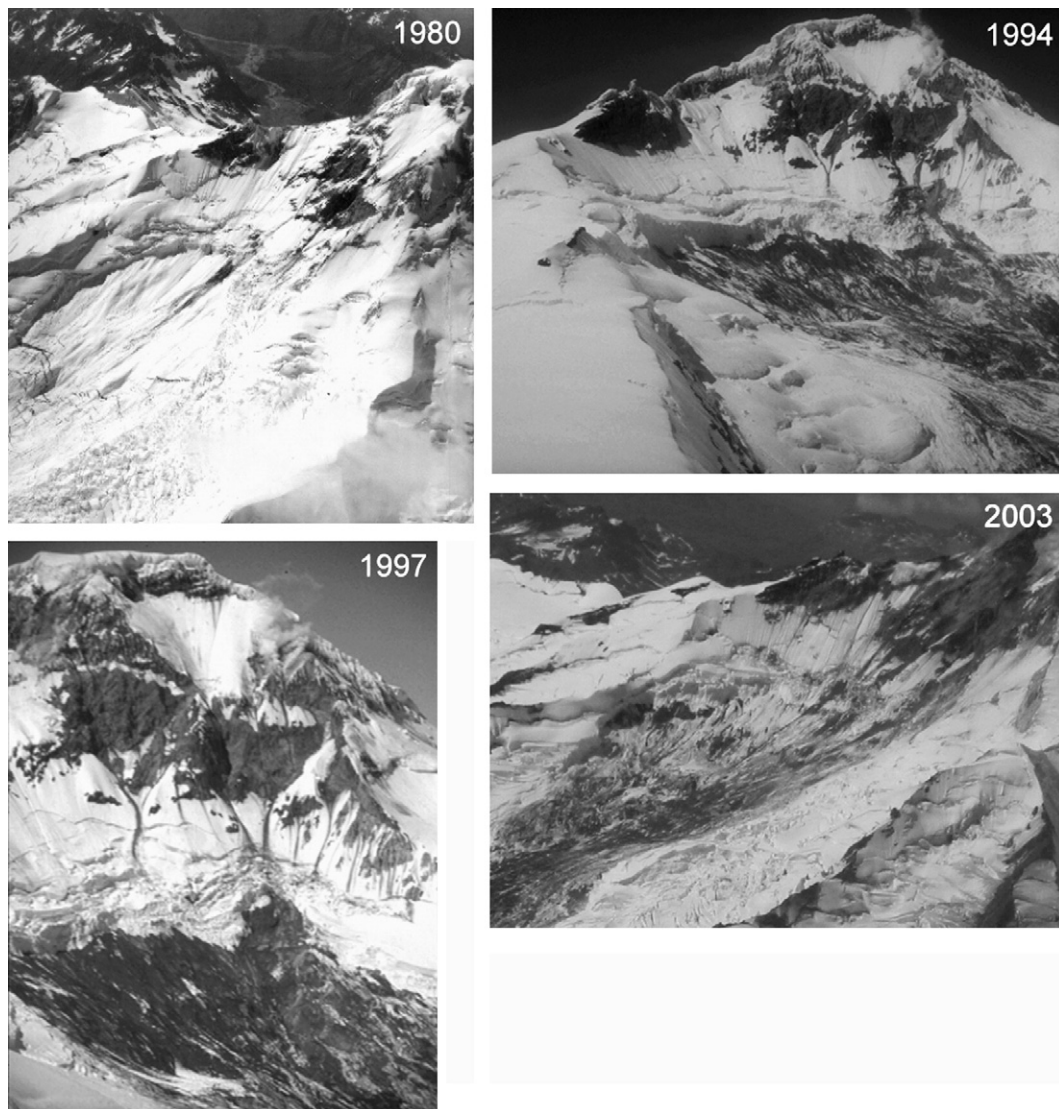


Fig. 4. Photographic comparison of failure zones of repeated Red Glacier avalanches from 1980 to 2003. The failure zones are almost identical and show that failure commonly involves bedrock and ice. The 1980 avalanche was taken on August 25, 1980 by L. Mayo, the June 30, 1994 avalanche on July 1, 1994 by the National Park Service, the May 19, 1997 avalanche taken on August 18, 1997, by C. Waythomas, and the July 25, 2003 avalanche on August 1, 2003, by R. Wessels.

frequency relationships of volcanic mass failures (McGuire, 1996; Fig. 5). Though we are aware of the generalized character of such graphical representations of magnitude-frequency relationships plotted on a log–log scale, this plot indicates that Iliamna events cluster off of the main trend of volcanic mass failures, indicating higher frequency at a given magnitude, or larger mass at a given frequency than other volcanic events. In comparison to volcanic debris avalanches Iliamna ice avalanches are at the lower end of the volume spectrum whereas in relation to other ice-rock

avalanches they are among the largest ones observed (Huggel et al., 2004; Pralong and Funk, 2005).

3. Monitoring

3.1. Seismic monitoring

The seismic network at Iliamna Volcano maintained by the AVO consists of 6 short-period instruments in operation since 1996, with lower-level monitoring since 1987. The stations range from 2.5 to 9 km from the

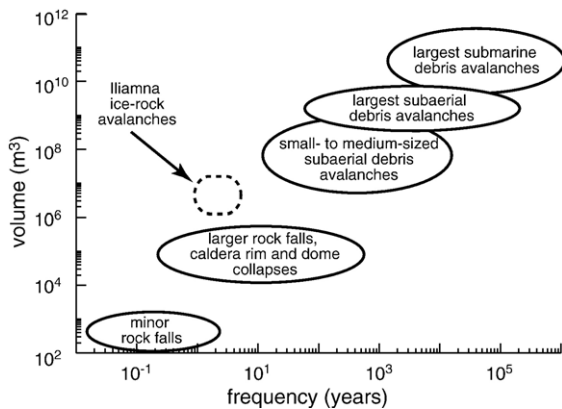


Fig. 5. Magnitude-frequency relationship of volcanic mass failures. Iliamna ice-rock avalanches show a tendency to be more frequent for the same magnitude or larger for the same frequency than commonly observed mass failures suggest (modified from McGuire, 1996).

summit at elevations between 823 and 2332 m asl (Fig. 1). All of the stations have short-period seismometers, and only station IVE has 3-component data. All avalanches since the 1997 event were recorded by the Iliamna seismic network on at least four stations. No seismic network existed in the 1960's and early 1980's that could detect avalanches, and the 1994 avalanche was recorded only by one seismic station, making detailed analysis impossible.

Several studies have shown that mass movements such as rockfall and debris avalanches (Weaver et al., 1990; Norris, 1994), snow avalanches (Suriñach et al., 2001), pyroclastic flows (Uhira et al., 1994; Calder et al., 2002; Jolly et al., 2002), and submarine landslides (Caplan-Auerbach et al., 2001) exhibit characteristic spindle-shaped seismograms. These signals were recorded in association with the Iliamna avalanches. However, unlike other mass-wasting events, Iliamna avalanches also exhibit an unusual seismic sequence up to two hours prior to failure. This signal is observed only in those avalanches believed to initiate in ice or at the ice-rock interface; snow avalanches and debris avalanches initiating in rock do not exhibit any precursory seismicity (Norris, 1994; Suriñach et al., 2001; Caplan-Auerbach et al., 2004). The typical seismic signal sequence for Iliamna avalanches starts with small ($M1$) discrete earthquakes that increase in occurrence rate for ~ 20 to 60 min (Fig. 6) before they gradually transform into a continuous ground-shaking. This portion of the signal lasts 15 to 60 min, increasing in amplitude (Caplan-Auerbach et al., 2004). The continuous ground-shaking culminates in a strong, broadband spindle-shaped signal believed to represent the actual avalanche and usually saturating the nearest sensors on Iliamna Volcano.

We propose that these seismic records can be used to locate the avalanche source zone, constrain the failure mechanism, and estimate avalanche velocities. Caplan-Auerbach et al. (2004) show that despite to low amplitude and emergent onset of the discrete earthquakes in the first phase of activity, hypocentral locations may be constrained by making use of waveform similarity. With this method earthquakes are found to cluster near the presumed headwall of their associated avalanche. This is a strong indicator that these events are associated with the avalanche and are not coincidental.

The precursory seismic signals associated with the Iliamna avalanches permit new insights into the failure mechanism. Caplan-Auerbach et al. (2004) and Caplan-Auerbach and Huggel (2007) interpret the earthquakes as discrete slip events at the base of glacier ice in the failure zone. The discrete earthquakes representing the initial stage of the avalanche seismic signal are highly similar in time series, representing a repeating source process. We interpret the period of continuous ground shaking as an evolution of the first phase; discrete events are now so numerous that they effectively merge into a continuous signal. In some events such as the September 10, 2004 event, discrete earthquakes can be identified within the continuous phase (Fig. 6). In other situations such as the February, 2004 event, individual earthquakes cannot be identified within the continuous signal. However, we observe that the two phases share common source spectra, suggestive of a common source process (Fig. 6). This failure progresses until the entire ice body fails and the avalanche initiates. Seismic signals similar to the discrete events are common in ice fields and glaciers, though not associated with ice avalanches, e.g. high-frequency (>10 Hz) extensional faulting within crevasse fields (Neave and Savage, 1970; Metaxian et al., 2003) or low-frequency activity as attributed to basal slip (Weaver and Malone, 1979). Headwall fracturing, like crevasse, would likely produce very weak seismicity due to the small size of the slip area (Metaxian et al., 2003).

The broadband, spindle-shaped seismic signal that follows the precursory signal represents the downslope transport of ice and rock (Caplan-Auerbach et al., 2004; Caplan-Auerbach and Huggel, 2007). The duration of this signal, combined with observed avalanche runout distance can therefore provide some constraint on avalanche speeds. The seismic signal has a gradual onset and taper and multiple failure events cannot be distinguished. However, given these constraints, we find that Iliamna avalanche have speeds of 22–70 m/s, with an average of ~ 43 m/s. Such speeds are broadly

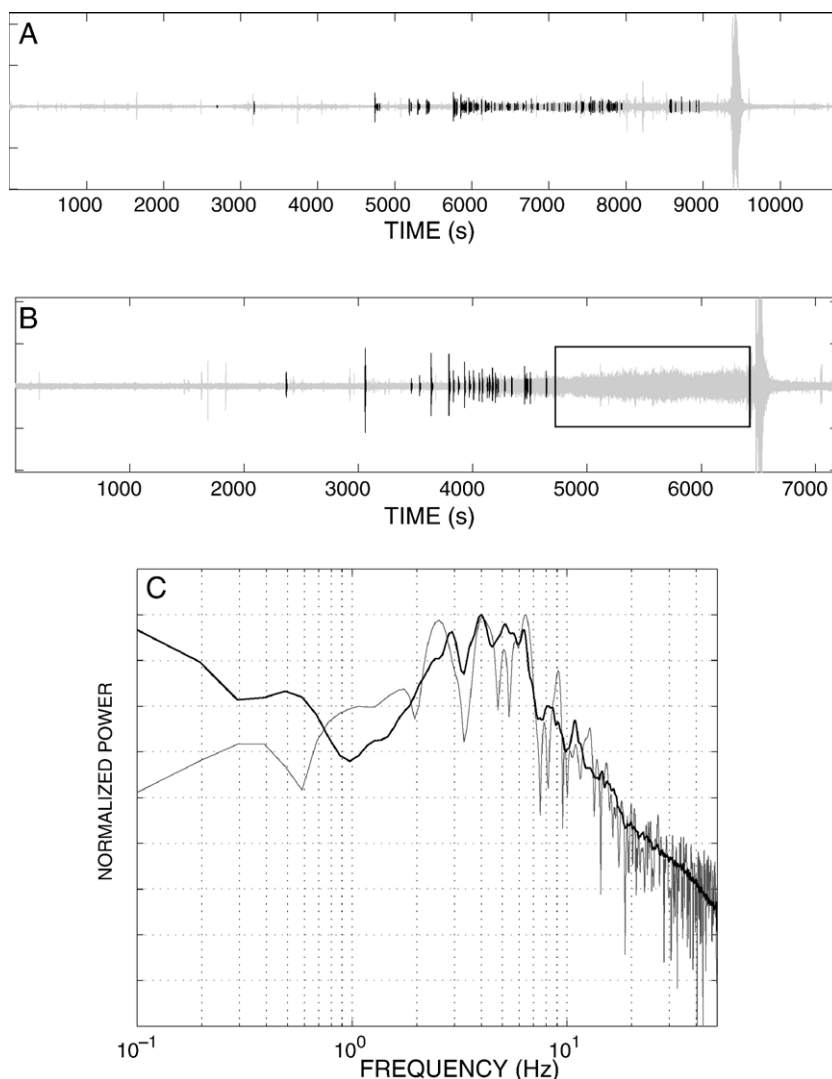


Fig. 6. Seismic records for two Iliamna avalanche sequences. (A) Seismic signal recorded during the September 10, 2004 event. The earthquakes highlighted in black are repeating earthquakes with an average correlation coefficient of 0.63. The multiplet continues throughout the period of continuous groundshaking (beginning at ~ 6000 s). (B) Seismic signal recorded during the February, 2004 event. Discrete repeating earthquakes (mean correlation coefficient 0.65) are only identifiable in the early part of the signal. However, the power spectra (C) of the discrete earthquakes (heavy line) and continuous signal (boxed in part (B)) of the February, 2004 event are highly similar, again suggesting a common source. The February, 2004 event (B) particularly well demonstrates the typical seismic signal evolution from discrete earthquakes (until ~ 4500 s) to continuous motion (until ~ 6500 s), eventually culminating into a spindle-shaped signal representing the actual avalanche.

consistent with other snow, ice and rock avalanches. For example, ice avalanches in Tibet were estimated to have traveled at 21–35 m/s (Van der Woerd et al., 2004), and the massive 2002 ice-rock avalanche from Kolka Glacier (Caucasus) moved at velocities of 50–80 m/s (Huggel et al., 2005).

The precursory seismic signals associated with Iliamna avalanches indicate that they may be useful for short-term warning. Such signals usually occur up to two hours before the actual avalanche. A main drawback at

the moment is the rapid, real-time recognition of the signal and its identification as an incipient avalanche. Seismicity is a common phenomenon in volcanic terrain, and precursory signals might therefore go unnoticed at first. The repetitive nature of the earthquakes, together with the increase in event occurrence rate, however, may make glacial failure identifiable. The transformation into continuous ground-shaking may then be the critical connector to unambiguously recognize a failure in the ice. Earthquakes originating in ice are likely to attenuate

more rapidly than those occurring in rock, hence rapid estimates of the quality factor Q , a measure of the degree of attenuation, could help discriminate between glacial and volcanic earthquakes. And finally rapid earthquake locations are necessary to determine where the avalanche may initiate and whether or not it poses a threat to nearby communities. Further investigation of these signals is therefore critical to identify which parameters are unique to ice avalanches and could be used for warning systems.

3.2. Airborne observations

Airborne observations from fixed-wing aircraft or helicopters are necessary to obtain visual information about conditions at Iliamna Volcano because of the remoteness and difficult access to the area. Overflights of the volcano are usually conducted if the seismometers capture an event of sufficient interest and weather permits. As shown above, the seismic signals allow us to locate the avalanche source such that airborne observations can be directly focused on the area identified. Observations and photographs taken during the flight are often suitable to assess the avalanche failure mechanism (e.g. ramp versus wedge failure), the material involved, the flow path characteristics, and to broadly estimate the thickness of the failure and deposits. Weather, funds and time permitting, more detailed field work on the ground can be undertaken based on the airborne observations. AVO has collected airborne volcanic gas data at Iliamna at least once per year since about 1990 (Doukas, 1995). Oblique photographs taken during fixed-wing flights are mostly used for qualitative analysis. However, techniques are available to transform oblique photographs into georeferenced images that allow mapping and other quantitative analysis (Corripio, 2004).

The summit region of Iliamna Volcano has also been monitored using airborne Forward Looking Infrared Radiometer (FLIR). Thermal anomalies related to fumarolic activity were detected at Iliamna although FLIR observations have been more extensively applied on other Alaskan volcanoes (McGimsey et al., 1999; Dean et al., 2004).

3.3. Satellite imagery

Landsat-7 Enhanced Thematic Mapper (ETM+) and ASTER data were evaluated to study Iliamna avalanches from space. Landsat-7 ETM+ records seven multispectral bands with a spectral range between 0.4 and 12 μm (visible to thermal infrared) with 28.5 m ground resolution (60 m for thermal bands) and includes

a panchromatic band with 15 m ground resolution. The satellite has a repeat cycle of 16 days and passes over the Iliamna area at about 9:30 a.m.

The ASTER sensor is a 14-band multispectral imager with visible and near-infrared (VNIR, 0.52–0.86 μm) bands in 15 m spatial resolution, and short-wave infrared (SWIR, 1.6–2.4 μm) and thermal infrared (TIR, 8.1–11.7 μm) bands with 30 m and 90 m resolution, respectively (Abrams, 2000). Due to these high-resolution multispectral capabilities, ASTER imagery has recently become a promising tool in detecting volcanic activity, applied for instance, to volcanic cloud, gas and thermal analysis (Pieri and Abrams, 2004; Ramsey and Dehn, 2004). ASTER has a repeat cycle of 16 days but given the ASTER's across-track viewing capabilities of up to $\pm 22.5^\circ$ for VNIR bands and 8.5 for SWIR and TIR bands, areas of interest can be viewed every 5 days at 0° latitude and more frequently at higher latitudes. Special programming of the ASTER sensor with repeat periods of 2–3 days has been accomplished in urgent cases such as natural disasters (e.g. Kääb et al., 2003).

For our purpose of avalanche monitoring at Iliamna Volcano, the seismically-derived time and location of the event allowed us to search for feasible Landsat and ASTER satellite images. Image availability is constrained by satellite repeat cycles, cloud coverage and seasonal restrictions such as low sun angle during the Alaskan winter. Special programming of the ASTER sensor could be an option for future avalanche events.

We first examine the possibilities of the visible and short-wave infrared bands of Landsat-7 ETM+ and ASTER for avalanche monitoring and then refer to thermal ASTER data. We used a Landsat-7 ETM+ scene from August 9, 2003 for analysis of the July 25, 2003 avalanche. The failure of the scan line corrector of the ETM+ sensor that has been present since May 2003 does not significantly affect image interpretation since Iliamna Volcano is located in the image center, and the error increases towards the image edge. The avalanche trajectory is easily traceable because the spectral reflectance of rock entrained within the avalanche causes it to stand out from the surrounding ice and snow (Fig. 2). Avalanche dimensions such as width and runout length may be estimated from these images, as well as slope of the initiation zone or the ratio of vertical descent to horizontal runout (H/L) in combination with digital elevation models (DEM). Evidence for super-elevation on the northern edge of the trajectory, and the presence of multiple flows and lobes in the deposit area allow us to analyze the flow dynamics of the avalanche (see Section 4).

The ETM+ multispectral bands of the 2003 event show that rock was involved from the starting point of the avalanche and hence the failure reached partly or completely to bedrock. The spatial image resolution is insufficient to identify the failure to be in ice or in rock. However, overflight observations from August 1, 2003 showing extended areas of exposed bedrock at the failure zone (Fig. 4), indicate that the failure mechanism was likely at the ice-bedrock interface. It is difficult to assess the amount of rock entrained along the avalanche trajectory using airborne or satellite-based observations. Even if rock and debris have only a surficial thickness of ~ 1 m, the total volume of entrained rock may be up to 4 million m^3 (based on a total avalanche affected area of approximately 4 km^2). Observations of similar avalanche deposits on volcanoes in the U.S. Cascades indicates that even a small percentage of rock in the deposit gives the avalanche a dark appearance (R. Iverson, personal communication, 2006), so the volume of entrained rock may be quite small.

To better understand the failure source of the 2003 avalanche, multispectral ETM+ data were analyzed in more detail. Following an image analysis technique proposed by Kääb (2005a) for ASTER multispectral bands, we combined the corresponding ETM+ bands 4 (NIR, 0.76–0.90 μm), 5 (SWIR, 1.55–1.76 μm), 6 (TIR, 10.4–12.5 μm), and 7 (SWIR, 2.08–2.35 μm). Bands 5, 6 and 7 were transformed into IHS (intensity, hue, saturation) space and back-transformed into RGB (red, green, blue) replacing the intensity component by band 4. The resulting false-color image depicts different rock

types on the surface. The southeast Iliamna summit region shows a distinctive rock type (Fig. 7) that corresponds to the zone of hydrothermally-generated clays on the uppermost section of the volcanic edifice (Waythomas and Miller, 1999). The rock involved along the avalanche trajectory has a different spectral signature than the hydrothermally altered rock from the summit area (Fig. 7). Possible explanations are that (1) rock freshly shattered by collisional forces in the avalanche exhibits a different spectral signature than in-situ rock, (2) the rock involved in the avalanche does not have its origin in the hydrothermally altered, clay-rich zone, or (3) mixing of rock and ice at the 30 m pixel scale has masked the altered rock spectra.

The image analysis confirms that the avalanche had its source in both rock and ice. It is not known if additional rock debris was entrained along the avalanche path or not, although this is likely given the extensive mantle of rock debris on the surface of the glacier. Ground-based investigations could provide more details on the type of rock and ice deposits. More detailed analysis of hydrothermally altered rocks in volcanic terrain may be possible by using hyperspectral airborne remote sensing, as was demonstrated by Crowley and Zimelman (1997) for Mount Rainier, Washington. Similar detection of minerals related to hydrothermal alteration was also achieved with ASTER (Rowan et al., 2003).

An ASTER scene taken on October 30, 2004 was used to study the September 10, 2004, Lateral Glacier avalanche. Recent snowfall and a low sun incident angle

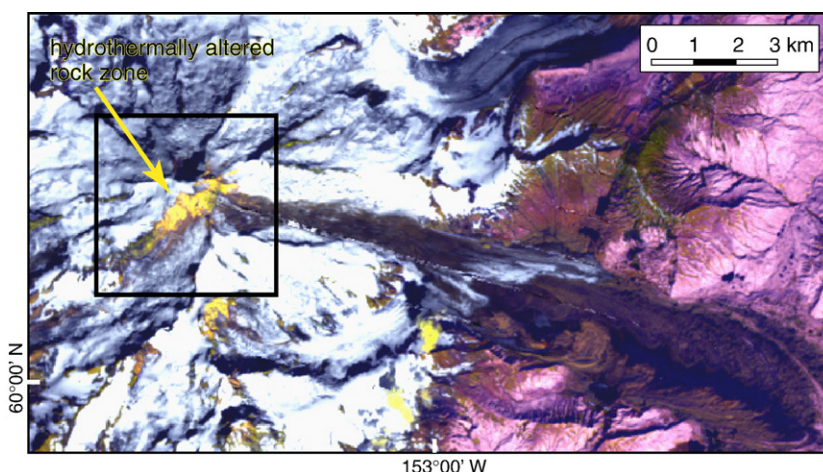


Fig. 7. IHS-RGB transformation of Landsat ETM+ bands 4, 5, 6 and 7 using an August 9, 2003, image (see text for a description of the method). This image processing technique allows separation of different lithologies. Hydrothermally altered rocks can be observed at Iliamna summit (yellow color). The same reflectance signature can only sparsely be distinguished along the avalanche flow path. The black rectangle indicates the extent of Fig. 8.

represent seasonally related obstacles which complicate the detection of the exact failure zone and avalanche path. However, an observational overflight was made 3 days after the event, and was used in combination with ASTER data to investigate the event. Avalanche deposits are clearly discernable in the ASTER image, and are estimated to be about 1–3 m thick, in agreement with aerial observations.

In addition to Landsat and ASTER, high-resolution satellite imagery can be a viable option for detailed studies. QuickBird and IKONOS are currently among the most prominent high-resolution sensors (Birk et al., 2003). First studies have recently been published using QuickBird and IKONOS imagery for mass flows such as landslides and avalanches (Metternicht et al., 2005; Huggel et al., 2006), including studies on debris flows on Mt. Spurr, another active ice-capped volcano in the Cook Inlet region (Coombs et al., 2006). In this study, a combination of satellite images and aerial photographs were used for assessing the February 9, 2004 avalanche on Umbrella glacier. Although recorded less than a week after the avalanche occurred, recent snowfall and reduced winter sunlight made analyzing the avalanche using these images difficult. Avalanche source and furthest runout point could be identified as well as the avalanche trajectory. Entrainment and deposition patterns along the trajectory, however, were difficult to differentiate. As with ASTER and Landsat imagery, deposit thickness can only be estimated crudely. The February 2004 event involved only ice and entrained snow, and occurred after a week of unseasonably warm weather.

ASTER is unique in providing 5 TIR bands with spatial resolution of 90 m. ASTER TIR data have been used in ice and volcano applications for identification of thermally related phenomena, i.e. mapping of glacier facies (Taschner and Ranzi, 2002) and glacial lakes (Wessels et al., 2002; Kargel et al., 2005), or detection of thermal anomalies as potential precursory eruption signals (Pieri and Abrams, 2005) and volcanic ash and sulfur dioxide emissions (Realmuto and Worden, 2000; Pieri et al., 2002). ASTER TIR bands allow the identification of relatively low thermal contrast, theoretically limited by a radiometric resolution with a Noise Equivalent Delta Temperature (NE Δ T) of ~ 0.3 K (Pieri and Abrams, 2004). Tonooka et al. (2005) validated the absolute temperature accuracy to be <0.4 K for any ASTER TIR band for a brightness temperature range of 270–340 K.

The Iliamna summit region is known to exhibit persistent fumarolic activity (Waythomas et al., 2000; Roman et al., 2004). These findings are based on

airborne observation and measurement, and thus depend on flight scheduling. It was therefore our objective to use ASTER TIR data as a tool to regularly monitor, locate and quantify the thermal features in the summit region, and to better constrain the possible relation between thermal anomalies, hydrothermal alteration and slope instability in rock and ice. We used two ASTER nighttime scenes from July 19 and August 22, 2003, as nighttime observations minimize the effect of surficial solar heating. In rock dominated zones as on the snow free, east face of the Iliamna summit, the effect of heating due to daytime solar radiation, clearly observable in the aspect-dependent temperature distribution of daytime TIR images, decreases in measured brightness temperatures of nighttime TIR data. Thus, nighttime detected thermal anomalies may be related more directly with geothermal processes.

ASTER Level 2 Surface Kinetic Temperature Product was used to obtain surface temperatures, (pixel-averaged temperature) of the Iliamna summit area. The ASTER Surface Kinetic Temperature Product provides an estimate of the surface temperature for each of the five ASTER TIR bands. This product iteratively corrects the calculated land-leaving radiance for the effects of downwelling atmospheric irradiance as it calculates and refines the temperature and emissivities. The Level 2 surface-leaving radiance and irradiance products are not only dependent on the quality of the at-sensor radiance but also on the quality of the atmospheric profiles and the topographic data based used (Gillespie et al., 1998).

The largest temperature anomalies in the July 19, 2003 image are found on the southeastern ridge of the summit region at about 2500 m asl, close to the source areas of the Red and Lateral Glacier avalanches (Fig. 8). This is an area of exposed hydrothermally altered rock and the site of the most pronounced fumarolic activity. Maximum difference to background temperature at the same elevation is 10 K with an absolute temperature maximum of 278 K. Another thermal feature is located at the Umbrella Glacier scar also in hydrothermally altered rock. Temperature anomalies are slightly smaller than those in the Iliamna summit region and are about 6 K with equal absolute maximum temperatures of 278 K. The temperature pattern in the August 22, 2003 image is similar to that determined from the July image, though less pronounced temperature anomalies are observed. Absolute temperature differences among the July and August images are due to short-term meteorological fluctuations. The thermal features detected in both images, however indicate a persistent geothermal activity in the summit region.

The temperature values referred to above are derived from the pixel integrated radiance emitted from all parts at all temperature within the pixel area. For ASTER TIR data the pixel area is $90 \times 90 \text{ m}^2$. Volcanic heat sources such as vents, fumaroles, or fractures typically cover areas much smaller than this (i.e. one or two orders of magnitude smaller) (Wright et al., 1999). The energy flux of an object is given by:

$$Q = \varepsilon \sigma T^4 \quad (1)$$

where ε is the emissivity, σ is the Stefan–Boltzmann constant and T the temperature in K. In order to calculate the brightness temperature T of a sub-pixel heat source of area A , we consider the total energy flux of the pixel

$$Q = (\varepsilon \sigma T_e^4)A + (\varepsilon \sigma T_b^4)A_b \quad (2)$$

with T_b being the (cooler) background temperature and A_b the total pixel area with T_b . From Eq. (1) and assuming a hot fraction f of the pixel (for ASTER TIR channels $f=A/8100 \text{ m}^2$), we derive the brightness temperature of the heat source (Pieri and Abrams, 2005):

$$T_e^4 = \frac{1}{f} (T_e^4 - (1-f)T_b^4) \quad (3)$$

where T_e is the effective pixel integrated brightness temperature measured by the ASTER TIR channel. For $T_e=278 \text{ K}$ and $T_b=273 \text{ K}$ as measured in the southeastern Iliamna summit area, $T=307 \text{ K}$, 446 K and 613 K for $A=1000 \text{ m}^2$, 100 m^2 , 25 m^2 , respectively.

Considering Eq. (1) with $\varepsilon=1$ (based on the commonly assumed black body properties of snow and ice at the long-wavelength range) and $\sigma=5.67 \cdot 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$, we calculate an energy flux of 315 W m^{-2} and 339 W m^{-2} for pixels with a uniform temperature of 273 K and 278 K , respectively. Assuming a heat source of 100 m^2 within one ASTER pixel with 278 K , the corresponding energy flux at this point is $\sim 3000 \text{ W m}^{-2}$, i.e. about one order of magnitude larger. An energy flux of this magnitude does not permit the existence of ice (for comparison: a 0.1 W m^{-2} flux over 1 year melts ca. 1 cm of ice) and most likely implies convective heat transport processes. Our calculations show a possible range of temperature and energy flux for reasonably sized heat sources. The effect on snow and ice depends on the size and temperature of the heat source. ASTER data and derived products indicate the possible existence of both low-temperature large-size and high-temperature small-size heat sources. Airborne observations confirm the pres-

ence of a number of fumaroles but we cannot reject the possibility of geothermal anomalies over larger areas. More detailed studies on the snow/glacier energy and mass balance in relation with ASTER data may help to unfold the effective thermal processes.

In addition to the application in the avalanche initiation area, the use of ASTER TIR images were also tested for the avalanche runout. The 2003 Red Glacier avalanche was used as a test case to detect avalanche deposits based on TIR data. A temperature difference calculation of the July 19, 2003 brightness temperature ASTER image from the corresponding image from August 22, 2003 (pre-and post-event images) showed that a clear distinction of the avalanche deposits using TIR data is not feasible. Such a technique might be more successful in case of fresh avalanche deposits in areas of strongly debris-covered glacier ice or beyond the glacier surface, and ultimately contribute to estimating the relative amount of ice and rock involved in the avalanche.

3.4. Remote sensing derived DEM's

Remote sensing-derived digital elevation models (DEM) have recently opened new opportunities in exploring topography-related changes on the Earth's surface as well as for a series of modeling applications (Stevens et al., 2004; Kääb, 2005b; Huggel et al., in

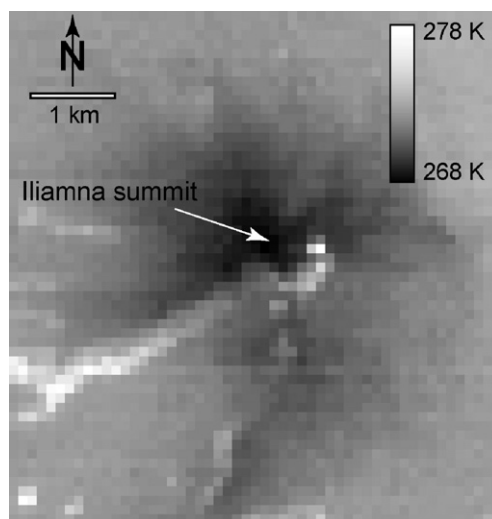


Fig. 8. 10.5μ pixel-integrated brightness temperatures shown for the Iliamna summit region based on a July, 19, 2003 ASTER image. Clear temperature anomalies can be distinguished in the southwestern summit sector coinciding with observed fumarolic activity and hydrothermally altered rocks. Darker grey values towards the summit area reflect lower surface temperatures with increasing elevation.

press). This is particularly true for remote regions such as Alaska where ground-based geodetic measurements are difficult to perform. In this study, we used DEM's derived from two different remote sensing systems to investigate their potential for assessment of topographic changes associated with avalanches and for flow modeling of avalanches (Section 4). The first DEM used here was generated by the Shuttle Radar Topography Mission (SRTM) in February 2000. SRTM was a single pass, synthetic aperture radar interferometry (InSAR) campaign after which high-quality DEM data with 1" (~30 m) and 3" (~90 m) resolution were released (Van Zyl, 2001). We used here the 30 m grid size resolution. Vertical errors of the terrain data are given as ± 16 m and ± 6 m for absolute and relative accuracy, respectively; the horizontal positional accuracy is ± 20 m at a 90% confidence level (Rabus et al., 2003). Absolute accuracy thereby relates to the error throughout the entire mission while relative accuracy describes the error at a local 200 km-scale which applies to the Iliamna data.

Two other DEM's were generated using ASTER along-track (back-looking) stereo imagery. The ASTER along-track viewing capabilities are particularly useful because stereo images acquired from the same point of time allow avoiding image matching problems during the DEM generation procedure. The accuracy of the grid-sized elevation points depends on factors such as the quality and geometry of the satellite image and terrain roughness. A number of studies evaluated ASTER-derived DEM's in different settings, including glaciated mountain terrain, and found vertical root mean square errors between 15 and 70 m depending on topographic conditions but with maximum errors of up to several hundred meters (Kääb, 2002; Hirano et al., 2003; Stevens et al., 2004; Kääb, 2005b; Huggel et al., *in press*). We used ASTER stereo images from October 9, 2002, and October 30, 2004 to generate the DEM's. Images from both dates are excellent and enabled us to produce DEM's of a very reasonable overall quality. We selected the area around Red Glacier to examine the use of satellite-derived DEM's to monitor changes of topography as related to avalanche processes. In Fig. 9 the 2004 ASTER DEM and the 2000 SRTM DEM are compared, with negative values referring to surface lowering during the period 2000 to 2004. We have no absolute elevation reference to precisely evaluate the DEM's. The National Elevation Data (NED) released by the U.S. Geological Survey in a 2 arc sec (~60 m) resolution version for Alaska has a vertical accuracy (± 7 to 15 m) comparable to the SRTM data but is assembled from 20 to 40 years old topographic map data, and hence

not suitable as reference elevation in dynamic glacial environments.

Given the system-provided elevation accuracy of SRTM data, confirmed by various studies, we attribute the large vertical errors in the steep terrain of the Red Glacier area to errors of the ASTER-derived DEM (Fig. 9). Maximum vertical errors in comparison with SRTM data range between -188 and 273 m and are depending on the aspect of the terrain due to the side and back-looking viewing geometry of the sensors. Elevation data are much more accurate in flatter terrain such as found in the lower and terminus section of Red Glacier, and may be feasible to derive glacier mass changes over longer periods (Racoviteanu et al., *in press*).

Our analysis shows that avalanche activity on Red Glacier between 2000 and 2004 (i.e. the 2003 event) did not cause changes in topography that were detected by repeat ASTER surveys. This is due both to the dimension of vertical changes of the terrain caused by the avalanche, as well as to the accuracy of ASTER DEM data. Typical deposit thicknesses of Red Glacier avalanches are a few meters and thus below the accuracy of ASTER-derived repeat DEM's. ASTER DEM's have been found to be useful, however, for analysis of avalanche deposits with thicknesses of several tens to more than hundred meters (e.g. the 2002 Kolka avalanche; Kääb et al., 2005). Topographic changes in the avalanche failure zone are usually larger in terms of elevation difference (on the order of a few tens of meters on Red Glacier). Unfortunately, and as in general with satellite and airborne derived terrain data, ASTER DEM's have higher errors in the steep terrain of failure areas, and thus are not suitable for quantitatively analysis. Laser altimetry measurements such as that performed on several Alaska glaciers including Tuxedni Glacier on the northern slope of Iliamna (Arendt et al., 2002) would be highly valuable to study avalanche dimensions but are rather expensive. For glaciological studies the relatively high elevation accuracy of both SRTM and ASTER data in flat terrain would be useful to estimate thickness changes of glaciers. We found elevation changes in the lower Red Glacier area between 2000 and 2004 in the range of -3 and $+3$ m with a slight increase in thickness in the upper zone. This is consistent with laser altimetry studies which showed a positive thickness change on Tuxedni Glacier of 0.17 m a^{-1} in the period 1995–2001 (Arendt et al., 2002).

4. Avalanche modeling and dynamics

In this section we evaluate how accurately the Red Glacier ice-rock avalanches can be replicated using a

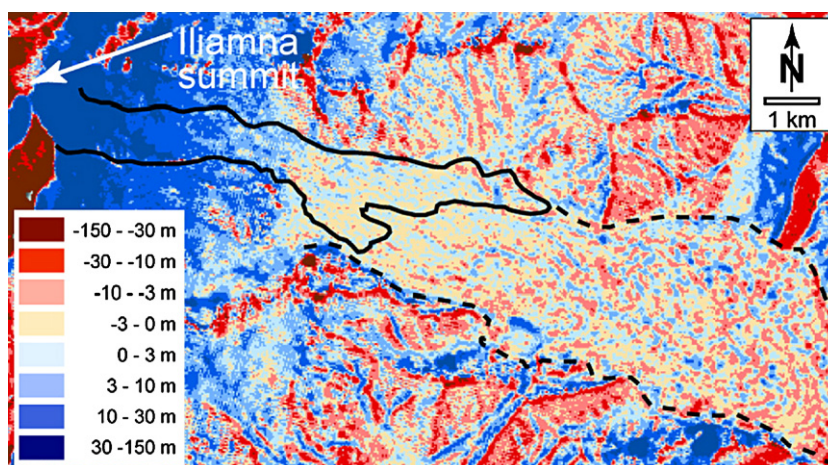


Fig. 9. Elevation differences derived from DEM's generated from an October 30, 2004 ASTER scene and 2000 SRTM data. Negative values indicate surface lowering between 2000 and 2004. Elevation differences larger than about 20–30 m are predominantly due to errors of the DEM's (mainly from the ASTER DEM) and are particularly present in steep terrain. The 2003 Red Glacier avalanche outline is shown by a solid line, the dashed line shows the extent of Red Glacier.

simple flow-trajectory model fully implemented in a GIS environment: the Modified Single Flow Direction (MSF) model was originally developed for debris-flow type processes (Huggel et al., 2003) but has also successfully been applied to ice-rock avalanches with volumes in the order of 10^6 m^3 (Noetzli et al., 2006). We concentrated our modeling studies on Red Glacier avalanches because they are best documented.

The model calculates the flow trajectory of the avalanche from a defined starting point and then applies a given height to length ratio (H/L) as the stopping condition for the avalanche. The basic input to the model is a DEM and one or several grid cells defining the starting location of the mass flow. The flow trajectory is calculated assuming that the mass flow follows the direction of steepest descent with possible lateral flow divergence to both sides. For this type of flow propagation, an algorithm directing flow to the steepest neighbor cell out of eight possible flow directions (D8-algorithm; O'Callaghan and Mark, 1984) is implemented, along with a flow diversion function F_d that allows the flow to divert up to 45° from the direction of steepest descent. Thus, the model is better able to simulate the characteristics of processes such as debris flows or avalanches flowing in confined channel sections (with largely limited spread due to channelized flow) and on relatively flat or convex terrain (with greater spread due to more diverging flow). Once the areas potentially affected by the mass movement are delineated, a function P_q assigns to each grid cell (1) a probability of being affected by the mass movement. P_q is a relative and conditional

probability in case an avalanche occurs. The relative probability corresponds to the model algorithm that calculates a higher flow resistance, and thus lower probability, when the flow diverges from the steepest descent direction (Huggel et al., 2003). Since a conditional probability is applied the model per se does not tell anything about the probability of occurrence of avalanches. An estimate of the return period, based on our record of Red Glacier avalanches for the past 13 years, yields a value of 3–4 years. For the past 30 years the return period would be about 5 years, but must consider the probably incomplete avalanche record for the 1980's.

The second part of the model calculates the maximum runout of the avalanche based on a defined H/L value. The model thus assumes a more or less abrupt stop to the mass flow. This is not necessarily valid, however, as avalanches and debris flows can transform into more mobile hyperconcentrated flows without any specific runout point (e.g., Pierson and Scott, 1985; Scott et al., 2001). On Iliamna, Holocene and historical debris avalanches are thought to have produced such flow transformation (Waythomas et al., 2000) but more recent ice-rock avalanches show a rather abrupt mass stop, as indicated by the form of frontal deposit lobes, similar to debris flows (Caplan-Auerbach and Huggel, 2007). We therefore assume that the model algorithm for runout calculation is adequate for simulation of Iliamna avalanches.

To define the H/L ratio for simulation of Iliamna ice-rock avalanches we analyzed the mobility of recent events. For Red Glacier avalanches observed volumes

are typically between 10 and 30 million m^3 with corresponding H/L values of 0.18 to 0.23 (Fig. 10, Table 1). Avalanches on Lateral and Umbrella Glacier are less well documented but observations indicate that the volume of these avalanches is up to an order of magnitude smaller than those on Red Glacier (Table 1). As shown in Fig. 10, H/L ratios of Iliamna avalanches are generally smaller (with correspondingly higher mobility) than ice avalanches in non-volcanic alpine terrains.

For modeling of Red Glacier avalanches airborne and spaceborne observations of the 2003 Red Glacier avalanche allowed us to precisely identify the failure zone, the avalanche trajectory and runout, and thus to apply the MSF model to this event. The failure zone of the avalanche, delineated based on the August 2003 Landsat image and an airborne photograph from August 1, 2003, represented the starting location for the MSF model. For first model runs topography was provided by the 2002 Aster derived DEM, representing the topography as it was one year before the event. We also used the SRTM terrain data for avalanche modeling to gain an understanding of the effect of DEM's on the avalanche modeling results. Both DEM's were used in a 30 m grid cell resolution.

The 2003 Red Glacier avalanche was simulated with the MSF model using an H/L value of 0.21 as observed for the real event (Fig. 11). The outline of the corresponding SRTM based modeling is indicated by a dashed line. Though the H/L value was held constant for the SRTM-based model, the runout fell short by

~900 m, or about 10% of the total flow length relative to the ASTER-based simulation. The failure location was identical for both model runs, and the difference in the runout distance resulted from topographic variations between the two DEM's. Similar differences of the runout length using MSF as well as LAHARZ (Iverson et al., 1998) in combination with ASTER and SRTM-derived DEM's were observed in lahar modeling studies (Huggel et al., in press).

The ASTER-based model of the flow trajectory achieved a good fit with the observed 2003 avalanche. In the runout zone the northern main lobe is reasonably represented by the model. The fact that the runout zone appears broader in the model than in reality may reflect the fact that the model does not take mass and kinetic energy into account. Instead, the model simply calculates avalanche flow according to the topography and does not consider the effects of momentum, which affects the model performance in the runout zone. The smaller southern lobe of the avalanche is not replicated by the model. It is interesting to note that this southern lobe is a persistent feature for all Red Glacier avalanches documented by airborne or spaceborne observation (1960, 1980, 1994, 1997, 2000, 2003 events). Photographic analysis of these events with layered and overlying flow structures, in particular those of 1980 and 2003 (Fig. 3), indicates that at least two consecutive avalanche flows occurred during each event. The southern lobe is thus a product of a second flow which occupied the southern part of the avalanche trajectory and overrode the first flow that was directed towards the northern runout lobe (Fig. 12). The seismic signals can be used to constrain the two avalanche flows in time. The broadband spindle-shaped signals representing downslope motion of the avalanche have durations of 150–450 s. Assuming an avalanche speed of 20–70 m/s (Table 1) and considering the distance traveled it is evident that the two avalanche flows are separated by a maximum of a few tens of seconds. The multiple pulses of energy exhibited in the seismic signals cannot clearly be attributed to multiple failures (Caplan-Auerbach and Huggel, 2007) but could be an indication of more than one major avalanche flow.

Flow dynamics can also be inferred from the 1980 and 2003 photographs. It is highly remarkable that the two separate avalanche flows represent consistent features through all documented Red Glacier avalanches. As for attributing the two flows to different sectors of the failure zone, an origin of the first flow from the southern failure zone is supported by the observation of a wedge-like glacier segment generally unaffected by the avalanche in the upper flow trajectory

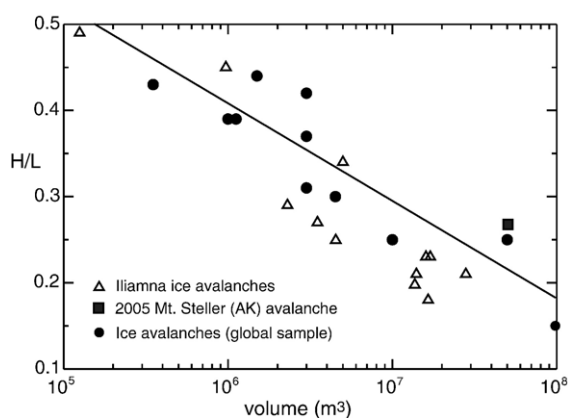


Fig. 10. Volume versus fall height (H) to runout length (L) of ice avalanches on Iliamna compared to other ice avalanches in non-volcanic terrain (a majority of data stems from events in the European Alps; Huggel et al., 2004, 2005). The Mt. Steller event refers to an ice-rock avalanche in the Bering Glacier area on September 14, 2005). A regression line based on the non-volcanic avalanches indicates that Iliamna avalanches have smaller H/L ratios and, thus, are more mobile.

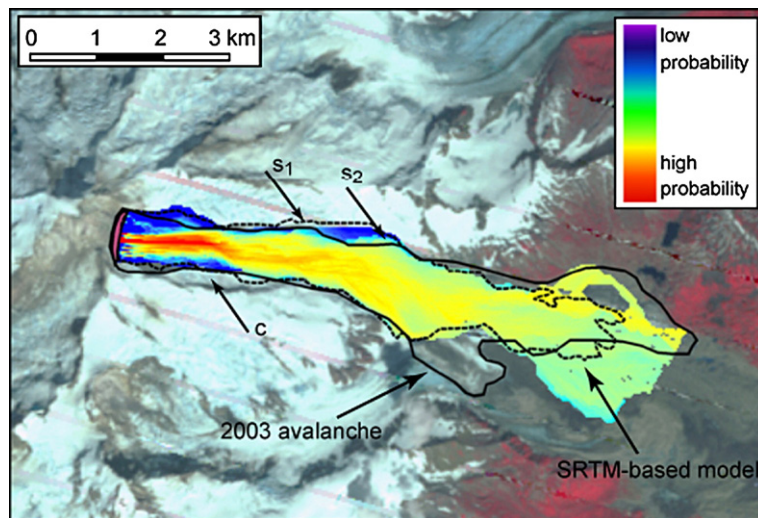


Fig. 11. Result of a simulation of the 2003 Red Glacier avalanche using the Modified Single Flow Direction model (MSF) in combination with a DEM derived from 2002 ASTER stereo images. Stopping conditions are defined by an H/L ratio of 0.21. Colors refer to a relative probability that a certain cell is affected in case of avalanche occurrence (cf. text). Also shown is the same simulation using the SRTM DEM, and the extent of the 2003 avalanche. s_1 and s_2 indicate superelevation-like lateral flow lobes while c refers to a wedge-like glacier segment not affected by the avalanche.

between 1400 and 2100 m asl (Fig. 12). Thus, the avalanche flow originating from the southern part of the failure zone was directed towards the center and left margin of the flow path. This is consistent with the evidence of two flow lobes resembling superelevations at the left (northern) flow path margin at about 950 and 1250 m asl., again a remarkably consistent feature of all

observed Red Glacier avalanches (Figs. 3, 12). However, the fact that the MSF model mimics both flow curves (yellow to green color scale, Fig. 11), indicates that there is no run-up process involved at these locations (the model does not simulate upward flow).

For a more detailed analysis of the dynamics of ice-rock avalanches at Iliamna more sophisticated dynamic



Fig. 12. Reconstructed flow dynamics of the 2003 Red Glacier avalanche. The temporal order of the two consecutive avalanche flows is shown by the number of the flow line. For s_1 and s_2 refer to Fig. 11. All these features can be consistently found with most Red Glacier avalanches. Note the snow and ice-free summit area of Iliamna.

models that more rigorously consider physical flow properties should be used. Among such models that have been applied to ice-rock avalanche-type rapid mass movements are Titan-2D (Sheridan et al., 2005), DAN3D (McDougall, 2006) or RAMMS (Christen et al., 2005). These models are more complicated in their use, computationally more intensive and require input parameters such as bed and internal friction, and turbulence terms that can be estimated from field data and iterative model runs.

5. Discussion

The avalanches on Iliamna Volcano are exceptional in terms of their large volumes and high occurrence frequency. To our knowledge, a similar combination of high-frequency and large-magnitude ice-rock failures has not been documented elsewhere. The similarity of failure model and propagation dynamics observed for Red Glacier avalanches is also noteworthy. Monitoring and analysis of these phenomena is important in fostering a better understanding of failure mechanisms on Iliamna, as well as to apply the results to ice-clad volcanoes in more populated areas with higher risk, such as Mount Rainier and Mount Baker in the Cascades, Pico de Orizaba in Mexico, Nevados del Ruiz and Tolima in Colombia, Cotopaxi in Ecuador or other volcanoes in the Andes.

Our goal in this study was to develop strategies to monitor ice-rock avalanches from ice-capped volcanoes. Due to commonly difficult access conditions we focused

on remotely applicable methods. The paper shows the application of a range of existing methods, i.e. seismic monitoring signal analysis, satellite based remote sensing, airborne observations and avalanche modeling. Fig. 13 provides a synthesis of addressed methods along a time axis, basically distinguishing between long-term monitoring, early warning, and event reconstruction and analysis. Early warning is currently the least developed part in terms of operational application. Long-term monitoring is the baseline activity and ideally leads to an improved understanding of failure conditions and avalanche mobility, providing early indication of possible mass instabilities.

In remote areas such as Alaska spaceborne observations are a particularly useful tool for monitoring. In this study we therefore used multispectral, including thermal, Landsat and ASTER data to analyze conditions relevant for mass failure. Image transformation techniques applied to a 2003 Landsat-7 ETM+ image was useful in identifying hydrothermally altered rock zones confirmed by previous field observations. Hydrothermal alteration can cause a reduction in rock strength during volcanic processes such as dike intrusion or non-eruptive degassing that generates or increases pore fluid pressure and thus promote lateral failure (Siebert et al., 1987; Day, 1996). Hydrothermal mapping may thus support geomechanical stability analysis as has been applied on volcanoes with much more detailed geologic information (e.g. at Mount Rainier, Reid et al., 2001). However, the relation between hydrothermal alteration and avalanche activity at Iliamna is not yet

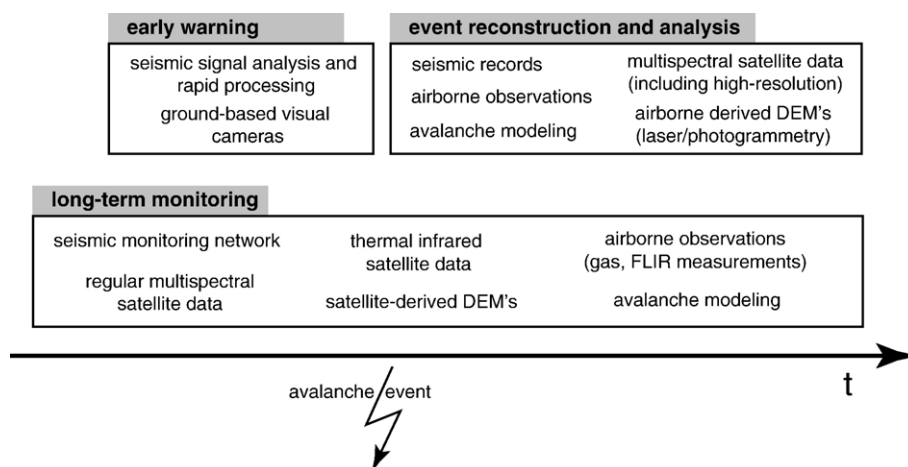


Fig. 13. Scheme representing the concept of (i) long-term monitoring, (ii) early warning, and (iii) event reconstruction and analysis on a time axis with reference to an avalanche event. The time axis is more indicative than quantitative. Long-term monitoring is a matter of years, early warning a matter of hours and event reconstruction and analysis can be done within days to years after the event. The monitoring methods within each category are aligned without referring to the time axis. The list of methods includes those addressed in this study and does not claim to represent a complete overview.

clear. Iliamna avalanches commonly fail in ice or at the ice-bedrock interface at the base of exposed hydrothermally altered rock. Reduced rock strength may favor instabilities at the base of the glacier (Fig. 14). A dike intrusion beneath Iliamna Volcano in 1996 (Roman et al., 2004) could have enhanced hydrothermal fluid processes resulting in increased pore pressure within the edifice, thus promoting instability at the base of the glacier. Thermal effects associated with volcanic activity are, in fact, another important destabilization factor at Iliamna. The ASTER based thermal analysis in the summit area has shown positive thermal anomalies. Repeated airborne observations of the northwestern summit area suggest that these thermal features are related to fumarolic activity. ASTER data and derived subpixel analysis could be used to constrain the size of the heat source in relation to temperature. Assuming a fumarole temperature of about 300 to 400 K results in a total heat source area of up to a few hundred square meters per ASTER pixel. Corresponding energy flux calculations with values of few thousands W m^{-2} strongly point to convective heat transport regimes along dykes or fumarolic vents. In case such excess heat be caused by conductive processes only, magmatic temperatures would be found at very shallow depths that were in contradiction to seismic findings (considering typical rock thermal conductivities of $\sim 2.5 \text{ W m}^{-1} \text{ K}^{-1}$). The suggested heat flow with related ground water transport and hydrothermalism indicates possible injection of liquid water at the glacier bed and enhanced ice melting. Short-term (seasonal) and long-term climatic effects and variations may also have an impact on temperature and stability conditions at the summit regions, and should be further investigated.

Further indication of increased heat flow at the Iliamna summit area comes from liquid water phenomena observed at the Red Glacier headwall (Fig. 14). Liquid water entering the glacier from the upstream headwall and together with water injection at the base of the glacier can strongly reduce the shear strength and promote failure. In fact, recent studies have found that Iliamna avalanches fail at lower slopes than ice avalanches in alpine non-volcanic terrains (Caplan-Auerbach and Huggel, 2007). The extraordinarily high frequency of large avalanches on Red Glacier is likely associated with high snow accumulation rates at Iliamna. The ice thickness is thus continuously increasing until the proportionally growing shear stress overcomes shear strength and failure occurs. Such periodic cycles of mass build-up and failure could also be an explanation for the striking similarity of the initiation zones of Red Glacier avalanches.

From a methodological point of view of long-term spaceborne TIR monitoring, we have confirmed the usefulness of ASTER thermal data for detection of low temperature thermal features as found by recent studies (Pieri and Abrams, 2005). A high instrumental sensitivity and spatial resolution is needed to overcome problems of the low signal-to-noise ratio of low temperature heat sources (Dehn et al., 2000). ASTER's sensor capabilities with $\text{NE}\Delta\text{T}$ of $\sim 0.3 \text{ K}$ are optimal; and its relatively high spatial resolution of 90 m allows better constraint on the size of heat sources. Detection of low temperature thermal anomalies is of significant interest for snow and ice-capped volcanoes because snow and ice can make it difficult to detect changes in geothermal heat flow due to their thermal buffer effect. Long-term monitoring of thermal features can also contribute to better detection of precursory signs of an eruption on Iliamna and other ice-clad volcanoes. Future

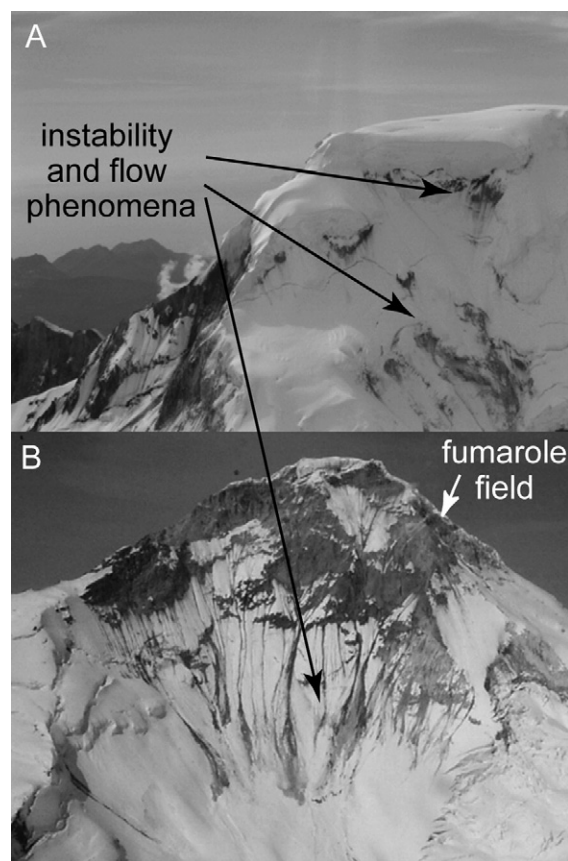


Fig. 14. Evidence for liquid water and small instabilities in hydrothermally altered rock in the summit region of Iliamna Volcano. A: instabilities at the snow/ice–rock interface at the north summit wall indicating existence of meltwater. B: Red Glacier headwall with several mixed flows involving water, snow/ice and rock debris (photos taken on August 7, 2004, by K. McGee).

studies could further investigate ASTER thermal data to better understand steady-state geothermal heat flow and local heat sources such as fumaroles, and its effect on the stability of glaciers on Iliamna. If corresponding resources are available, spaceborne TIR measurements can be complemented by specific airborne FLIR campaigns for higher-resolution results.

The real-time seismic network on Iliamna is part of a long-term monitoring effort, an important tool for detection and location of avalanches, as well as the crucial component of possible future early warning of avalanches. As regards early warning, of special relevance is the characteristic precursory signal that seismic instruments record up to two hours before failure of ice (Caplan-Auerbach et al., 2004; Caplan-Auerbach and Huggel, 2007). Whether these signals may some day be used for avalanche warning depends on the feasibility of timely and unambiguous identification of precursory avalanche signals. It also depends upon more practical aspects of signal processing and the timing of warnings issued to the public. Although there is need for more investigation of the relationship between avalanche failure and corresponding seismic signals, the repetitive nature of the signal in combination with the increasing occurrence rate of events allows a clear recognition of an ice failure process. The phase of discrete earthquakes about 2 h before failure is a first indication of an impending failure. Because repeating low-frequency earthquakes are not uncommon in volcanic regions, identification of the signal as precursory to an avalanche may require observation of the continuous ground shaking that occurs 0.5 to 1 h before failure. In other words, the time available for warning may be ≤ 0.5 h. To ensure effective warning within this period of time, a clearly defined chain of semi to fully automated processes would have to be developed including rapid seismic signal processing, reliability checks, and information transmission to responsible government agencies. In consideration of the current understanding and available techniques, timely seismic signal detection and processing is the weakest component. Future efforts should therefore be directed to improve rapid hypocentral locations, seismic focal mechanisms, and estimates of source volume of such ice-failure processes. Seismic instruments could be supported by automatic video cameras with real-time transmission. Large avalanches are typically preceded by smaller failure events that could be detected by the camera, and thus the reliability of early warning releases could be increased.

From a hazards point of view, Iliamna avalanches pose little risk to population or infrastructure due to the remoteness of the mountain. In more populated areas,

however, similar mass failures from ice-clad volcanoes could have devastating consequences, such as at Mount Rainier for example (Hoblitt et al., 1998). The operational lahar warning system at Mount Rainier (Driedger and Scott, 2002) may, in fact, be a model for a future warning system for ice avalanches. Lahars are detected by acoustic flow monitors and have arrival times of ~ 40 min or less depending on the location along the flow path. These time scales are similar to what we believe could be a realistic warning time for ice avalanches. In consideration of the described technical potential and limitation, a two or three-stage warning could be implemented, where the first stage is merely an alert based on the precursory avalanche signal and possibly complementary visual information ~ 2 h before possible failure. The second warning phase would be activated if the transition into continuous ground shaking was observed (~ 0.5 to 1 h before failure), and the third phase would consist in an urgent evacuation alarm released when the spindle-shaped seismic signal is recorded. Obviously, the system would need to be adapted to any local situation. For instance, according to avalanche speed and travel path length, the time for the urgent last warning stage may allow only a few minutes to rush out of the avalanche flow path, but still be better than no alarm and able to save lives.

We have also presented several methods for avalanche reconstruction and analysis, including spaceborne and airborne imagery, DEM analysis and GIS-based avalanche modeling. Avalanche mapping is best done using ASTER and Landsat data in conjunction with DEM analysis while the study of avalanche dynamics is best supported by airborne observations, velocity constraints provided by seismic records, and numerical avalanche modeling. Simple GIS-based avalanche models can map potentially affected areas (or reproduce inundated areas from past avalanches) but have limited capabilities for understanding avalanche dynamics. More physically based models with numerical solutions to the equations of motion allow deeper insight.

ASTER-derived DEM's have proven to be a reasonable basis for avalanche models. Our analysis of the mobility of Iliamna avalanches has shown that for their volume they achieve greater runout than other ice avalanches (Fig. 10). The higher mobility of Iliamna avalanches may be due to the fact that the flow path is largely over glacial ice that exerts a lower friction than that in non-glaciated terrain. None of the documented avalanches has shown flow transformation to more mobile lahar-type processes. Field evidence collected by Waythomas et al. (2000), however, indicated that lahars resulting from flank collapse and debris avalanche have

repeatedly occurred during late Holocene and historical times. It is remarkable and important for hazards assessment that the most recently dated lahar (90 ± 60 yr BP) may not have been associated with an eruption. This means that the frequent avalanches observed recently could be significantly enlarged by a major instability of the hydrothermally altered rock (possibly a flank collapse) in the absence of an eruption. Under these conditions, avalanche and lahar mobility would be much higher than that observed for recent avalanches. The potential of non-eruption related large mass failures at Iliamna and its significance for hazards on other volcanoes underlines the importance of monitoring and modeling studies at this volcano.

6. Conclusions

Iliamna Volcano is unique because it frequently produces large ice-rock avalanches. We have presented an extended record of avalanche activity for the past few decades demonstrating that Iliamna avalanches are beyond the domain of commonly found frequency-magnitude scales of mass failures in volcanic terrains.

We have applied a variety of monitoring and modeling methods to better understand the nature of Iliamna avalanches, and have outlined how they fit into a concept of (1) long-term monitoring, (2) early warning, and (3) event reconstruction and analysis. For highly remote volcanoes such as Iliamna, spaceborne observations and the automatic seismic network are the primary tools for long-term monitoring. For instance, ASTER thermal data, with its high instrumental sensitivity, is fundamental in the study of low temperature thermal anomalies on ice-capped volcanoes, and thus is critical to detect signs of increased volcanic activity and its relation to mass failures. Coupling of such thermal information with distributed glacier mass balance and 3-D energy flux models could greatly improve the understanding of failure mechanisms in the future.

Seismic signal processing is the core of any suggested early warning effort. We have shown the potential and limitations that currently exist for a possible warning system, and have outlined a possible design of such a warning system in the future. Techniques for rapid identification and analysis of precursory seismic signals, and avalanche source volume estimates should thereby be further developed to exploit their potential towards avalanche hazard warning.

We have furthermore shown that documentation and analysis of avalanche events in remote regions can be achieved by investigating spaceborne and airborne images, and avalanche dynamics can be studied by

additionally integrating seismic signals, satellite-derived terrain data and avalanche flow modeling.

An avalanche hazard exists at Iliamna Volcano, but because the area is uninhabited, the risk to life and property is low. The development and application of monitoring techniques for ice-rock failures, however, may be of major interest to other ice-capped volcanoes where the risks are more serious. We have provided an example of assessment and monitoring techniques that could be applied to other remote and difficult to access volcanoes, and which may contribute to improvements in understanding of mass failure and corresponding assessment of hazards.

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