The 2005 Mt. Steller, Alaska, Rock-Ice Avalanche: A Large Slope Failure in Cold Permafrost

Christian Huggel, Stephan Gruber
Glaciology, Geomorphodynamics & Geochronology, Department of Geography, University of Zurich
Jaqueline Caplan-Auerbach
Geology Department, Western Washington University, Bellingham WA, USA
Rick L. Wessels
U.S. Geological Survey, Alaska Science Center - Alaska Volcano Observatory, Anchorage AK, USA
Bruce F. Molnia
U.S. Geological Survey, Reston VA, USA

Abstract
This paper describes and analyzes the exceptionally large rock-ice avalanche of 40 to 60 million m³ volume that occurred in 2005 from the south face of Mt. Steller (Bering Glacier region, Alaska), which has steep glaciers at the summit. Analysis of seismic signals revealed a series of precursory rock/icefalls and a special sequence interpreted as slip and deformation in glacier ice. Reconstruction of the thermal conditions based on regional climate and radiosonde data yielded mean annual ground surface temperatures of -10 to -15°C for the failure area. Because the slope failure was at depths of meters to decameters we also performed numerical modeling of a 2D temperature profile across the mountain. Results showed that the existence of a hanging glacier in the summit area induces a deep-seated thermal anomaly. We subsequently outline a number of processes that may be effective for slope destabilization with the given thermal conditions.

Keywords: cold permafrost; Mt. Steller, Alaska; rock-ice avalanche; seismic signals; steep glacier; thermal modeling.

Introduction
A large rock-ice avalanche of 40 to 60 million m³ occurred on 14 September 2005 from the southern flank of Mt. Steller in the Bering Glacier-Bagley Ice Field region. The initial failure from a maximum elevation of 3100 m a.s.l. involved significant volumes of both rock and ice from steep glaciers. The avalanche mass travelled for almost 10 km and was deposited on Bering Glacier. As we will show, the failure was from areas in cold permafrost conditions, with the area of failure being thermally disturbed by an overlying steep glacier. Understanding of such large slope failures is important in the context of atmospheric warming and the potentially severe consequences in case of similar events in populous regions.

Increasing temperatures can destabilize frozen rock (Gruber & Haeberli 2007). Recent studies have demonstrated that not only rock surface temperatures but also temperature distribution at depth should be considered for slope stability, and have simulated the effects of projected climate change on the thermal regimes of different mountain topography (Noetzli et al. 2007). In Alaska, atmospheric warming and a related increase of permafrost temperatures have been generally strong in the 20th century. According to borehole observations in low-land areas, permafrost temperatures in the 20th century warmed by 2–4°C by the early 1980s (Lachenbruch & Marshall 1986) and up to 2–3°C during the past two decades (Osterkamp & Romanovsky 1999, Osterkamp 2007). The rise of permafrost temperatures, however, has not been as consistent as the rise of air temperatures in Alaska, mainly because of the influence of local factors (e.g., snow cover) on the energy balance (Osterkamp 2007). Knowledge on the evolution of permafrost temperatures in Alaskan high-mountain areas is scarce.
Steep glaciers in mountain walls can induce complex thermal anomalies in perennially frozen bedrock. A limited number of studies have shown that even in cold permafrost conditions, overlying glaciers can create temperatures close to phase equilibrium at the ice-bedrock interface (Wegmann et al. 1998, Haeberli et al. 1999). Because on-site access to large high-mountain walls is very limited and often impossible, investigations are typically restricted to remotely based measurements and modeling, although systematic rock temperature measurements exist in the Alps where site access is comparably easy (Gruber et al. 2004).

Seismometers have been used to study rapid mass movements resulting from slope failures (e.g., Weaver et al. 1990, Norris 1994). More recently, seismology has been used as a tool to analyze slope failure processes up to two hours before avalanche initiation (Caplan-Auerbach et al. 2004, Caplan-Auerbach & Huggel 2007), thus revealing new possibilities for the investigation of slope failures.

This study aims at reconstructing the 2005 failure and avalanche at Mt. Steller and the factors that led to this event. Although the site geology is fundamental for the slope failure we will concentrate here on the thermal conditions at the failure site and related transient effects such as atmospheric warming and overlying glaciers. More generally, we want to improve our understanding of large slope failures in steep terrain in cold permafrost and discuss the possible influence of thermal disturbance.

The 2005 Mt. Steller Avalanche

Mt. Steller (3236 m a.s.l., 60°13′N, 143°05′W) is part of the Waxell Ridge, a bedrock massif that separates the Bagley Ice Field from Bering Glacier (Fig. 1). Climatically, Mt. Steller is located close to the divide between the warmer and more humid climate of coastal Alaska and the drier and colder interior of Alaska. Geologically, the Steller S-face consists of tertiary sedimentary rocks that are layered sub-parallel to the surface slope in the failure zone.

The Waxell Ridge is a very remote area with difficult access conditions and almost only visited from the air. The 14 September 2005 rock-ice avalanche from Mt. Steller was identified because its associated seismic signals were recorded at seismometers throughout Alaska and around the world. The Alaska Earthquake Information Center reported that the event had an equivalent local magnitude of 3.8, while analysis of global long period waves yielded a magnitude of 5.2 (G. Ekstrom, personal communication, 2005). Due to the complicated access conditions of Mt. Steller, we based the reconstruction of the rock-ice avalanche on available remotely operating systems such as satellite imagery, airborne observations, and seismic recordings. We used a Landsat ETM+ scene taken a few hours after the avalanche on 14 September 2005 and photographs from a fixed-wing flight the day immediately after the event, repeated in Summer 2006 and 2007. Topographic information was derived from the USGS NED (2 arc sec, ~60 m) digital elevation model (DEM) and available topographic maps. Data from climate stations and radiosonde measurements in the region were used for temperature reconstruction at the Steller site.

The 2005 rock-ice avalanche initiated in the S-face of Mt. Steller that has an average slope of 45° and an elevation drop of 1600 m. At the uppermost section, this face is covered by steep glacier ice which extends over the ridge to the northern side. At the time of the avalanche, the S-face of Mt. Steller was extensively covered by snow, as is typical
of mountain walls in this region. The photographs taken the
day after the event show that a significant part of the hanging
glacier, along with large volumes of bedrock, was involved
in the avalanche (Fig. 2). We estimate that 3 to 4.5 million
m$^3$ of glacier ice with ice thickness of 20 to 30 m failed. The
failure volume of rock is difficult to assess without precise
topographic data. It is evident that almost the entire S-face
was affected by the avalanche, but it is not clear which
bedrock areas actually failed and which ones were only
affected by the passing avalanche. We estimate that bedrock
failed between 2500 and 3100 m a.s.l. and crudely estimate
the initial rock volume at 10 to 20 million m$^3$. Additionally,
another 2 million m$^3$ of snow may have been involved in the
initial avalanche.

The rock and ice mass from the Mt. Steller avalanche
impacted the glacier at the toe of the S-face that extends
from ~1700 m a.s.l. towards the south, and eroded several
millions of m$^3$ of glacier ice. The avalanche then traveled on
the glacier surface in a laterally confined valley for about
4 km until it reached the relatively flat surface of Bering
Glacier where the mass spread and stopped on the debris-
covered ice (Fig. 3). The total horizontal run out distance
was 9 km, whereas the drop height was 2430 m, with the
uppermost failure point at ~3100 m a.s.l. and the lowest
run.out point at 670 m a.s.l. The total avalanche volume
deposited on Bering Glacier can be reconstructed with an
area of 4 km$^2$ and an average deposit thickness of 10 to 15 m
using the undulating topography of the moraine ridges that
were filled by the avalanche deposits as a height reference.
This yields a total avalanche volume of 40 to 60 million m$^3$;
and thus, the 2005 Mt. Steller avalanche ranges among the
largest avalanches observed in recent decades worldwide.
These volume estimates furthermore indicate that the initially
failed glacier ice made up about 10% of the total avalanche
volume, and that probably about 5 to 30 million m$^3$ of ice,
snow, and debris were entrained along the avalanche path.

Seismic Response

Seismic recordings played a particularly important role in
the detection and analysis of the 2005 Mt. Steller avalanche.
First analyses of seismic signals recorded at several Alaskan
stations showed spindle-shaped seismograms typical of
mass movements such as rockfall and debris avalanches
(Weaver et al. 1990, Norris 1994, Caplan-Auerbach et al.
2004) or snow avalanches (Suriñach et al. 2001). Based
on the duration of these signals and the horizontal runout
distance, we estimated an avalanche speed of ~100 m/s
or possibly even more. It is not completely clear why the
avalanche produced such a large seismic signal that was
recorded all over the world, but the steep topography with
the high S-face and the resulting strong impact at the toe of
the face must have contributed to this. The large size of the
seismic signal also supports our estimate that a very large
mass of >20 million m$^3$ was involved in the initial failure.

Another remarkable aspect of the seismic signal analysis

![Seismic signal surrounding the 2005 avalanche at Mt. Steller. The top panel shows the time series of groundshaking as recorded at
station KHIT, 12 km to the SW of Mt. Steller. The bottom panel is a spectrogram representing signal strength at different frequencies for the
time series, with white representing stronger signals. The avalanche is visible at ~2150 seconds into the record. Because the amplitude of the
avalanche is so large, a close-up of the precursory time series is shown in the inset. Note the different vertical scales on the two time series.
(We acknowledge the Alaska Earthquake Information Center for operating the network and providing the data.)](image-url)
at Mt. Steller was an unusual precursory seismic sequence occurring up to 30 minutes prior to failure. It should be noted that avalanches initiating in snow or rock have not been observed to exhibit precursory seismicity (Norris 1994, Suriñach et al. 2001, Caplan-Auerbach et al. 2004). Recent studies at Iliamna Volcano (3050 m a.s.l., 60.03°N, 153.09°W) in the Cook Inlet region of Alaska, however, have demonstrated that such precursory signals do occur with avalanches that initiate in ice or at the ice-bedrock interface (Caplan-Auerbach & Huggel 2007). The Mt. Steller precursory seismic signals mimic those at Iliamna in that they exhibit a series of discrete earthquakes which increase in occurrence rate for ~15 minutes before they gradually transform into a continuous ground-shaking (Fig. 4). The 15–20 minute continuous signal eventually culminates in a strong, broadband, spindle-shaped signal believed to represent the actual avalanche. At Iliamna, Caplan-Auerbach & Huggel (2007) interpreted the precursory seismic signals as deformation and slip movement in the ice with slip rates accelerating as failure approaches, and we propose the same mechanism for the Mt. Steller event. The evidence for relating the precursory seismic signals to failure in ice and not in rock supports a model in which the ice of the subsequently failed hanging glacier began to move over 30 minutes prior to failure. This, however, does not necessarily imply that the Mt. Steller avalanche initiated in ice and not in rock. Closer observation of the seismic signal (Fig. 4) shows that a number of smaller avalanches, represented by broadband, spindle-shaped signals, occurred prior to and during the precursory slip events. While the signals of these precursory slip events are well-defined at specific frequencies (i.e., at ~2, 3 and 4 Hz, Fig. 4) the smaller avalanches are identifiable by their broadband spectrum (i.e., all the way up to 10 Hz and more) at ~750, 1000, 1200 and 1500 seconds (Fig. 4). This suggests that the first stages of failure included rock, and that these initial slope failures could have triggered slip along the base of the hanging glacier. Unfortunately, because of the small (<M1) magnitude of the events and sparse nature of the regional seismic network, precise epicentral locations cannot be calculated for the precursory seismicity. However, examination of S-P times at station KHIT suggests a location at a distance consistent with a source at Mt. Steller.

**Permafrost Analysis and Failure Interpretation**

The purpose of this section is a first estimate of the permafrost conditions at the failure site, including the thermal regime at depth. Our thermal model presented here provides some general and basic insights but may have limitations compared to real conditions at Mt. Steller. We highlight the thermal interaction of permafrost with glacier ice and possible relations to slope stability and failure.

The reconstruction of the thermal ground conditions at the failure site was chiefly based on radiosonde data from Yakutat, located 270 km SE of Mt. Steller, and the closest regional meteorological stations (Cordova, Yakutat, McCarthy, Chitina, Ernestine, and Thompson Pass, 3 to 760 m a.s.l.). The Yakutat radiosonde data yielded a mean annual air temperature (MAAT) of -10.5°C at 3000 m a.s.l. considering the period 1994–2007. However, vertical temperature extrapolation from the closest meteorological stations in the warmer and more humid climate of the Alaskan S-coast using a lapse rate of 0.0065°C m⁻¹ derived from radiosonde data resulted in a MAAT of -15.5°C at the 3000 m a.s.l. level. Some, but not all, of this temperature difference may be explained by the fact that the MAAT extrapolated from ground-based climate stations was derived from a 50-year record and, therefore, does not fully reflect the recent warming in Alaska. For subsequent assessment and thermal modeling, we applied the radiosonde-based MAAT value since it may reasonably be assumed that the temperature record of the more homogeneous troposphere is a more accurate approximation of conditions at Mt. Steller than are local ground stations. We set the mean annual ground

![Figure 5. 2D rock temperature distribution in a N-S cross section of Mt. Steller. Distance and elevation a.s.l. are in meters, isotherms in °C. A: Rock temperature without considering overlying glaciers. B: Rock temperature with overlying glaciers (ice depth not in scale). Note the temperature differences at the summit area for A and B.](image-url)
surface temperature (MAGST) 3°C warmer than MAAT for the S-face and 1°C warmer than MAAT for the N-face of Mt. Steller (Haebeli et al. 2003, Gruber et al. 2004). Our analysis of thermal conditions at Mt. Steller was concerned with the temperature distribution at the surface and at depth since the failure depth reached meters to decameters depth. Recent studies using a modeling scheme with surface temperature (Gruber et al. 2004) and 3D subsurface heat conduction calculation (Noetzli et al. 2007) have demonstrated the distribution of temperature for idealized 3D topography such as ridges. For Mt. Steller, we calculated a 2D temperature profile along a N-S cross section. Subsurface temperatures were simulated using a steady-state, two-dimensional, finite-element, heat conduction model of 10.5 km width having a base 2000 m below sea level. The upper boundary condition was given by estimated surface temperature (see above), and an inward heat flux of 0.08 W/m² was set at the lower boundary. The thermal conductivity for rock was assumed to be homogeneous and isotropic at 2.5 W/m/K, a reasonable average value for sedimentary rock. Noetzli et al. (2007) have shown that realistically small variations of the thermal conductivity do not significantly affect the model result. Transient model runs were not considered because the corresponding boundary conditions for this remote area are poorly known and would introduce additional uncertainty.

We first modeled a temperature profile assuming there was no summit glacier on Mt. Steller (Fig. 5A). Results show steeply inclined isotherms at the summit area with heat flux from S to N, and less inclined isotherms below the summit. Studies in the Alps have demonstrated that steep glaciers in conditions with MAAT of about -5 to -10°C have a cold-based front frozen to the ground but can show much warmer or even phase-equilibrium temperatures at the upper part (Haebeli et al. 1997, 1999). This is due to latent heat dissipation from percolating and refreezing meltwater in the snow and firn layer. For the second model, which includes the summit glacier ice (Fig. 5B), we, therefore, assumed cold ice for the front of the S-face glacier; entirely cold ice conditions for the N-face glacier; and temperate ice for the upper part of the summit ice apron, as well as for the glaciers at lower elevations of the N and S face. Model results show the deep-seated thermal anomaly induced by the glacier ice with bedrock temperatures at the summit region close to phase transition up to several decameters depth (Fig. 5B). Exposed bedrock in the S-face below the hanging glacier is several degrees colder.

Based on our assumptions, the existence of temperate ice and liquid water at the Mt. Steller summit area is possible. Relatively large amounts of liquid water on the bedrock of the formerly glacier-covered failure zone (Fig. 2) photographed a few hours after the avalanche in cloudy weather conditions likely also hint at this; however, this water could also stem from immediate snow/ice melting after the event. Irrespective of the source of liquid water (i.e., from the base of the glacier and/or subsurface rock, or from recent snow/ice melting), it is evidence of quite significant melting conditions at the ~3000 m a.s.l. level at Mt. Steller.

Despite incomplete information, we hypothesize a temperature-related destabilization, with a likely influence of the strong recent warming in Alaska. A MAAT increase of 2–4°C during the past decades could have penetrated several decameters into the bedrock; additionally, the Mt. Steller summit glacier likely experienced a transition to warmer temperatures where infiltration has become more frequent and has warmed large portions of the glacier, possibly to phase equilibrium temperatures. The Yakutat radiosonde data, in fact, is evidence that temperatures above freezing repeatedly persisted at elevations of the Mt. Steller summit in the past few years as late as September. The ~10 days prior to the 2005 failure were characterized by particularly warm temperatures above freezing; and correspondingly enhanced melting could likely have contributed to the slope failure.

A system of well-developed cracks is observable in air photos and could have experienced corresponding effects of hydrostatic pressure variations. However, the 2005 slope failure also involved large parts of bedrock at lower elevation that was not glacier-covered but was in cold permafrost conditions (Fig. 5). It is not clear which mechanisms contributed to the slope failure in this zone, but an effect of the upper warmer part is imaginable. For instance, variations of hydrostatic pressure and effective stress induced by the upper part could cause micro fractures and progressive failure in the lower part (Eberhard et al. 2004).

Discussion and Conclusions

We have described the 2005 rock-ice avalanche from Mt. Steller in the Bering Glacier region, Alaska, which was one of the world’s largest slope failures and avalanches of the past decades. We have focused on the conditions of failure, with a particular eye on the surface and subsurface thermal regime. Seismic signals contributed to an improved understanding of the failure mechanism by providing evidence of precursory rock/ice-falls and indication of deformation and slip of the overlying glacier ice. It is only recently that such processes in glacier ice prior to failure were discovered in seismic signals and more investigation is needed to better constrain the involved mechanisms.

The MAGST reconstruction at the failure zone was mainly based on radiosonde data and yielded temperatures of about -4 to -8°C. Numerical modeling allowed us to estimate the subsurface temperature distribution at Mt. Steller, demonstrating the deep-seated thermal effect of overlying steep glaciers on bed rock temperatures at depth. The radiosonde data should well reflect the recent strong warming in Alaska, and, according to these temperatures, the assumption of polythermal and temperate ice in the S-face and on the summit is reasonable. Nevertheless, there is an uncertainty in the boundary conditions of the thermal model which may range within ~2–3°C.

Our understanding of temperature-driven slope destabilization processes at mountains with permafrost is still very incomplete. So far, based on this study and a
number of recent similar slope failures (Haeberli et al. 2003, Huggel et al. 2005, Fischer et al. 2006), we conclude that the existence of steep glaciers in cold permafrost mountains is an important and quickly changing factor of slope stability.

Acknowledgments

These studies were partly supported by funds of the Swiss National Science Foundation and the USGS Mendenhall Postdoctoral Program. We very much thank R. Homberger and P. & D. Claus for providing photographs. Helpful comments by P. Deline, M. Wegmann, and the editor D. Kane are acknowledged.

References


