GÉORISQUES IV GEOHAZARDS

RECONNAISSANCE OBSERVATIONS OF THE JULY 24, 2007 ROCK AND ICE AVALANCHE AT MOUNT STEELE, ST. ELIAS MOUNTAINS, YUKON, CANADA

Panya. S. Lipovsky
Yukon Geological Survey - Government of Yukon, Whitehorse, Yukon, Canada, Panya.Lipovsky@gov.yk.ca
Stephen G. Evans
Department of Earth and Environmental Sciences - University of Waterloo, Waterloo, Ontario, Canada
John J. Clague
Department of Earth Sciences - Simon Fraser University, Burnaby, British Columbia, Canada
Chris Hopkinson
Applied Geomatics Research Group - Centre of Geographic Sciences - Nova Scotia Community College, Lawrencetown, Nova Scotia, Canada
Réjean Couture & Peter Bobrowsky
Geological Survey of Canada - Natural Resources Canada, Ottawa, Ontario, Canada
Göran Ekström
Lamont-Doherty Earth Observatory - Columbia University, New York, United States
Michael N. Demuth
Geological Survey of Canada - Natural Resources Canada, Ottawa, Ontario, Canada
Keith B. Delaney & Nicholas J. Roberts
Department of Earth and Environmental Sciences - University of Waterloo, Waterloo, Ontario, Canada
Garry Clarke & Andrew Schaeffer
Department of Earth and Ocean Sciences - University of British Columbia, Vancouver, British Columbia, Canada

RÉSUMÉ
Une avalanche catastrophique de roc et de glace est survenue le 24 juillet 2007 sur le flanc nord du Mont Steele, Territoire du Yukon, déposant des débris sur le glacier Steele. Cette même pente a été lieu d'au moins trois petits glissements de terrain au cours des jours et des semaines précédents l'événement principal. Des évidences d'activité antérieure de glissements de terrain dans la région sont observables sur des photographies aériennes historiques datant des années 1930. L'événement du 24 juillet fut l'une des plus grandes avalanches rocheuses documentées au sein des montagnes St. Elias au cours du dernier siècle et l'une des 16 avalanches rocheuses connues ayant survenues sur des pentes rocheuses adjacentes à des glaciers dans la Cordillère canadienne depuis 1947. L'enregistrement de données séismiques indique que l'événement a duré approximativement 100 secondes et a généré une onde de surface à longue période de magnitude 5.2. Nous avons initié des recherches afin d'étudier la morphologie des dépôts du glissement de terrain, les causes et les mécanismes de rupture, ainsi que les impacts sur le bilan de masse du glacier. Nos travaux mettent en lumière les bénéfices d'une coopération multidisciplinaire lors d'investigation d'événements catastrophiques.

ABSTRACT
A catastrophic rock and ice avalanche occurred on the north face of Mount Steele, Yukon Territory, on July 24, 2007, depositing debris onto Steele Glacier. In the days and weeks preceding the event, at least three smaller landslides initiated from the same slope. Earlier landslide activity at this location is evident on historical photographs dating back to the 1930s. The July 24 event was one of the largest rock avalanches documented in the St. Elias Mountains in the past century and is one of 16 rock avalanches known to have occurred from rock slopes adjacent to glaciers in the Canadian Cordillera since 1947. Seismic records indicate that it lasted approximately 100 seconds and had a long-period surface-wave magnitude of 5.2. We have initiated research to study the morphology of the landslide deposits, the causes and mechanisms of failure, and impacts on glacier mass balance. Our work highlights the value of multi-disciplinary cooperation for investigating catastrophic events.

1. INTRODUCTION

In July 2007, at least three rock and ice avalanches occurred on the steep glaciated north slope of Mount Steele, Yukon Territory, Canada. The largest of these events (hereafter referred to as the "main event"), occurred at 17:57 h local time on July 24 (July 25, 00:57 UTC). This event was one of 16 large rock avalanches onto glaciers that have been documented in the Canadian Cordillera since 1947 (Evans and Clague 1999). Several other rock avalanches have been documented in nearby Alaska since 1964 (Post 1967; Jibson *et al.* 2006; Molnia *et al.* 2006). The

In : J. Locat, D. Perret, D. Turmel, D. Demers et S. Leroueil, (2008).
Comptes rendus de la 4e Conférence canadienne sur les géorisques: des causes à la gestion.
Proceedings of the 4th Canadian Conference on Geohazards : From Causes to Management. Presse de l'Université Laval, Québec, 594 p.

occurrence of these events highlights that steep rock slopes adjacent to glaciers are particularly prone to catastrophic landslides.

This paper briefly summarises the physical setting, event chronology, and preliminary characterisation of the July 2007 rock and ice avalanches at Mount Steele. Reconnaissance field observations, seismological records, and high-resolution aerial LiDAR survey data were used to support this work. Discussions and collaboration, involving a diverse team of scientists from Canada and the United States, have facilitated reporting of important findings in a timely fashion, demonstrating the value of multi-disciplinary cooperation in the investigation of catastrophic events.

2. PHYSICAL SETTING

Mount Steele (61º05'35.4''N, 140º18'38.4''W, 5067 m a.s.l.) is the fifth highest mountain in Canada and the tenth highest peak in North America. It is located in an uninhabited region of southwest Yukon Territory, in Kluane National Park (Figure 1). The mountain lies within the Icefield Ranges of the St. Elias Mountains, in an area of extremely rugged, snow- and ice-covered mountains that are surrounded by broad valley glaciers.

The July 2007 ice and rock avalanches initiated at 4650 m elevation on the steep north face of Mount Steele. The face is blanketed by approximately 30 m of glacier ice and firn and descends over 2100 m to upper Steele Glacier (Figure 2). Steele Glacier flows approximately 35 km from the base of Mount Steele to its terminus at 1160 m a.s.l. Steele Creek flows from the toe of the glacier and joins Donjek River 12 km to the east.

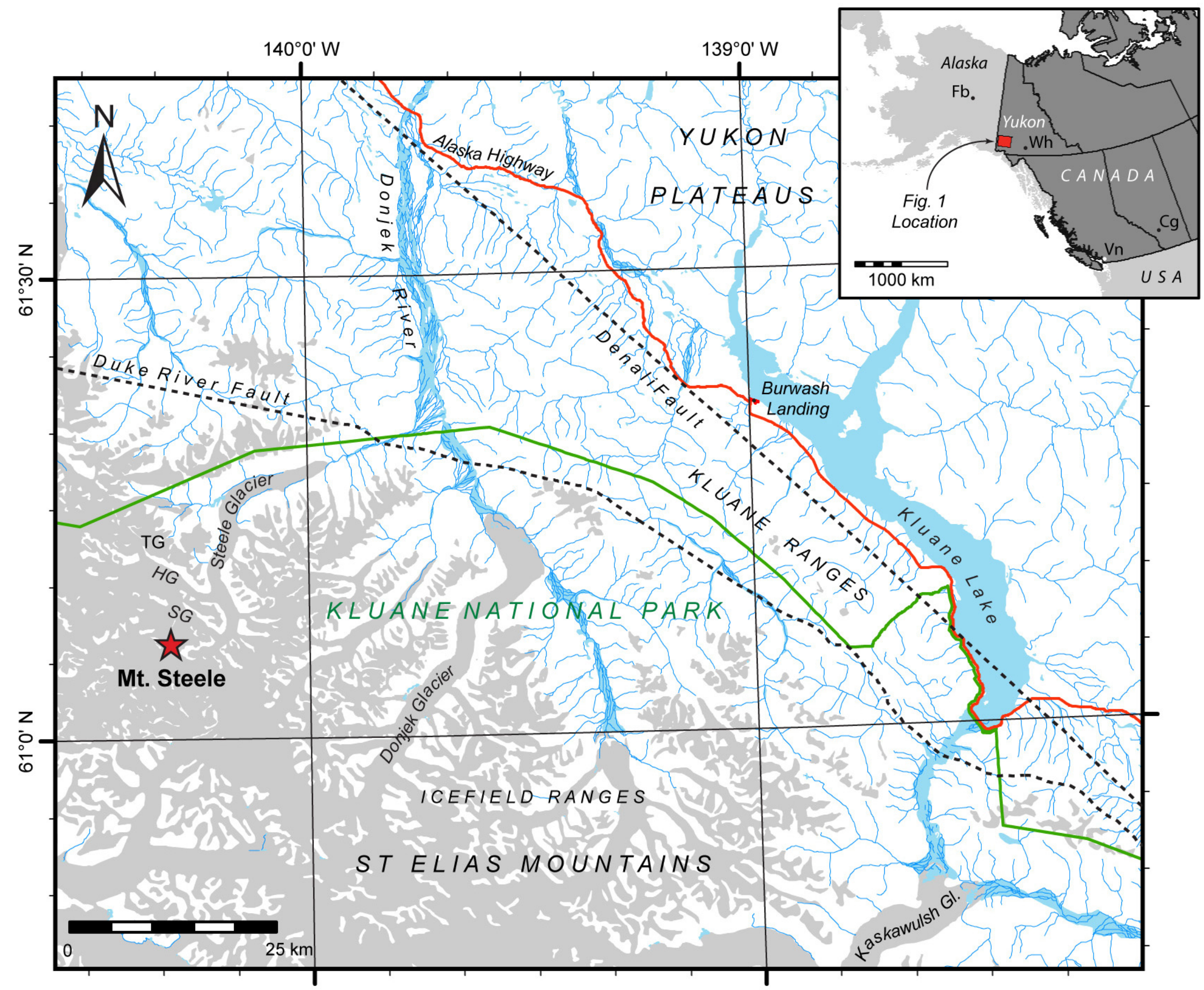

Figure 1. Map showing location of Mount Steele and major physiographic features. SG = Steele Glacier, HG = Hodgson Glacier, TG = Trapridge Glacier. Selected cities shown in inset map (Wh = Whitehorse, Vn = Vancouver, Cg = Calgary, Fb = Fairbanks).

The Alaska Highway crosses Donjek River about 40 km downstream from its confluence with Steele Creek (Figure 1). The highway is Yukon's main transportation corridor and parallels a proposed natural gas pipeline that would deliver gas from the North Slope of Alaska to markets in the conterminous United States. The nearest settlement to Mount Steele is Burwash Landing (807 m a.s.l), which is located 76 km northeast of the peak.

Burwash Landing has a semi-arid continental climate, with mean annual precipitation of 280 mm and mean annual temperature of -3.8° C (Environment Canada normals for 1971-2000). At a weather station at 2670 m a.s.l., 52 km southeast of Mount Steele, the mean annual temperature between 2003 and 2005 ranged from -8.8° C to -9.5° C (C. Zdanowicz, unpublished data). The mean annual temperature at 5000 m a.s.l. is estimated to be -22° C (Smith *et al.* 2004).

The geology of Mount Steele has not been mapped in detail, but regional geological maps show the north face of Mount Steele to be composed of granodiorite, diorite, and gabbro of the Late Miocene Wrangell Suite (Dodds and Campbell 1992). These rocks intrude late Proterozoic to Triassic volcanic and sedimentary rocks of the Alexander Terrane (Wheeler *et al.* 1991; Dodds and Campbell 1992; Gordey and Makepeace 2003).

Active seismicity and rapid rates of tectonic uplift in southwest Yukon are related to convergence and subduction of the Pacific plate beneath the North American plate off the south coast of Alaska (Horner 1983; Everard and Savigny 1994; Bruhn *et al.* 2004). Two major northwest-trending fault systems, the Denali and Duke River faults, are located 30 and 65 km, respectively, from Mount Steele. The Denali Fault is active in nearby Alaska (Haeussler *et al.* 2004), but not in Yukon (Clague 1979). Earthquake epicentres in southwest Yukon are instead concentrated along the Duke River Fault system. The extreme relief seen in the St. Elias Mountains today is largely a result of rapid tectonic uplift combined with accelerated regional erosion by glaciers, streams, and landslides (Pavlis *et al.* 2004; Spotila *et al.* 2004).

3. EVENT CHRONOLOGY

The 2007 rock and ice avalanches traveled down a steep gully system on the north face of Mount Steele (Figure 2). Previous landslides at the same location have been noted on historical photographs taken during scientific expeditions in the late 1930s (Wood 1972; F. Wood, unpublished data, 1939).

Despite the remoteness of Mount Steele, the July 2007 rock and ice avalanche events have been very well documented. Fresh rock debris is evident in the gully system in photographs taken by glaciologists flying to Trapridge Glacier on July 14, 2007. A day later, the glaciologists noted a large crevasse that had developed in the glacier immediately above the gully system. On July 21, a park warden photographed the deposits of at least two fresh debris flows that reached the bottom of the gully system.

On July 22, at approximately 13:25 h local time (Pacific Daylight Time), the glaciologists at Trapridge Glacier witnessed a large ice avalanche that initiated when a slab of ice broke away from the north face below the crevasse noted a week earlier (Figure 3a). The slab rapidly fragmented as it descended the steep slope, and the avalanche deposited ice and snow over approximately 2 km^2 of Steele Glacier. At the leading edge of the avalanche, a plume of fine airborne ice and dust particles climbed the 275 m high ridge on the far side of Steele Glacier and traveled down to and across Hodgson Glacier, a total distance of at least 8 km (Figure 2). During aerial surveys flown over the next two days, the debris was estimated to consist of 5% rock and 95% highly fragmented ice and snow; no large fragments of ice or rock were observed.

The Alaska Earthquake Information Centre (AEIC) reported that the July 22 ice avalanche generated a local magnitude (M_L) 2.1 seismic event (N. Ruppert, personal communication, 2007). The event was distinguished from an earthquake based on the large difference between surface and body wave magnitudes (Ekström *et al.* 2007).

On July 24, at 17:57 h local time, a larger mass movement at Mount Steele (the "main event") produced a local magnitude (M_L) 3.4 seismic event. The long-period surface-wave magnitude was estimated to be M_s 5.2, and modeling of the waveforms suggested a duration of 100 seconds (Ekström 2006; Ekström *et al.* 2007). Another, much smaller mass movement was detected by the AEIC about 1.5 hours later (N. Ruppert, personal communication, 2007).

4. CHARACTERISATION OF THE MAIN EVENT

On August 2, the site was photographed during a fixed-wing reconnaissance survey. On August 12, bulk debris samples were collected, a GPS survey was conducted, and additional photographs were taken using helicopter support. During both visits, small failures from the source zone were observed. A high-resolution, airborne LiDAR survey was also flown over Mount Steele on August 12 by the Geological Survey of Canada in partnership with the Applied Geomatics Research Group (Centre of Geographic Sciences, Nova Scotia Community College).

Due to the extreme ruggedness of the terrain and ongoing landslide risk, detailed ground examination of the source and debris zones was not possible. Nonetheless, the landslide source area and deposit zone were precisely delineated using the LiDAR survey data, together with the GPS survey data and 1:50 000-scale digital national topographic data (Figure 2).

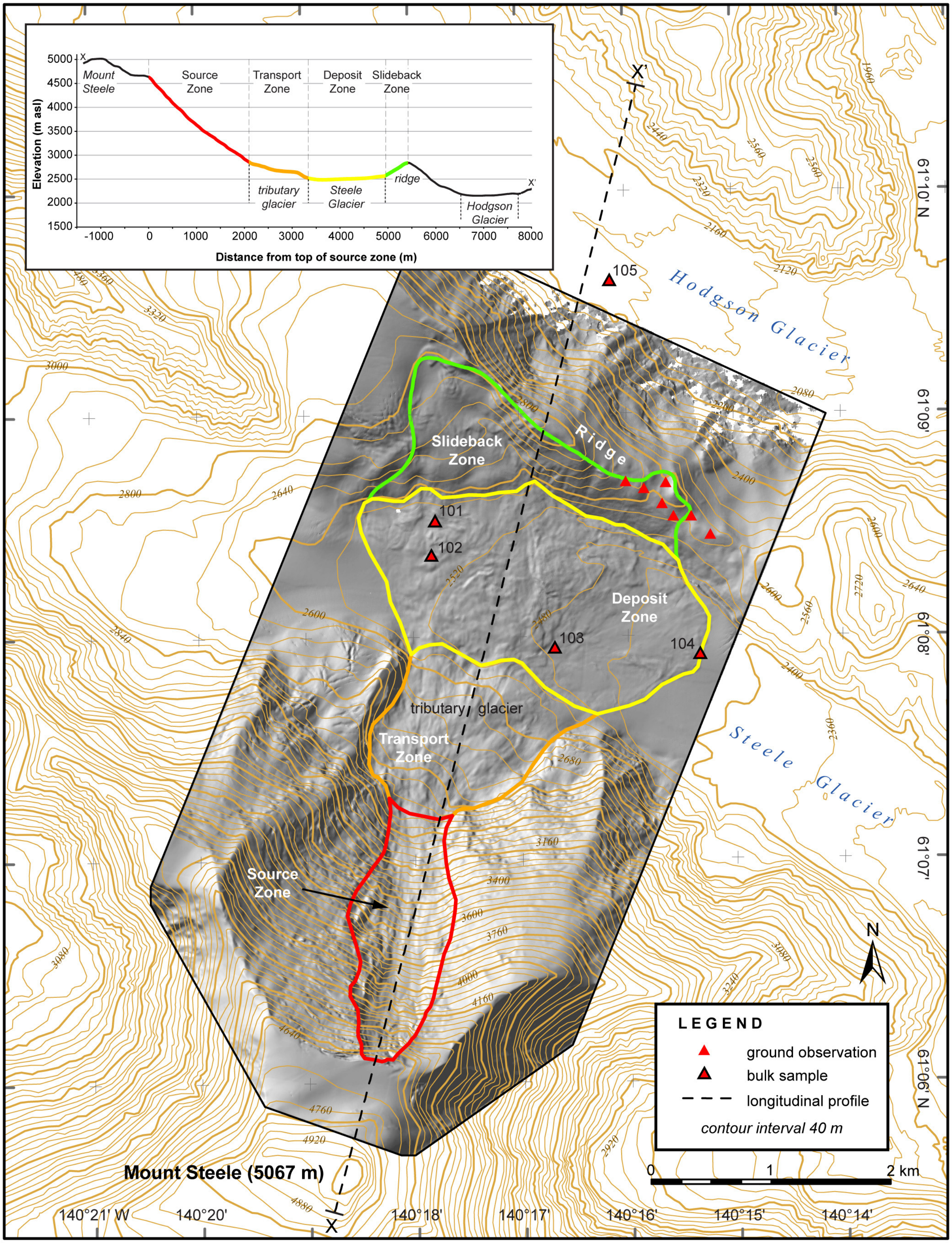

Figure 2. Map of the July 24 rock and ice avalanche site. Hillshade image derived from LiDAR survey data. Contours are generated from 1951 aerial photography (source: National Topographic Database, Natural Resources Canada). Inset shows longitudinal profile along line X-X'.

4.1 Source Zone

The main event initiated at 4650 m a.s.l. on the north face of Mount Steele, just beneath the edge of a bench about 400 m below the summit (Figure 2). The prominent, curved main scarp is up to 540 m wide. Below the main scarp, a steep gullied slope with an average gradient of 44° descends 1750 m in elevation to a small tributary glacier that flows into Steele Glacier (Figure 2). The entire slope from the main scarp down to the tributary glacier was the source of the rock and ice that failed in the main event.

Rock fragments in the deposit consist of hornblende-biotite-quartz diorite and tonalite, and plagioclase-hornblende-biotite porphyry. The presence of slickensides, sericitic alteration of feldspars, and red- to dark-brown oxidization of fracture surfaces suggests that the source zone rocks are within a fault zone. Three set of steeply dipping discontinuites are also apparent in photographs of the source zone.

4.2 Deposit Zone

The main event deposited a sheet of ice and rock debris that covers an area of 3.66 km^2 across the entire width of Steele Glacier. The surface of the debris sheet was chaotic and hummocky. Based on visual inspection from a helicopter, the debris appeared to range in thickness from 4 to 15 m, suggesting an average thickness of about 7.5 m. LiDAR mapping indicates a greater average thickness of 22 m. These average thickness values suggest minimum and maximum estimates for the main event volume of 27.5 and 80.5 Mm^3, respectively. Further data analysis and field work will be required to better constrain these values.

Some of the coarse avalanche debris reached the crest of, but did not overtop, the 275 m high ridge on the north side of Steele Glacier. This material descended back down onto Steele Glacier in a process we refer to as “slideback” (akin to fall back described by Heim in 1932) (Figure 2). This led to significant thickening of the avalanche deposits at the base of the ridge (Figure 4a).

Figure 3. The north face of Mount Steele, showing the location of the rock and ice avalanche source zone. (a) Photo taken on July 14, 2007, showing fresh debris from small landslides that had recently occurred in gully system. Also note large crevasse (dashed line) above gully system, outlining slab of ice that failed on July 22, 2007 (photo by A. Schaeffer). (b) Source zone scar produced by July 24 main event. Note CN Tower (553 m tall) superimposed for approximate scale (photo by P. von Gaza, August 2, 2007).

The July 24 deposit is much finer than typical rock avalanche deposits (Figure 4b). This, in combination with the aforementioned physical characteristics of the rock fragments in the debris, suggests that the source rock mass was intensely fractured before it failed. Only scattered boulders were observed in aerial surveys of the debris, and none of these was larger than 3 m across. Several large ice blocks, up to 2 m across, were also observed near the crest of the ridge separating Steele and Hodgson glaciers. The solid portion of four bulk samples collected on August 12 average 62% coarse fragments (>2mm), dominantly of pebble size. The remaining fine-grained material consists, on average, of 72% sand, 20% silt, and 8% clay.

Seven to 35% of the bulk sample mass was water, which is assumed to represent snow and ice that was incorporated into the avalanche. Although no surface water was visible within the debris sheet on photographs taken the day after the main event, numerous small ponds had developed in and adjacent to the debris sheet by August 2 (Figure 4a).

4.3 Mobility and simple dynamic analysis

The mobility of the main event was lower than other rock avalanches of similar volume that have occurred on glaciers (Evans and Clague 1988, 1999). The maximum descent from the main scarp to the surface of Steele Glacier was 2164 m, and the maximum travel distance of the debris was 5.76 km. The travel angle or fahrböschung (arctan[H/L]) of the main event, measured to the distal edge of the slideback zone (near the crest of the ridge separating the Steele and Hodgson glaciers) is 18º (H = 1855 m and L = 5766 m).

As indicated on seismological records, the main event lasted approximately 100 seconds. Over the maximum travel distance, the average velocity of the debris is therefore 58 m/s. This value, however, is a minimum average velocity, because the estimated duration may include the period of slideback, which occurred after the maximum travel distance was reached. The energy-head formula suggests a minimum velocity of 73 m/s for the debris that ran up to the crest of the distal ridge on the north side of Steele Glacier.

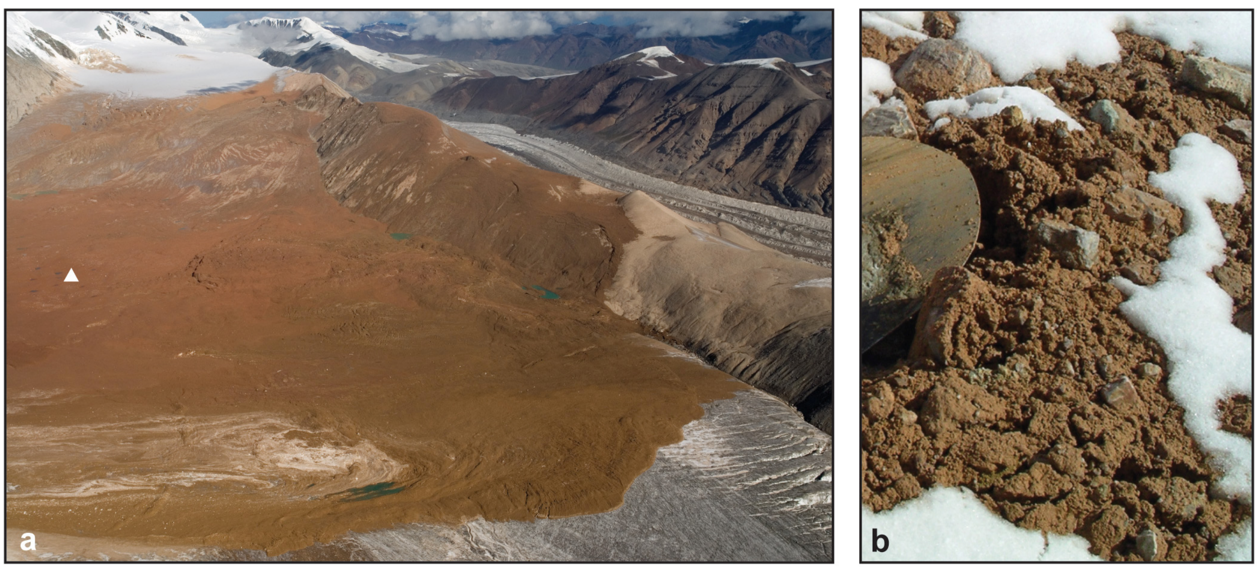

Figure 4. Debris deposited on Steele Glacier by the July 24 rock and ice avalanche. (a) View to northwest, showing ridge that impeded runout and caused slideback of material onto Steele Glacier (photo by P. von Gaza, August 2, 2007). (b) Surface of debris sheet at bulk sample site 102 (approximate location shown with white triangle in photo “a”). The fine texture of the debris is typical of the entire deposit (note standard shovel blade for scale) (photo by P. Lipovsky, August 12, 2007).

5. CAUSAL FACTORS

Large landslides adjacent to glaciers in northwest North America are commonly triggered by earthquakes (Post 1967; Evans and Clague 1999; Jibson *et al.* 2006) or are associated with abnormally high air temperatures (e.g., Bovis and Jakob 2000), but neither of these played a significant role in the main event at Mount Steele. Sixteen earthquakes between M_L 2.0 and 4.1 were recorded within 300 km of Mount Steele between July 1 and 24, 2007, but none occurred at or near the time of the July 22 or July 24 mass movements. However, repeated ground vibrations from frequent earthquakes in the region have likely played a role in weakening the source rock mass.

Temperature records from Burwash Landing indicate that the main event occurred after 10 days of warmer-than-average, but not abnormally high, air temperatures. Daily minimum temperatures remained above normal for most of July, but daily maximum temperatures were dominantly below normal during this period.

Several other factors may have gradually decreased the strength of the source rock and ice, including ongoing physical and chemical weathering, local fault activity, englacial meltwater, and possible permafrost degradation. Other processes that likely slowly increased stresses acting on the slope, and thus can be considered causative factors, include tectonic uplift, glacial erosion at the toe of the slope, recurrent landslides in the gully system, and debuttressing of the north face due to possible thinning of Steele Glacier in the 20th century.

6. SUMMARY

In July 2007, at least three rock and ice avalanches occurred on the north face of Mount Steele, in the same location as earlier landslides documented in historical photographs. The largest event occurred on July 24, depositing between 27.5 and 80.5 Mm^3 of ice and rock debris on Steele Glacier and traveling up to 5.76 km with a maximum vertical descent of 2164 m. Seismological records suggest that the minimum mean velocity was 58 m/s.

This event ranks among the largest documented landslides in western Canada, but was much less mobile than other rock avalanches of similar volume that have occurred on glaciers. A 275 m high ridge at the north margin of Steele Glacier impeded runout at the distal edge of the debris. Unconfined spreading of the debris laterally across Steele Glacier also contributed to the low mobility.

The failures were not triggered by earthquakes, and air temperatures in the weeks prior to the event were not exceptional. Other factors gradually reduced the strength of the source zone rocks and increased the stresses operating on the slope. Debris characteristics suggest that the plutonic rocks in the source zone have low rock mass strength and are highly sheared.

Cooperation between a diverse team of scientists has hastened efforts to document the recent events at Mount Steele and will hopefully continue in the future. Further study is required to more precisely determine the causes, geometry, and dynamic behaviour of the rock avalanche, and to characterise the impact of the debris sheet on the dynamics and mass balance of Steele Glacier.

7. ACKNOWLEDGEMENTS

Many people facilitated our research efforts and made valuable contributions to this study: Steve Israel (Yukon Geological Survey); Peter von Gaza (Pixel Mapper Geoscience); Doug Makkonen (Trans North Helicopters); Lance Goodwin, Andy Williams, and Donjek Upton (Icefield Ranges Expeditions); Dr. John Barlow and the Canadian Consortium for LiDAR Environmental Applications Research (C-CLEAR) field crew; Lloyd Freese (Kluane National Park); Christian Zdanowicz (Geological Survey of Canada); Dr. Natalia Ruppert (Alaska Earthquake Information Center, University of Alaska Fairbanks); and Dr. Gerald Holdsworth (Arctic Institute of North America, University of Calgary). We also gratefully acknowledge Dr. David M. Cruden and Dr. Andrée Blais-Stevens for reviewing this paper.

8. REFERENCES

Bovis, M.J., and Jakob, M. 2000. The July 29,1998, debris flow and landslide dam at Capricorn Creek, Mount Meager Volcanic Complex, southern Coast Mountains, British Columbia. *Canadian Journal of Earth Sciences*, Vol. 37, pp. 1321-1334.

Bruhn, R.L., Pavlis, T., Plafker, G., and Serpa, L. 2004. Deformation during terrane accretion in the Saint Elias orogen, Alaska. *Geological Society of America Bulletin* , Vol. 16, pp. 771-787.

Clague, J.J. 1979. The Denali Fault system in southwest Yukon Territory – A geologic hazard? *In* Current Research Part A, Geological Survey of Canada, Paper 79-1A, pp. 169-178.

Dodds, C.J., and Campbell, R.B. 1992. Geology of Mount St. Elias map area (115B and F[E1/2]), Yukon Territory. *Geological Survey of Canada*, Open File 2189.

Ekström, G. 2006. Global detection and location of seismic sources using surface waves. *Bulletin of the Seismological Society of America*, Vol. 96, pp. 1201-1212.

Ekström, G., Hansen, R.A., Pavlis, G.L., and Lipovsky, P.L. 2007. Seismological detection and analysis of recent landslides in Alaska and the Yukon. *Eos 88(52), Fall Meeting Supplement*, Abstract S52B-05.

Evans, S.G., and Clague, J.J. 1988. Catastrophic rock avalanches in glacial environments. *Proceedings of the 5th International Symposium on Landslides*, *Vol. 2. Edited by* C. Bonnard. Lausanne, pp. 1153-1158.

Evans, S.G., and Clague, J.J. 1999. Rock avalanches on glaciers in the Coast and St. Elias Mountains, British Columbia. *Proceedings of the 13th Annual Vancouver Geotechnical Society Symposium*, Vancouver, pp. 115-123.

Everard, K.A., and Savigny, K.W. 1994. Neotectonic effects of landslide distributions, Yukon, Canada. *In Proceedings, 7th International Congress, International Association of Engineering Geology*. *Edited by* R. Oliveira, L.F. Rodrigues, A.G. Coelho and A.P. Cunha. Lisbon, pp. 1811-1820.

Gordey, S.P., and Makepeace, A.J. 2003. Yukon digital geology, version 2.0. *Geological Survey of Canada* Open File 1749 and *Yukon Geological Survey* Open File 2003-9(D), 2 CD-ROM.

Haeussler, P.J., Schwartz, D.P., Dawson, T.E., Stenner, H.D., Lienkaemper, J.J., Sherrod, B., Cinit, F.R., Montone, P., Craw, P.A., Crone, A.J., and Personius, S.F. 2004. Surface rupture and slip distribution of the Denali and Totshunda faults in the 3 November 2002

M7.9 earthquake, Alaska. *Bulletin of the Seismological Society of America*, Vol. 94, pp. S23-S52.

Heim, A. 1932. Bergstruz und Menschenleben. Fretz and Wasmuth Verlag, Zurich, Switzerland, 219 pp. [in German].

Horner, R.B. 1983. Seismicity in the St. Elias region of northwestern Canada and southeastern Alaska. *Bulletin of the Seismological Society of America*, Vol. 73, pp. 1117-1137.

Jibson, R.W., Harp, E.L., Schulz, W., and Keefer, D.K. 2006. Large rock avalanches triggered by the M 7.9 Denali Fault, Alaska, earthquake of 3 November 2002. *Engineering Geology*, Vol. 83, pp. 144-160.

Molnia, B.F., Agneli, K.M., Bratton, D.A., Keeler, R.H., and Noyles, C. 2006. Meltwater induced glacier landslides – Waxell Ridge, AK. *Eos 87(52), Fall Meeting Supplement*, Abstract C31A-1247.

Pavlis, T.L., Picornell, C., Serpa, L., Bruhn, R.L., and Plafker, G. 2004. Tectonic processes during oblique collision: Insights from the St. Elias orogen, northern North American Cordillera. *Tectonics*, Vol. 23, pp. 1-14.

Post, A. 1967. The Alaska earthquake March 27, 1964: effects on hydrologic regimen. *US Geological Survey* Professional Paper 544-D.

Smith, C.A.S., Meikle, J.C., and Roots, C.F. (editors) 2004. Ecoregions of the Yukon Territory: Biophysical properties of Yukon landscapes. *Agriculture and Agri-Food Canada*, PARC Technical Bulletin No. 04-01, Summerland, BC, 313 pp.

Spotila, J.A., Buscher, J.T., Meigs, A.J., and Reiners, P.W. 2004. Long-term glacial erosion of active mountain belts: examples of the Chugach-St Elias Range, Alaska. *Geology*, Vol. 32, pp. 501-504.

Wheeler, J.O., Brookfield, A.J., Gabrielse, H., Monger , J.W., Tipper, H.W., and Woodsworth, G.J. (compilers) 1991. Terrane map of the Canadian Cordillera. *Geological Survey of Canada*, Map 1713A, scale 1:2 000 000.

Wood, W.A. 1972. Steele Glacier, 1935-1968. *In* Icefield Ranges Research Project scientific results, volume 3. *Edited by* V.C. Bushnell, and R.H. Ragle, *American Geographical Society and Arctic Institute of North America*, pp. 1-8.