Vampire rock avalanches, Aoraki/Mount Cook National Park, New Zealand

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ABSTRACT

Rock avalanches fell from Vampire (2645m) peak onto Mueller Glacier in Aoraki/Mount Cook National Park (AMCNP) during 2003 and January 2008. An unwitnessed and previously unrecorded 2003 event has been inferred to have occurred sometime between 23 February and about November 2003 from dated images and photographs. Approximately 120,000 m^3 (± 40,000) of rock collapsed from a 65º slope between 2440-2560 m. Release involved complex failure on joint surfaces and sandstone-argillite bedding. The falling debris was directed down a gully, through the Bannie Glacier icefall, and out 1.9 km across Mueller Glacier, where it formed a 280,000 m^2 deposit. Some unknown time afterward (probably during the same collapse sequence, but clearly prior to 2006) up to 100,000 m^3 of the debris deposit collapsed and formed a remobilised tongue spreading further down the glacier. The 2003 avalanche dropped a maximum height of 890 m and the angle of reach was 24º.

The next avalanches fell from a different source area on the south face of Vampire during January 2008. There were no direct witnesses to these avalanches either, but recordings made by the national seismograph network and field observations allow inference of a more precise event sequence. Avalanche-type shaking of 60s, equivalent in amplitude to a M_L 2.4 tectonic earthquake, was recorded on Monday 7 January at 2349 (NZDT) and was followed by 45s of shaking at M_L 2.5 on Sunday 13 January at 0923 (NZDT). About 150,000 m^3 (± 50,000) of rock fell from a 73º slope between 2380-2520 m, in a retrogressive collapse involving rock wedge failure on joints in a prominent sandstone layer. Debris fell down Vampire's south face, out across Bannie Glacier, was deflected as it rose 80 m across the southeast spur of Bannie, before continuing down the Bannie Glacier icefall and out 1.7 km across Mueller Glacier. During the 13 January collapse, debris accumulated against the southeast spur of Bannie, and was involved in a secondary collapse down the Bannie icefall. Three distinct lobes are present in the 300,000 m^2 debris deposit, which overlies most of the 2003 avalanche debris (which had been disturbed by glacier movement 2003-2008). Some erosion and remobilisation of older debris occurred. Calculated debris deposit volumes can be reconciled with rock failure volumes, given a 20-30% coefficient of expansion, poorly defined amount of erosion of ice and debris along the flow path, and other large uncertainties in the calculations.

The Vampire rock avalanches of 2003 and 2008 part of the natural process of erosion in the central Southern Alps. Other recent rock falls of note are Mount Beatrice (23 November 2004), Douglas Peak (18 February 2008), Mt Spencer (6-7 April 2008) and Mt Halcombe (24 April 2008). The main factors contributing to gravitational failure are steep slope angles, low rock mass strength, accentuated by rock mass dilation (joint opening) and stress relief in response to glacial and permafrost recession in high alpine areas. Prolonged above freezing temperatures were recorded at the time of the January 2008 Vampire slope collapse, but no direct trigger has been identified.

KEYWORDS

Vampire, Mueller Glacier, Aoraki/Mount Cook, rock avalanche, rock fall, landslide, Southern Alps, Main Divide, Douglas Peak, Mt Halcombe, Mt Spencer

1.0 INTRODUCTION

Rock falls and rock avalanches are the major erosion process shaping ridge crests and alpine summits in the Southern Alps, and a significant natural hazard in the region (Whitehouse 1983; Whitehouse & Griffiths 1983; Hovius et al. 1997; McSaveney 2002). Rock avalanches are distinct from rock falls in that they involve fluid-like behaviour of large (generally >100,000 m^3) volumes of rock. Although such events are commonly triggered during severe earthquakes (e.g. Speight 1933; Hancox et al. 2002, 2003), most recent large rock avalanches in the Aoraki Mount Cook National Park, including the Aoraki/Mount Cook avalanche (1991), Mt Fletcher (1992), and Mt Adams (1999) rock avalanches (McSaveney 2002; Hancox et al. 1999, 2005) were not caused by earthquakes. Rock avalanches need not have a direct trigger – only the existence of extremely steep slopes and unfavourably fractured rock in the source areas.

An average occurrence rate of rock avalanches >1 million m^3 was estimated at 1 per 100 years in the Southern Alps (Whitehouse & Griffiths 1983), until an historical rate of 1 per 20 to 30 years for rock avalanches greater than 1 million m^3 was determined for the shattered rocks and precipitous slopes near the Main Divide (McSaveney 2002). However, the occurrence of several very large ($\geq 10^{6\text{-}7}$ m^3) rock avalanches in the New Zealand Southern Alps in the last 17 years, including those on Mt Cook (1991), Mt Fletcher (1992), Mt Adams (1999), and more recently in John Inglis valley (Olivine Range, 2006), North Young River (Haast Pass area, 2007), all of which were 'spontaneous' slope collapses, suggests that the frequency of large rock avalanches in the alps may have increased significantly over the last two decades (G. Hancox, pers. comm., 2008).

A significant rock avalanche occurred from the Main Divide onto Mueller Glacier in Aoraki/Mount Cook National Park (AMCNP) during early January 2008 (Figure 1). Rocks fell 800 m from the south face of Vampire (2645 m), one of the peaks forming the Main Divide; the falling rocks formed a fluid-like debris flow spreading 1.7 km out across Mueller Glacier (Figure 2). Active rock fall at the site was first noticed by Greg King (Pilot for The Helicopter Line) during a scenic flight on 11 January. The national seismic network (http://www.geonet.org.nz/) recorded avalanche-type earthquakes in the area at 23:49 on 7 January (NZDT, Event 379079) and 09:23 on 13 January (Event 379382). GNS Science and Department of Conservation (DoC) personnel flew over the region separately on 16 January, observing and photographing the debris, path and source area. It was immediately recognised that the avalanche deposit comprised a number of lobes representing a series of recent flows, and these were deposited across considerably older debris which had been disturbed by glacial movement. The January 2008 debris was strewn across Mueller Glacier in much the same location, overlying much of the older deposit, but did not extend quite as far down and across the glacier.

Searches of historic photographs, aerial photography and satellite imagery were undertaken for comparison with the new photographs, in order to try to establish the timing and sequence of events (e.g. Figure 3). Satellite images from the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), NASA Terra sensor, and Digital Globe imagery (http://earth.google.com/) constrained the older rock avalanche to have occurred between February and November 2003. No events identifiable as having been caused by rock avalanches were located using the national seismograph network in 2003, probably because the seismic network at the time was less sensitive than at present. Detailed reconstruction maps of the Vampire rock avalanches were developed (Figures 4 & 5) together with a profile (cross-section) along the central fall line of the avalanches (Figure 6).

There appear to have been no direct witnesses to any of the rock avalanches (or they have yet to come forward). The south face of Vampire and Mueller Glacier is in full view of Barron Saddle hut, which has had regular visitors since 2003, but seems to have been unoccupied when the avalanches occurred during the evenings of 7 and 12-13 January 2008. Nearby Mueller Hut, 6 km to the east, was occupied, but there is no view of the avalanche area from this site. Importantly, the 2003 avalanche was of similar magnitude to the January 2008 event(s), but appears to have passed unnoticed, unreported and unrecorded until highlighted during January 2008. During our investigations, we also found evidence for other significant avalanches and rock falls from peaks along the Main Divide, but which are unrecorded in the geological literature, and a series of rock falls occurred in the neves of the Fox and Franz Josef Glacier. Although less than the commonly cited threshold of 1 million m^3, they are significant geomorphological events which add to the record of events needed to predict avalanche frequency and hazard in this region (Whitehouse & Griffiths1983; McSaveney 2002). This report aims to record and document the Vampire and other avalanches for future reference.

2.0 STAFF ACTIVITIES

News that a rock avalanche had occurred in the AMCNP reached Simon Cox (GNS Science Dunedin) by satellite phone (via GNS Science management and field call-in procedure) on the evening of 15 January. He was at Welcome Flat in the nearby Copland Valley, and immediately set about obtaining permission for a helicopter pickup from Welcome Flat hut the following morning. Permission was granted by radio through DoC Fox Glacier, and Jamie Scott of Karangarua (Franz-Fox Helicopter Services, Hughes 500) was engaged. A flight was taken over the Mueller Glacier area between 9.00 and 9.40am on Wednesday morning, 16 January. Sally Jackson (DoC Hut Warden, Welcome Flat) and Craig Freeman (GNS Science Field Assistant) were also present on the flight. The avalanche debris, path and source area scar were viewed and photographed from the air. No landings were made within Aoraki/Mount Cook National Park and no samples collected.

Further work by Simon Cox was delayed (due to other fieldwork commitments) until 21 January, when he visited DoC at Aoraki/Mount Cook. An exchange of digital photographs was made between DoC and GNS Science. Some interim measurements had been completed by Don Bogie, Acting Aoraki/Mount Cook Area Office Manager, who had flown over the site on the afternoon of 16 January. Shortly afterward, DoC notified the media of the event and supplied them with images together with information on location and some preliminary estimations of avalanche statistics (e.g. volume = 1 million m^3; fall height = 900 m; run out length = 2 km).

Upon returning to Dunedin, post-avalanche photographs were examined in detail and compared with as many pre-avalanche photographs as possible. Simon Allen, Geography PhD student at University of Canterbury, alerted GNS Science to the ASTER satellite photographs which showed the older rock avalanche in some images. Photographs of a large rock avalanche that fell prior to 1955 a little further down the Mueller Glacier, sourced from Mt Isabel (2598 m), were also located. Evidence of the avalanche activity was pieced together and compared with the GeoNet seismic record. Rock falls in the Franz Josef and Fox Glacier neves during February-April 2008 were observed and photographed by Greg King.

3.0 GEOLOGICAL SETTING

Vampire (2645m) peak is located on the Main Divide of the Southern Alps, on the northern (true left) side of Mueller Glacier, 8 km west of Mount Cook Village (Figure 1). Bannie Glacier is a tributary which flows from the base of the south face of Vampire, over a steep icefall, and contributes ice to Mueller Glacier (Figure 2).

Vampire is composed of Torlesse greywacke rocks of the Rakaia terrane. The rocks are moderately stratified, with alternating light and dark layers of sandstone and argillite, from 1–70 m thick. Bedding dips steeply toward the west (010/60ºW), cutting obliquely across the south face of Vampire. The rock sequence is mapped as weakly metamorphosed semi-schist (Cox & Barrell 2007), which has been intensely and sheared in faulting, and crosscut by and uplifted on the Main Divide Fault Zone (Cox & Findlay 1995). A weak cleavage is developed parallel to bedding.

The Vampire rock massif is cut by faults, which juxtapose rocks of textural zone 2B against textural zone 2A, and form eroded gullies on both the north and south faces (Cox et al. 1997). Rock strata (transposed bedding) has been locally rotated and steepened by the faults, and cross-fractures (joints) are locally developed between these faults. Many of the cross fractures are orange-stained with quartz-ankerite and limonite, hosting gold at very low concentrations (Cox et al. 1997). The cross fractures dip southeast “out of” the south face of Vampire and form planes which promote wedge-failure collapse of the mountain side.

Rock avalanches are known to have occurred previously in the Mueller Glacier area from peaks of the Main Divide (McSaveney 2002). A large rock avalanche fell from Mt Isabel during the early 1950’s, was followed by a further fall of rocks from the peak during the 1960’s, and a large rock fall occurred from Mt Thomson in 1996 (Figure 1). By way of contrast, a gigantic (>100 million m^3) slowly creeping landslide has been developing on the western side of the Sealy Range along the true right side of Mueller Glacier where the toe of the slope and buttressing ice has been removed by ongoing wasting of the glacier (Figure 1; Hancox 1998; Cox & Barrell 2007). While the landslide poses a potential hazard, its rates of creep movement (being monitored by DoC) and sliding processes are very different from the rock avalanches which appear more common on the steeper true left (Main Divide) side of the glacier.

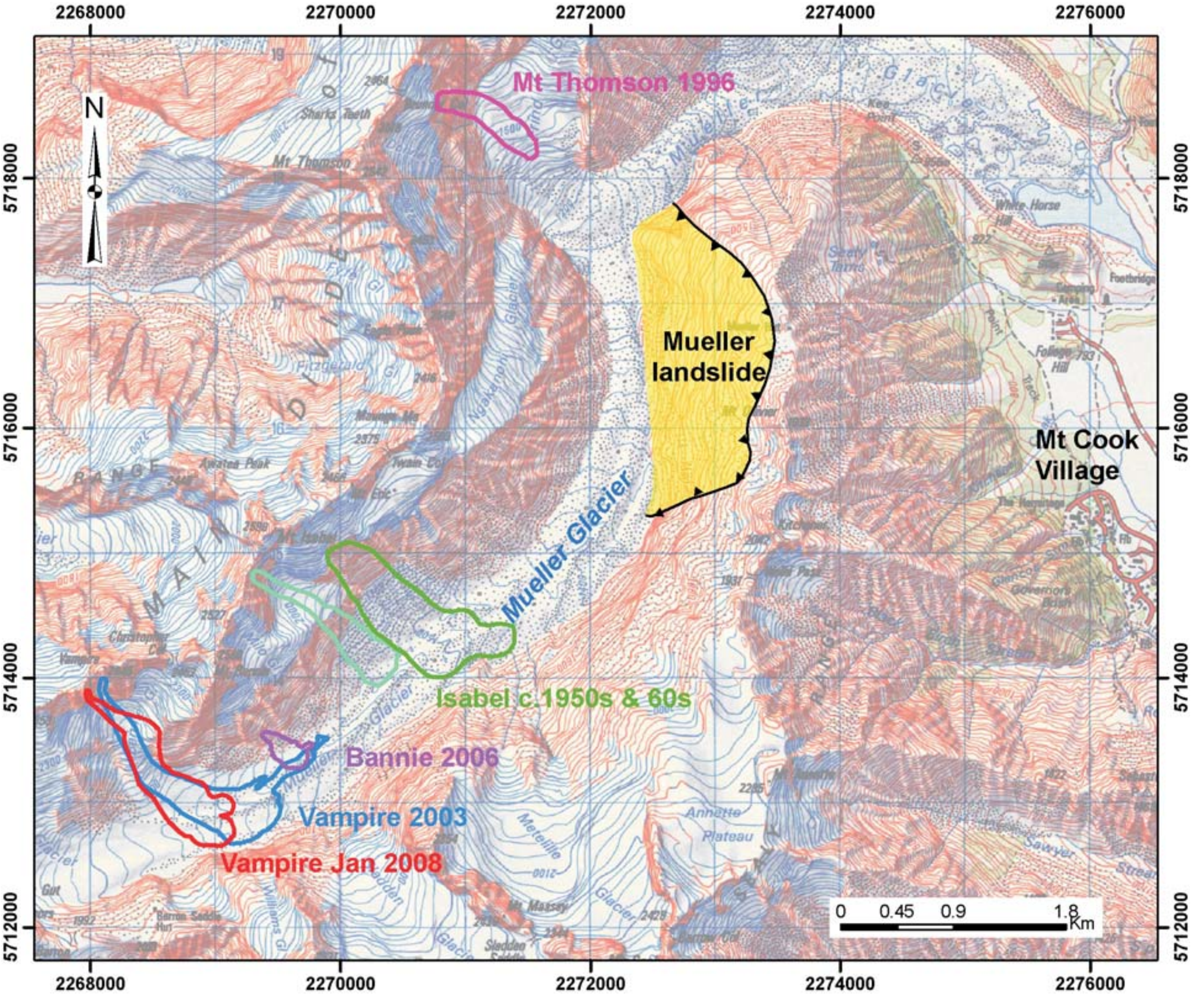


Figure 1 Location map showing Vampire and Mueller Glacier, relative to the Mount Cook Village. The location of major rock falls, rock avalanches and the Mueller landslide (discussed in the text) are also shown. Base map is from the NZMS 260 series (H36) with coordinates in NZMG.

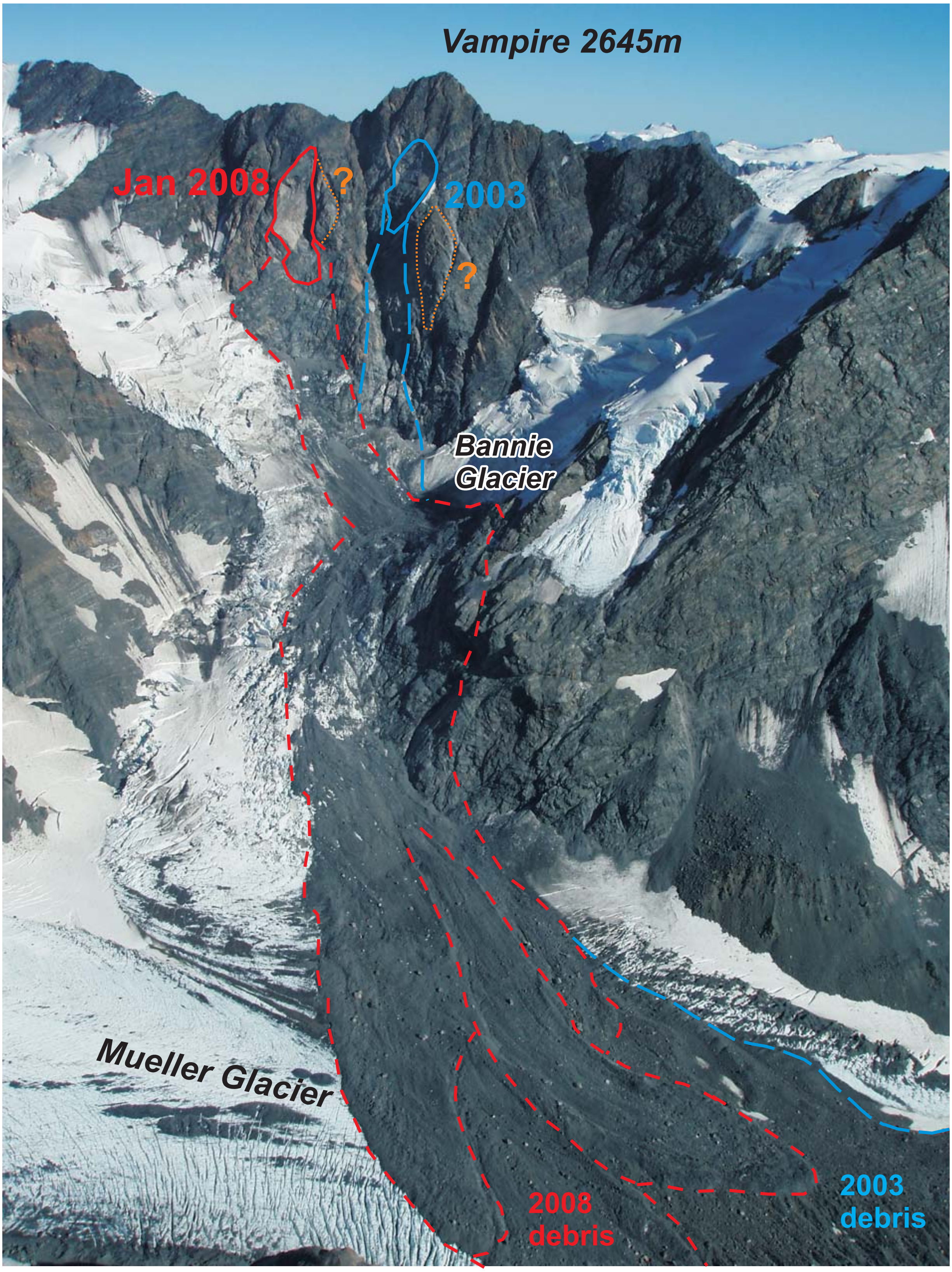


Figure 2 Overview of Vampire (2645m) and the Mueller Glacier, showing avalanche source area, path, and deposits. Photograph: S. Cox/GNS Science, 16 Jan 2008.

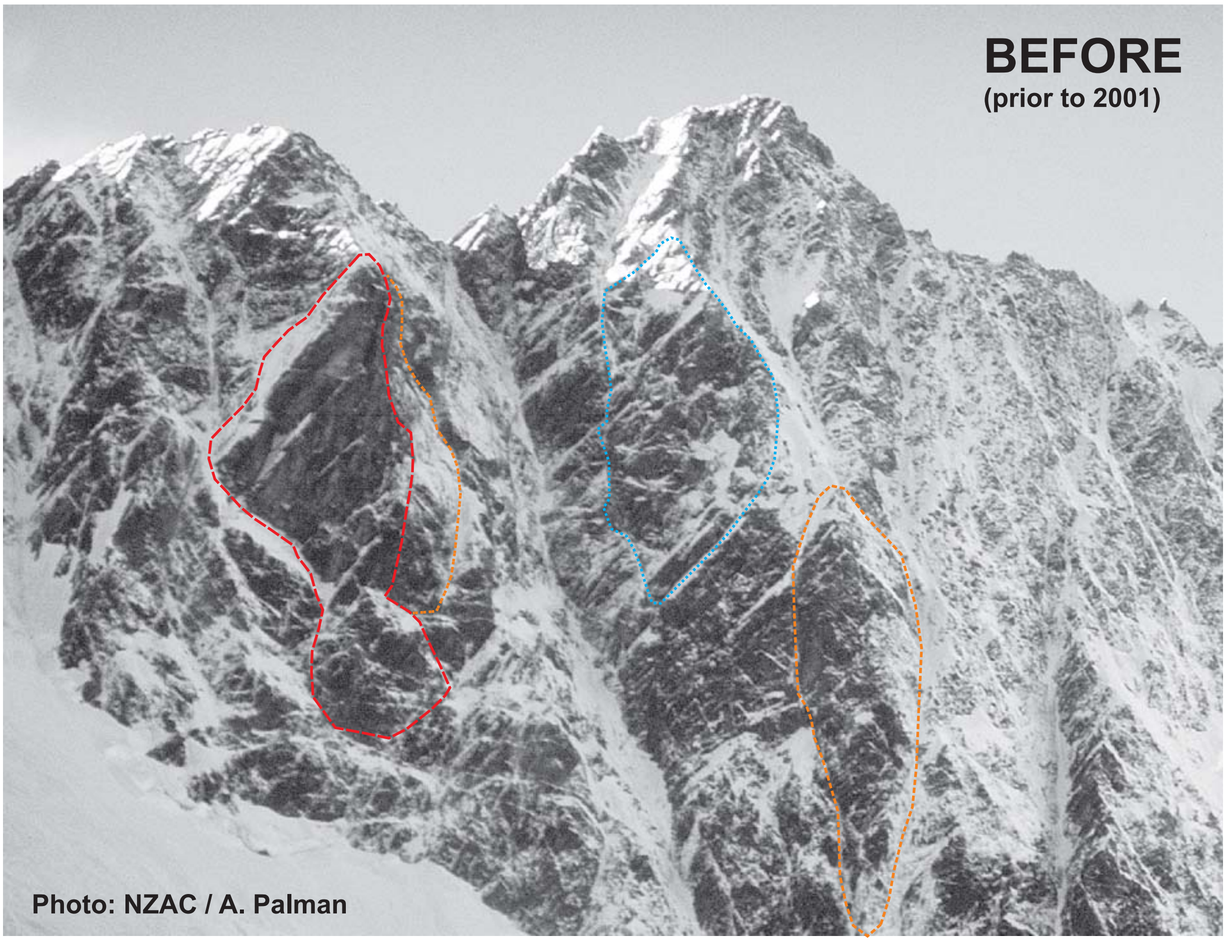


Figure 3 Views of Vampire (2645m) before and after the avalanches. Red and blue lines show the area of rock failure in 2008 and 2003, respectively. The orange lines delineates areas of rock where failure is thought to be imminent. Photographs: A. Palman/NZ Alpine Club, prior to 2001 (top); S. Cox/GNS Science, 16 Jan 2008 (bottom).

4.0 2008 AVALANCHE(S)

Rock-failure area

Dust and fresh rock debris indicated the January 2008 avalanching was sourced from a buttress on the southwest (true right) side of Vampire (Figure 7), between 2380 and 2520m elevation, beside a route climbers call “Notforustwo” (Palman 2001). A light-coloured scar is present where rock has fallen from a thick layer of greywacke sandstone, with an area of intensely fractured and broken sandstone-argillite below. The scar is approximately 140 ± 10 m high, with a maximum width of 100 ± 10 m. Measurements on scaled photographs indicates the scar area is in the vicinity of 8000 m^2. Pre- and post-avalanche photographs (Figure 3) were compared to estimate the thickness of the failed area, which has a maximum 30 ± 10 m. By allocating thicknesses of between 10 and 25 m to domains within the failure area, the rock failure volume is estimated to be 150,000 m^3 (± 50,000 m^3).

Pre-failure slopes on the face were 73º, which are very steep for mountains in the central Southern Alps. Post-failure the slopes remain equally steep, now composed of a planar vertical wall above a moderately sloping planar ramp. The collapse, or collapses, involved wedge failure on joint (fracture) surfaces and bedding in the sandstone. Open joints of similar orientation form large blocks adjacent to the failure area.

Flow path

Apart from a short section of rock immediately below the source area, the avalanche travelled mostly on snow and ice. Thin traces of debris were left on rock ledges and snow immediately below the scar area, and thickened on the lower-angled slopes of Bannie Glacier further below. Debris fell down the face of Vampire, crossed Bannie Glacier, was channelled over/down the Bannie Glacier icefall, then onto and across Mueller Glacier. The height difference from the rock failure area to the debris flow toe was 800 m, over a map distance of 1.7 km. For the most part, the flow followed topography (Figure 4). Some debris rose 80 m as it crossed the southeast spur of Mt Bannie (Figure 6), and the flow was deviated clockwise by 20º down the icefall. The angle from tip of the source area to toe along the fall line (Fahrböschung of Heim, 1882; Hsü 1978) is 27.5º.

An indication of the general direction of flow is provided by streaks and ridges within the debris and by scour marks (Figure 8). At the top of the icefall, adjacent to the area where the flow path rises on the Mt Bannie spur, a prominent debris ridge is developed at right angles to the general direction of flow. Nearby, the veneer of debris is thin, and ice is exposed with striations both in the general direction of avalanche flow and downslope towards the icefall. We infer a secondary collapse has occurred here, remobilising debris that was piled against the south east ridge of Bannie, and collapsing the debris pile downslope across the general direction of avalanche flow. The debris ridge (yellow dotted line, Figure 8) marks levee deposition at the uphill lateral margin of the secondary collapse. The secondary collapse was the last event in the local sequence at this site, but may have been part of a continuous avalanche-debris flow sequence. It occurred after the main flow(s) have passed because the debris ridge is fresh and shows no sign of having been eroded or overridden by subsequent debris from the source area. Within the icefall the flow scoured the ice to a smooth grooved surface, and may have involved collapse of crevassed seracs within the icefall.

Deposit

Rock avalanche debris was deposited in lobes across Mueller Glacier (Figure 4), covering an area of 300,000 m^2 in the same vicinity as the 2003 avalanche deposit (see below). The new debris could be easily distinguished from the older deposit on 16 January 2008 because the newer deposit contained more fine-grained material (dust), had not yet been crevassed by glacier movement, nor disturbed by rainfall runoff. The deposit lobes have well-defined, rounded fronts comprising well-defined arcuate ridges.

"Crosscutting" relationships based on debris ridges and internal flow patterns delineated three debris lobes (Figure 9). The youngest lobe (2008/3) has an area of 95500 m^2 (area in plan view, calculated from GIS). It overlies two other lobes, which have inferred areas (based on a regular, rounded lobe geometry) of c.180,000 m^2 (2008/1) and c.140,000 m^2 (2008/2) but a greater run out distance. The 2008/3 lobe appears to have been deflected down valley (anticlockwise) slightly by a 5-10 m high medial-moraine ridge on the glacier, but this ridge does not seem to have affected flow and deposition of the 2008/1 and 2008/2 lobes. These observations suggest the deposition events may have been getting progressively smaller, but there is no information within the deposits to determine whether they were separated by minutes, hours, or days. (It is inferred below that 2008/3 was deposited on 13 January, whereas 2008/1 & 2 deposited on 7 January).

There are some internal textures and features worthy of note within the lobes. 2008/1 and 2008/3 appear to have different surface textures at their fronts, with more large boulders. On the true left margin of 2008/1 there are two large boulders, approximately 3 x 3 x 3m, which have slid across the ice and cleared a path through debris for 10-15 m (see red arrows, Figure 9). The skid marks probably represent the final slowing of these boulders as they came to rest, but it is conceivable the boulders were deposited with the rest of the debris and have been mobilised afterwards by sliding on the icy slope (due to the pull of gravity). Either way, the thickness of the deposit can be observed to be <0.5 m at this location.

Many large boulders can be seen on lobe 2008/2, the largest being around 6 x 4 x 3 m (72 m^3). This lobe has a series of longitudinal ridges, oriented about 15º to the true right margin. These reflect lateral shear and lateral spreading (McSaveney 1978), with influence from underlying topography of medial moraine ridges and crevasses in the glacier underneath. A view sideways across the deposit from the undisturbed white ice indicated the 2008/2 deposit lobe is mostly <2 m thick.

If it is assumed that the entire deposit of all three lobes is, on average, around 0.5-1 m thick then the maximum deposit volume is 150,000–300,000 m^3. This is consistent with the calculated rock failure volume of 150,000 m^3, which would expand by 20-30% as it changed from greywacke rock (density 2.65t/m^3) to a greywacke gravel deposit (1.60-1.8t/m^3) with addition of ice and rock debris (including the 2003 avalanche debris – see below) eroded from the flow path area.

Seismic record

The national seismograph network (http://www.geonet.org.nz/) recorded shaking on Monday 7 January at 2349:20 (NZDT) at the Fox (FOZ), Jackson Bay (JCZ), Wanaka (WKZ), and Mavora Lakes (MLZ) stations in an event distinguishable as an avalanche. Arrival-time differences were used to place the epicentre of shaking at lat 43.7, long 169.9E, about 13 km west of Aoraki/Mount Cook village (2264000mE, 5719000mN). Minor signals were also detected at the Earnscleugh (EAZ) and Whether Hill Road (WHZ) stations, in the southern South Island. The strongest shaking was recorded at the Fox (FOZ) seismometer, located closest to Vampire at Karangarua, just 27 km to the northwest (Figure 10). The event lasted for about 60 seconds, with two distinct peaks occurring in signal amplitude within the first 45 seconds. The peak amplitude of the shaking had a local event magnitude of M_L2.4. The intensity of shaking was estimated to be MMIII-IV in the vicinity of Aoraki/Mount Cook Village, which is about equivalent to the vibration caused by the passing of heavy traffic or earthquakes which wake light sleepers and cause little damage. Closer to the epicentre, shaking is expected to have reached MMV or higher, which is equivalent to earthquakes which wake most sleepers and cause alarm to people in the area. We interpret the two peaks to record two separate pulses of rock fall in a retrogressive collapse.

A similar event on Sunday 13 January at 0923 am at the same location was recorded by the Fox (FOZ) (Figure 10), Lake Benmore (LBZ), Waitaha Valley (WVZ), Jackson Bay (JCZ), Wanaka (WKZ), Mavora Lakes (MLZ) stations, with minor signals at Otahua Downs (ODZ) and Tuapeka (TUZ) stations. The event lasted for about 45 seconds, with shaking first rising above background at 0923:40 (local time), increasing in intensity over the first 15 seconds, then decaying (unevenly) towards background levels over the next 30 seconds. The local magnitude of this event was M_L2.5. A small burst in signal amplitude also occurred at about 0925:00 (NZDT) which could be a record of a further, smaller, stress-release spall of rock from the site or secondary collapse of material (Figure 10).

Inferred sequence of events

Seismic coda record the unloading, sliding, friction and impacts during rock avalanches, and suggest there were three main episodes – two in close succession (20-seconds apart) on 7 January, and a third on 13 January 2008. We surmise that these broadly relate to the three lobes of debris observed on Mueller Glacier. There is no information by which the source area can be subdivided and attributed to retrogressive phases of collapse, although a large precarious block remains for which a fourth collapse appears imminent (Figure 11). Much of the scar outlined on Figure 7 appears to have been present when it was seen by Greg King (Helicopter Line pilot) on 11 January, together with some debris down on the Mueller Glacier (G. King, pers. comm.). In order to produce M_L2.5 shaking on 13 January, we believe that a significant amount of material must have fallen from the scar area. Secondary collapse of debris down the Bannie Glacier icefall presumably occurred as part of this event, and may have been responsible for the burst of signal at 0925:00.

We infer from these observations that:

1) On 7 January approximately 100,000 m^3 rock mass failed in the source area, leaving behind a large scar. The event lasted about 60 seconds, involving two distinct pulses of M_L2.4 shaking which probably represents separate collapses, but could be impact of debris first on the Bannie Glacier followed by impact on the Mueller Glacier. Debris fell to the Mueller and formed debris lobes 2008/1 and 2008/2.

2) On 13 January, two days after Greg King had observed the failure scar, there was a further collapse of perhaps 50,000 m^3 from the source area, followed by a secondary collapse of debris and probably also ice from just above the Bannie icefall at 2000-2100 m. Debris fell down the Bannie Glacier icefall and produced the youngest debris lobe

observed (2008/3, 95500 m^2). Impact of the avalanching debris caused the observed 45 second M_L2.5 seismic signal.

Other contributing factors

The main factors contributing to failure of rock on the Vampire massif are its very steep slopes, low rock-mass strength, and gravity. Rock mass dilation and joint/defect opening, ice wedging, stress relief, reduction in permafrost and observed 'ice binding' are now more frequently observed in the high peaks in AMCNP (pers comm. G. Hancox 2007). It is only a matter of time before steep mountain slopes of greywacke suffer significant gravitationally induced stress and fail (Augustinus 1995). The sizes of the 2003 and 2008 avalanches, which were defect-controlled failures along bedding and joints, appear to have been constrained in part by the thickness of bedding and spacing and extent of joints developed between the faults that coincide with the main gullies in the south face. In this respect Vampire differs from larger avalanches from Aoraki/Mount Cook or Mt Fletcher, which involved larger volumes of intensely jointed and fractured rock (McSaveney 2002).

There was no tectonic earthquake trigger immediately prior to the 2008 event. The last significant earthquake felt in the near vicinity was a M_L4.1 on 1 October 2007, which was located below Fox valley (Event 372301) close to, or on, the Alpine Fault. Since the rock avalanche did not occur during or immediately after the earthquake, it is not regarded as a trigger for slope failure. Rainfall measured in the Mt Cook Village for the 48 hours prior to 8am, January 8, totalled around 50 mm although this amount is hardly considered significant for this region of the Southern Alps characterised by extreme annual precipitation quantities and rainfall intensities (NIWA National Climate Database - http://cliflo.niwa.co.nz).

The air temperature in the vicinity of the source area can be estimated approximately from hourly temperatures recorded at Mount Cook Village (765 m) (NIWA National Climate Database - http://cliflo.niwa.co.nz) by applying a 0.006ºC/m atmospheric temperature gradient to remove a 10.4ºC temp difference between Aoraki/Mount Cook village and 2500 m (Figure 12). The average hourly temperature between 2300-2400 hrs at Mount Cook Village, when the avalanche occurred on 7 January, was 15.1ºC. At 2500m this would have corresponded to temperatures (5.4ºC) well above freezing level at 2500 m and followed five consecutive evenings getting progressively warmer, and at least 62 hours above a predicted 0 ºC. On 16 January 2008 at 9am, we observed water seeping from fractures in the scar area (see Figure 7), indicating there had again been no sub-surface freeze during the previous evening. Temperatures on the evening of 7 January (overnight minimum hourly average 14.3ºC equating to 3.9 ºC at 2500 m) were equivalent to those leading up to 16 January (overnight minimum hourly average 14.3ºC), so we infer that freezing did not occur and liquid water was most likely present in the rock mass at the time of the main avalanche (2349 on Monday 7 January). As there are no patches of snow on the face immediately above the failure scar, water is either stored precipitation within the fractures, or possibly from flow of melt through the massif from the snowfield on the northern side of Vampire (see Figure 1).

5.0 2003 AVALANCHE

Reconstruction

The 2008 avalanche deposited debris directly in an area of older debris that could be distinguished because of its fluvial and glacial modification. Events relating to the older avalanche were deduced from dated photos and images. Much information can be obtained from Digitial Globe satellite images currently available on Google Earth, and ASTER images from NASA. Key observations are listed in Table 1. The older avalanche is constrained to have occurred sometime between 23 February 2003 and 4 February 2004. Remnant winter snow appears to cover rock debris in the ASTER image of 4 February 2004, indicating the avalanche probably occurred prior to the end of winter snow accumulation and melting at 1700-1800 m in 2003, which we expect was no later than November.

Table 1 List of photographs and images used to deduce the earlier history of Vampire avalanches.

Date	Photo	Observations
1955	RNZAF B/W oblique	Photos show only minor dusty debris below the south face of Vampire. Photo C55 shows Mt Isabel avalanche debris very clearly, although already disturbed by crevasses/glacial movement.
1965	NZ Aerial Mapping photo 3724/41	No debris beneath Mt Vampire. Further rock fall has occurred beneath Mt Isabel.
25 April 2002	ASTER	No avalanche debris beneath Vampire, but small piles of rock beside medial moraine on Mueller Glacier are old rock falls.
23 Feb 2003	ASTER	Much fresh snow. Possible small area of rock fall (or blue ice) in the Bannie Icefall, but no major avalanche lobe.
4 Feb 2004	ASTER	Avalanche lobe (2003/1) present, crosscutting medial moraine ridge, with remobilised tongue (2003/2). Partially overlain by remnant, white, winter snow beneath the SE spur of Mt Bannie – which constrains the avalanche to have occurred prior to the main accumulation and melting of winter snow.
24 Jan 2006	ASTER	Avalanche debris very clear, partially covered in fresh white snow. Small rock fall from Bannie does not appear to be present.
4 May 2006	Digital Globe (Google Earth)	Two lobes very clear, although partially covered with new snow. Rock fall from Bannie present on top of debris tongue (2003/2).

Rock-failure area

Comparison of pre-2001 and new oblique photographs (Figure 3) indicated an area of rock between 2440 and 2560m has fallen from a buttress immediately below the main summit of Vampire (Figure 7), beside a different climbing route called “Nosferatu” (Palman 2001). In January 2008 this area was free from fine dust, had a small patch of old snow, and looked comparatively stable. The failure area is approximately 120 ± 10 m high, with a maximum width of 110 ± 10 m. Digitising from scaled photographs indicates that the scar area is in the vicinity of 6500 m^2. Pre- and post-avalanche photographs (Figure 3) were compared to estimate the thickness of the failed area, which has a maximum 20 ± 10 m. By allocating thicknesses of between 10-25 m to selected domains within the failure area, the rock-failure volume is estimated to be 120,000 m^3 (± 40,000 m^3) which is similar to the 2008 failure volume (150,000 ± 50,000 m^3).

Pre-failure slopes on the face were 65º, which is less than the 73º of the 2008 failure, but still well above average for mountains in the central Southern Alps. Post-failure, the slopes do not show any single failure plane, but is complex with alternating layers of bedded greywacke sandstone and argillite dipping northwestward obliquely in towards the face. Two prominent planar joint surfaces dip moderately southwest into the gulley between Vampire’s two peaks (Figure 7). A prominent pinnacle of rock below the 2003 source area has open joints/fractures, bedding, and slope that are similar in orientation to those in the 2003 failure area (Figure 11). Failure of the pinnacle is likely, since all the necessary defects are in place.

Flow path

Little is known of the exact flow path of the 2003 avalanche as it is now covered by 2008 debris, and it is partially covered by snow in the 4 February 2004 image immediately following the collapse. Apart from a short section of rock in the gully immediately below the source area, it is presumed the path of avalanche was on ice and snow down and across the Bannie Glacier, channelled through the icefall out onto the Mueller Glacier. Assuming the avalanche was directed by the gully and followed topography, its flow path down the Bannie Glacier is likely to have been straighter and more direct than the 2003 avalanches (Figure 5). The pattern of the debris toe suggests at least some of the flow deviated anticlockwise down the Mueller Glacier. The total drop from rock-failure area to debris toe was 890 m, over a run out distance of 1.9 km. The angle from tip of the source area to toe along the fall line (Fahrböschung of Heim, 1882; Hsü 1978) is 24º.

Deposit

Only a small area of the deposit is currently exposed, where it escaped burial by the 2008 avalanche. Images of the deposit in 2004-2006 showed it was comprised of two distinct areas (Figure 5). There is a major lobe (2003/1) which appears to be a single large deposit of c. 280,000 m^2 (Figure 9). The deposit overran, but did not obscure, the medial moraine ridge of the Mueller Glacier. By January 2008 this 2003/1 deposit had become heavily crevassed. The deposit thickness seems to be considerably less than the c. 10m height of the medial moraine. If it is assumed that it is between 0.5-1 m thick on average (i.e. similar to 2008), then the maximum deposit volume is 140,000 - 280,000 m^3. This is broadly consistent with the calculated rock failure volume of 120,000 ± 40,000 m^3 (allowing for 20-30% expansion), because both figures contain considerable uncertainties.

A second narrow tongue-like area of debris (2003/2, Figure 9) extends beyond the area of the main 2003/1 deposit. The Digital Globe image of 4 May 2006 (Google Earth) shows this feature, now buried by the 2008 avalanche, through a light cover of snow. A strong channel was developed within the 2003/1 debris, as far up as 1760 m, and extended 600 m beyond the 2003/1 toe following a curving, branching path down-valley to 1580 m. The debris tongue is aligned within a trough on the true left (Bannie Glacier ice) side of the medial moraine ridge on Mueller Glacier, constrained by the location of the ridge. We interpret this to be a remobilisation feature, caused by collapse of 2003/1 debris, which accumulated on ice with c.17º slopes. The tongue comprises around 70,000 m^2 of deposit, locally 2-4 m thick. It potentially involved remobilisation of 100,000 m^3 of debris, making it a substantial feature in its own right.

There is no information to determine how long after the main avalanche the remobilisation of debris took place. It initiated from upon a steep icy slope of c.17º that would have been unstable. It could have occurred within the same sequence as the 2003/1 debris flow, perhaps seconds or minutes after, or it could have been days or weeks later (but prior to 4 February 2004) relating to melting and shifting of glacial ice underneath. A small rock fall from the cliffs of Mt Bannie deposited a pile of rocks on top of the debris tongue sometime between 24 January and 4 May 2006 (Figures 1, 9).

Seismic record

In 2003 the closest station in the national seismograph network to Vampire was Waitaha Valley (WVZ), at a distance of 100 km. A significant upgrade to the network occurred during the period June to October 2004, with the opening of seismographs at Fox Glacier (FOZ October 14), Lake Benmore (LBZ June 4) and Jackson Bay (JCZ June 23). Consequently, the record and location of earthquakes during 2003 was not as accurate and precise as those of today and may be incomplete. In addition, location of avalanche-type events is not always straightforward because, unlike tectonic earthquakes, they do not always have a clear separation of P and S waves. Location can only be done using arrival time differences which ignore the effect of topography and carry some uncertainty.

All events within 50 km of Vampire were examined in the period from 1 January 2002 to 31 December 2004. About 30 events were recorded during 2003 (prior to the network upgrade), but these were tectonic earthquakes and none appear to be avalanche-type events. Avalanche-type shaking was recorded on 3, 9, 10 November 2004 and 8, 23 December 2004 (U.T.) following the network upgrade. Because the timing of the 2003 avalanche event is not precisely known, it is not possible to make comments on causes, or if there is any possible link to earthquake triggering.

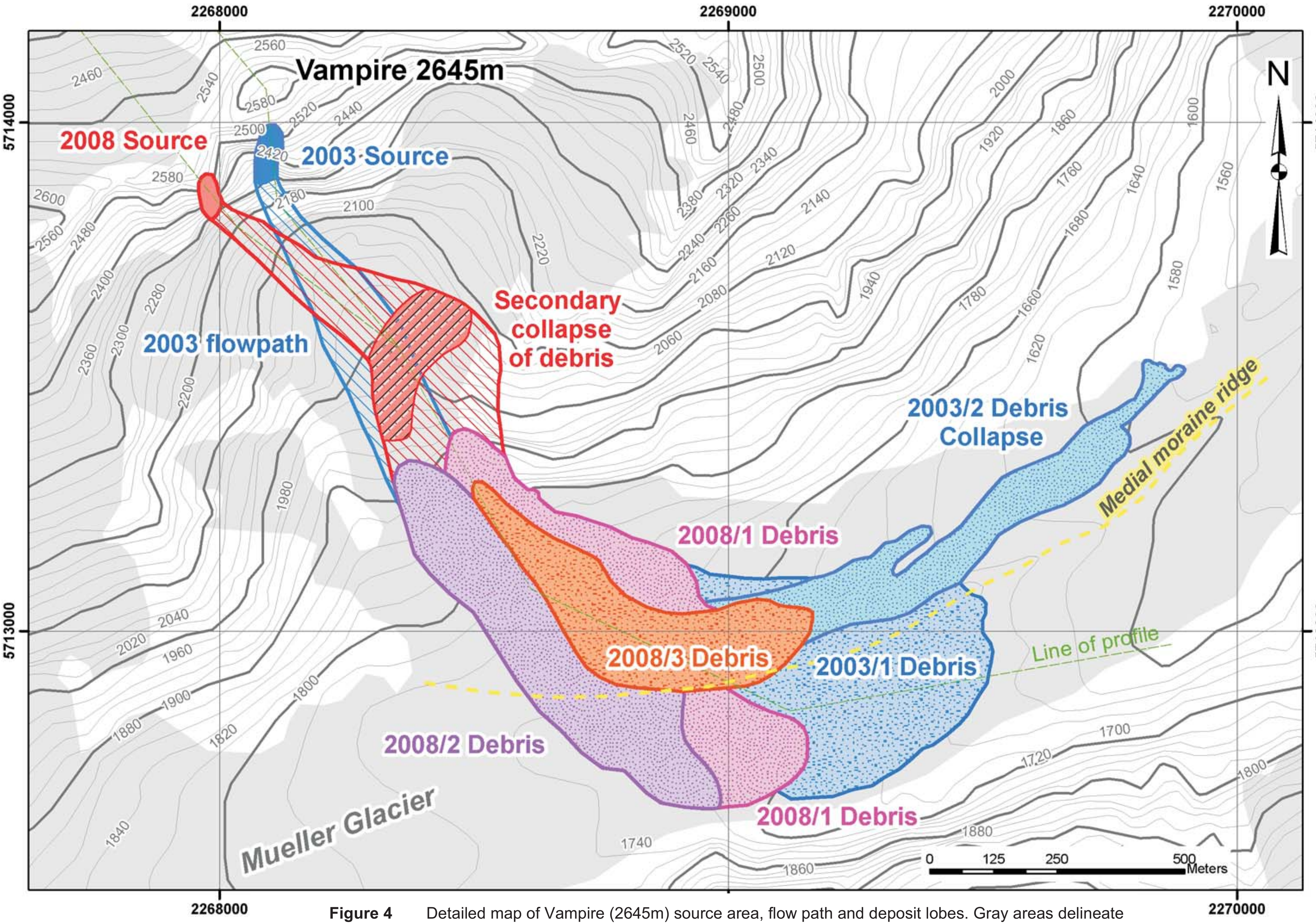


Figure 4 Detailed map of Vampire (2645m) source area, flow path and deposit lobes. Gray areas delineate the location of permanent snow and ice. The green line delineates the position of the profile shown in Figure 6. Coordinates are in NZMG.

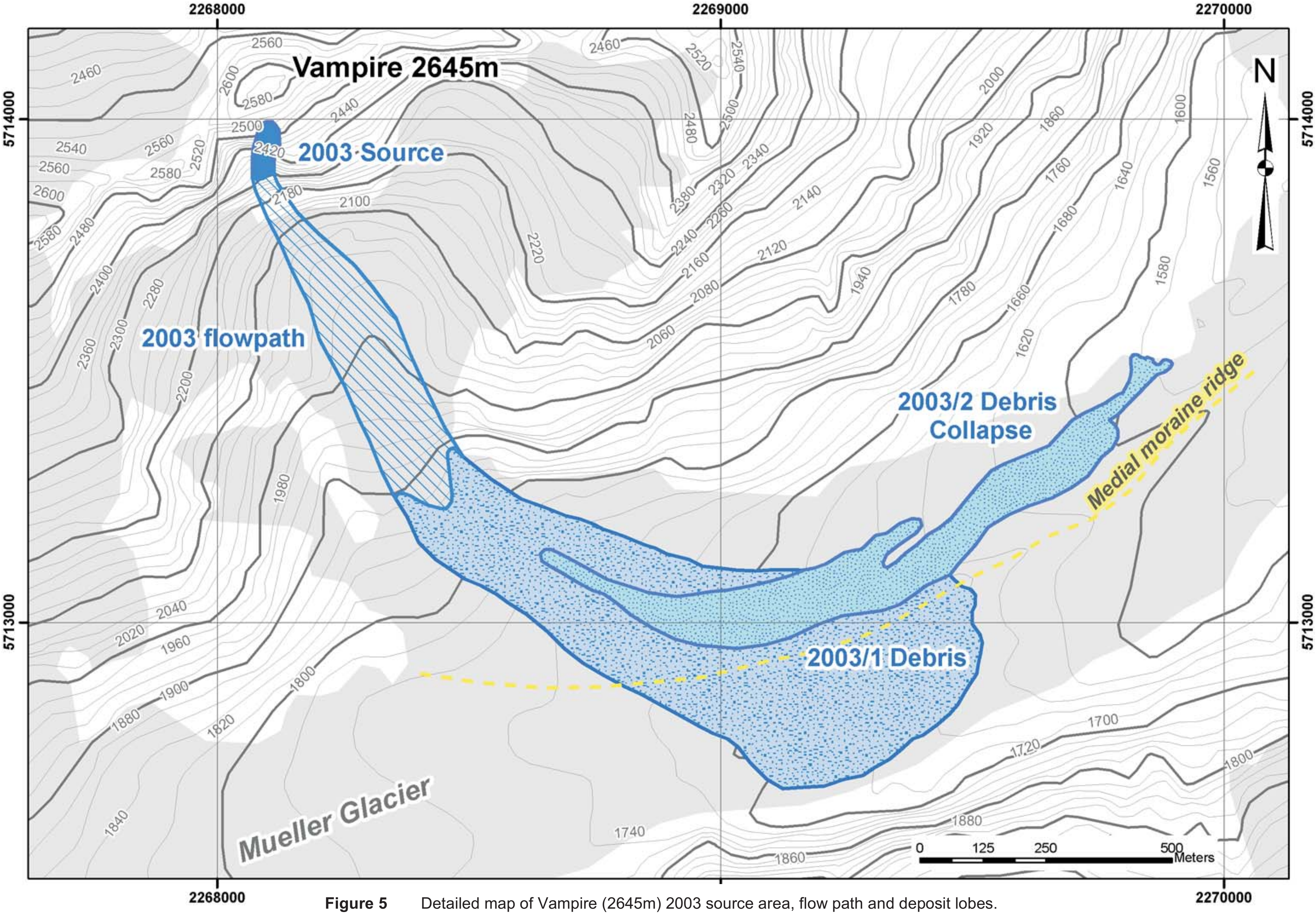


Figure 5 Detailed map of Vampire (2645m) 2003 source area, flow path and deposit lobes.
Gray areas delineate the location of permanent snow and ice. Coordinates are in NZMG.

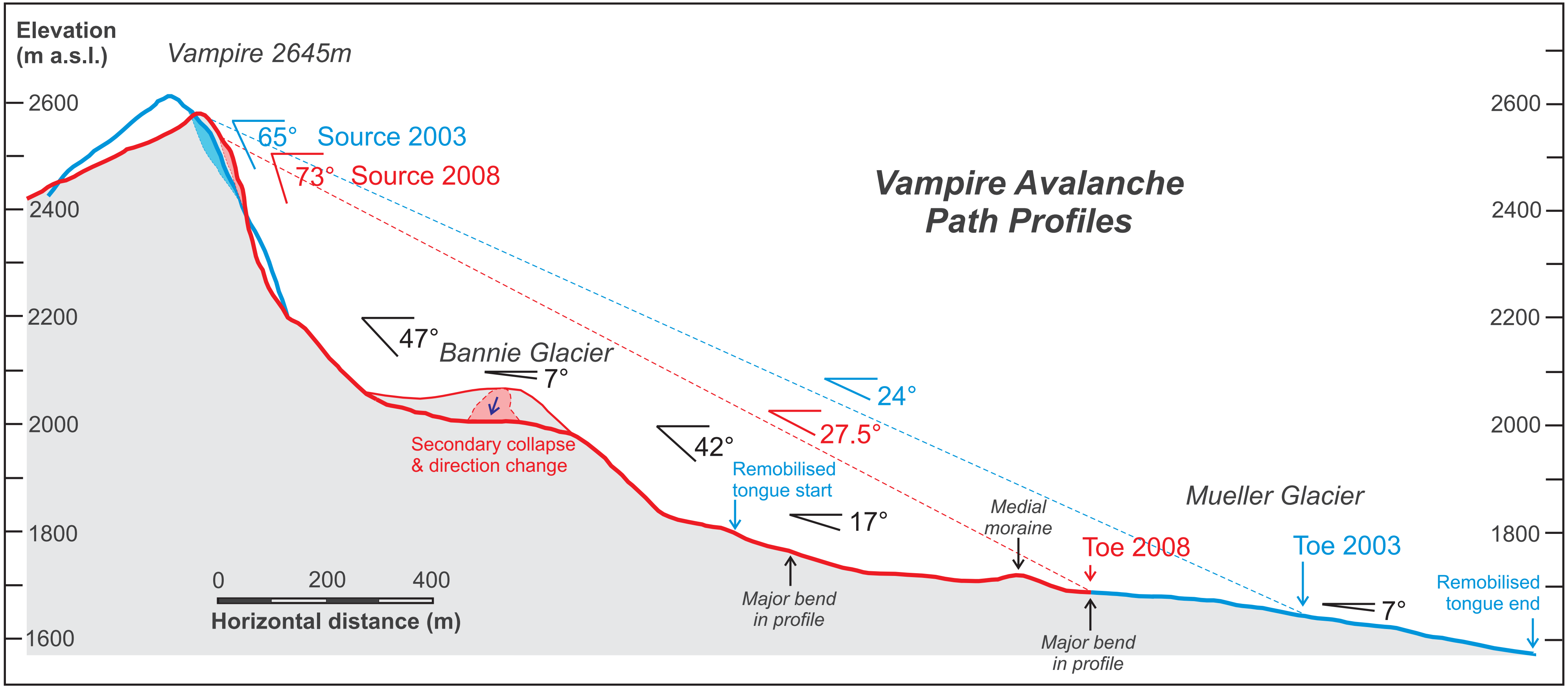
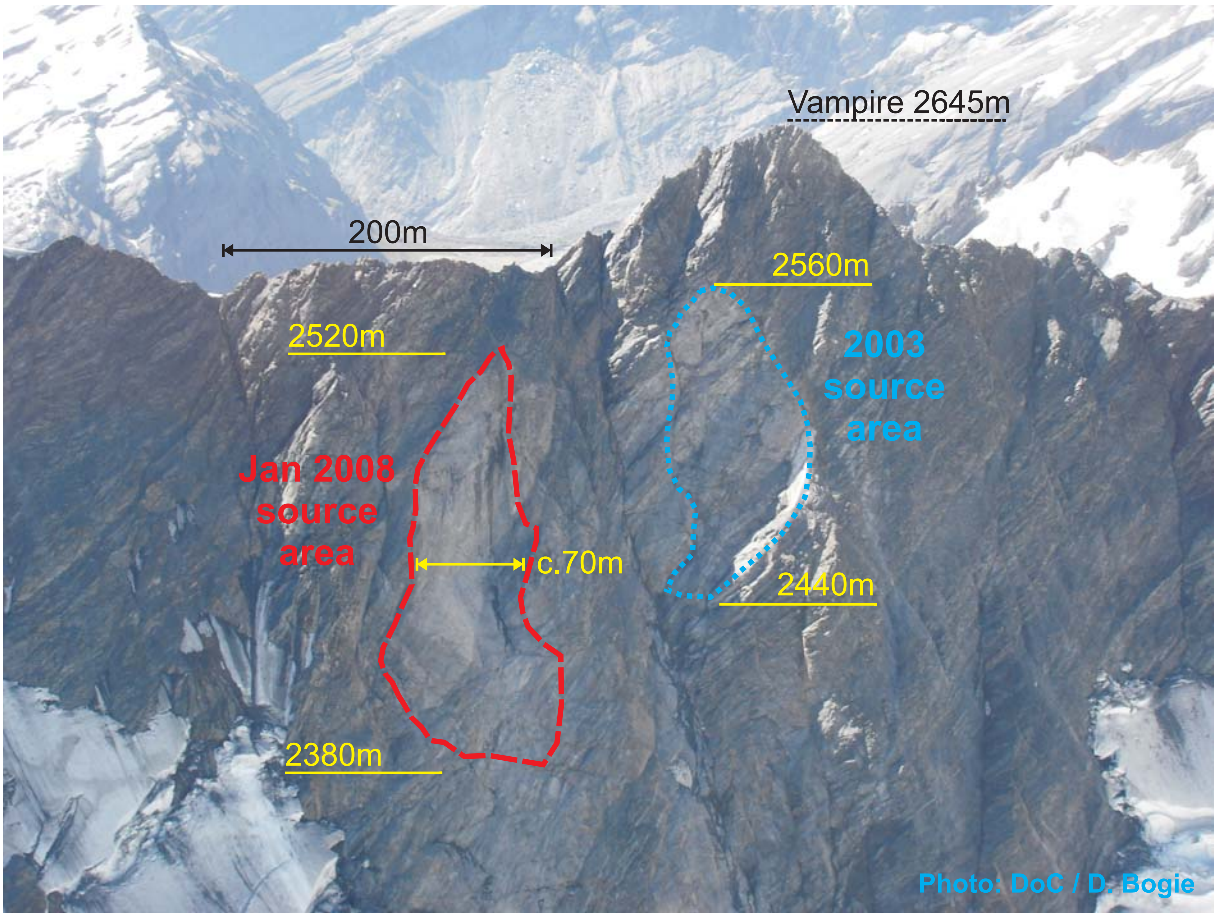


Figure 6 Vampire (2645m) avalanche profiles – 2008 (red) and 2003 (blue). The mid-section of the 2003 flow path is not shown, as it is the same as the main profile of the 2008 avalanches. Note the secondary collapse of debris where the flow path rises over the SE spur of Mt Bannie. (Horizontal scale = vertical scale).



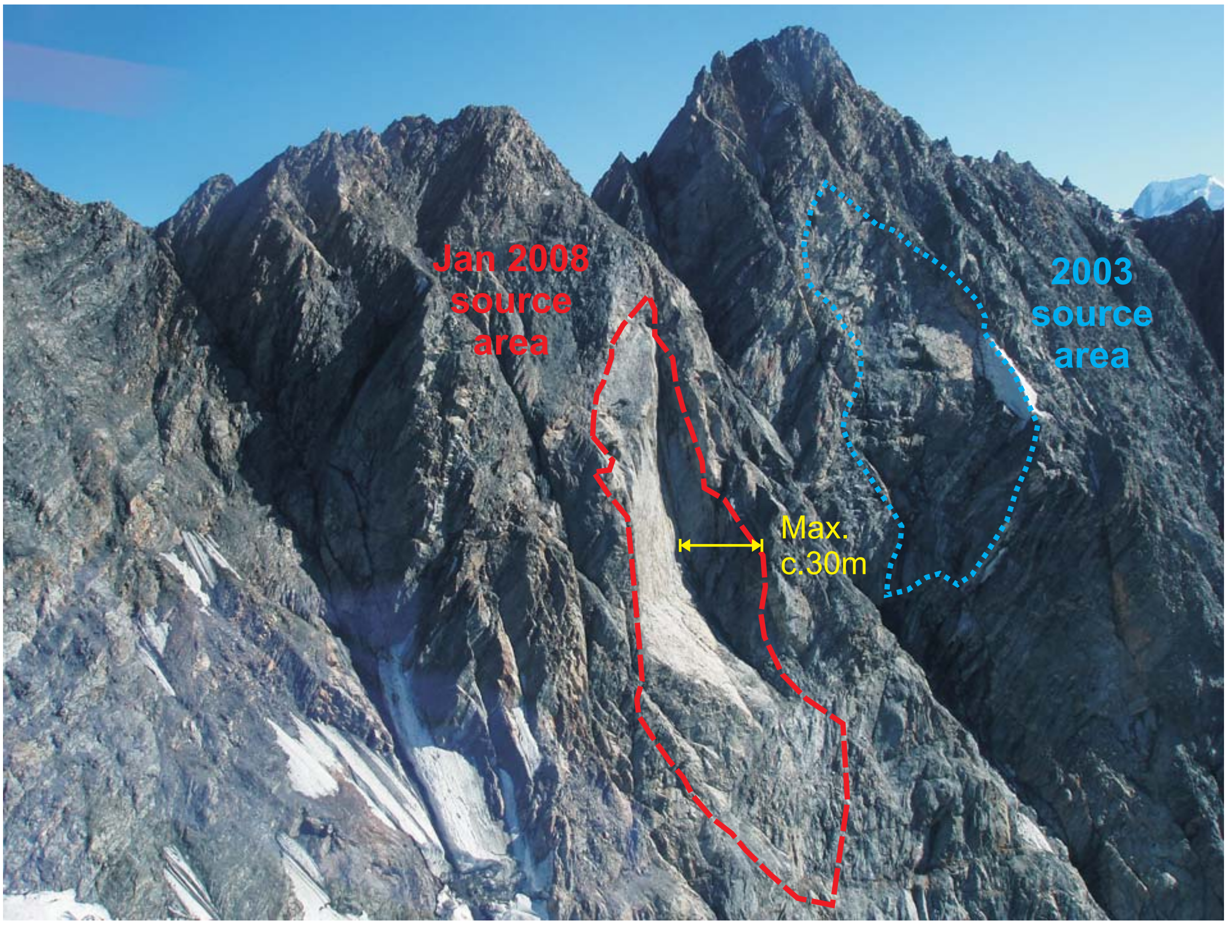


Figure 7 Rock failure areas on the south face of Vampire. Rock collapsed from the light coloured scars in January 2008 (red) and during 2003 (blue). The Jan 2008 scar area is approximately 140 m high and 70 m across. Photographs: D. Bogie/DoC, 16 Jan 2008 (top); S. Cox/GNS Science, 16 Jan 2008 (bottom).

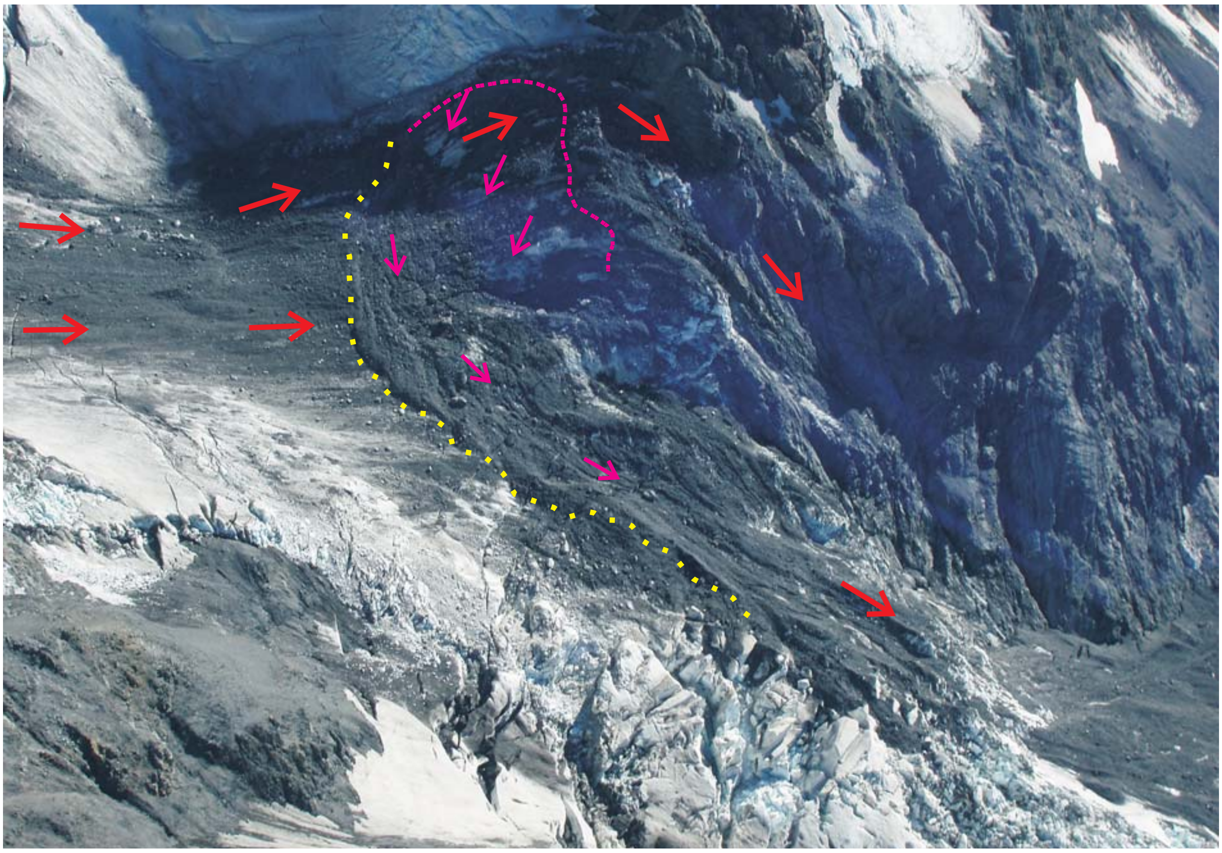


Figure 8 January 2008 avalanche flow path. Top - looking straight down the flow path, onto the Bannie Glacier (foreground) and Mueller Glacier (far distance). Bottom – looking across the Bannie Glacier icefall towards the SE spur of Mt Bannie. Arrows indicate the main direction of flow (red) and secondary collapse flow direction (pink/purple). Note the ridge of debris (yellow dots) developed at a high angle, and relatively undisturbed by, flow of the main avalanche.
Photographs: S. Jackson/DoC, 16 Jan 2008 (top); S. Cox/GNS Science, 16 Jan 2008 (bottom).

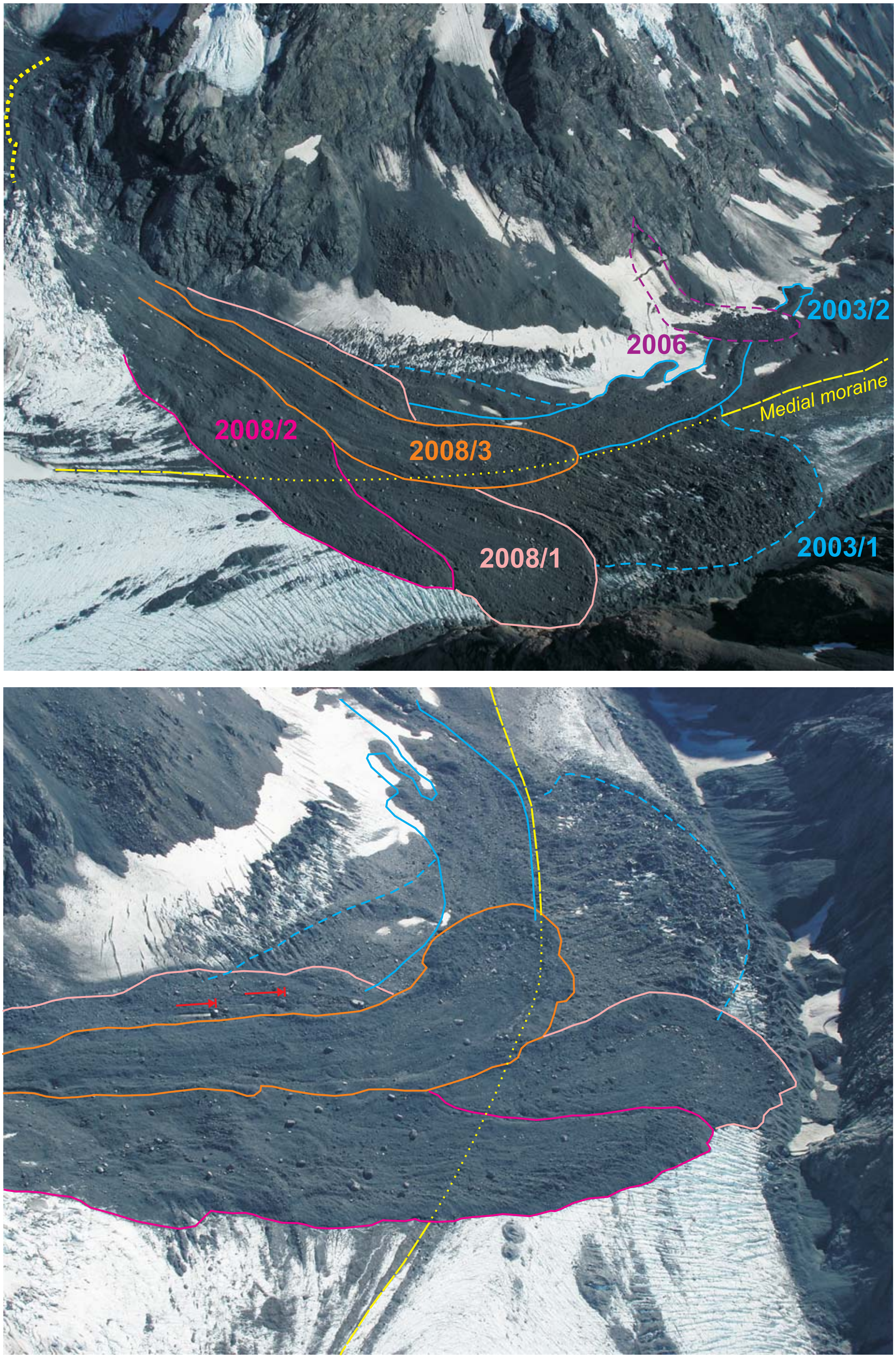


Figure 9 Lobes of debris on the Mueller Glacier deposited from avalanches off the south face of Vampire. A medial moraine ridge on the glacier (yellow dashed line) can be seen buried beneath some of the lobes (yellow dashed line). Boulders the size of cars lie amongst rocky avalanche debris, two (marked with red arrows) developed prominent skid marks in the debris.
Photographs: S. Cox/GNS Science, 16 Jan 2008.

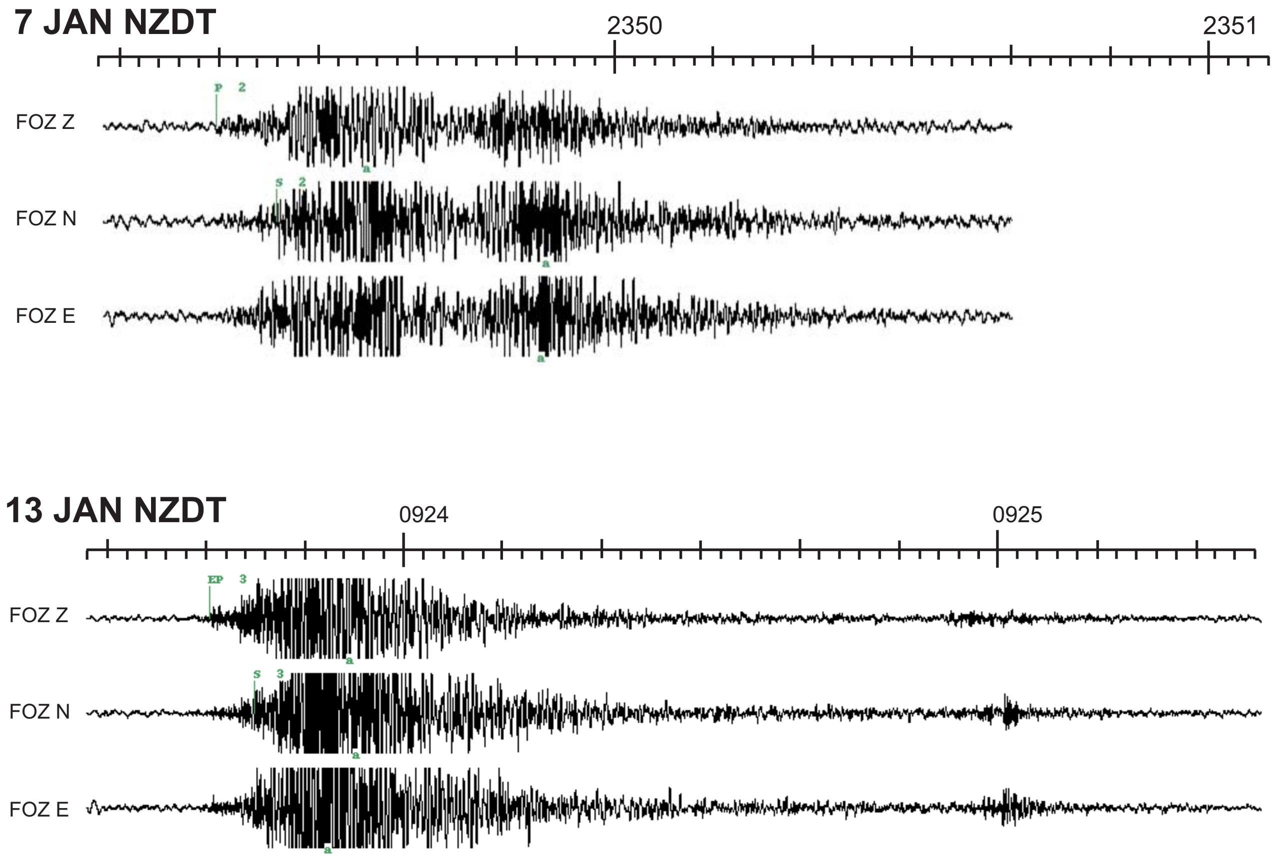
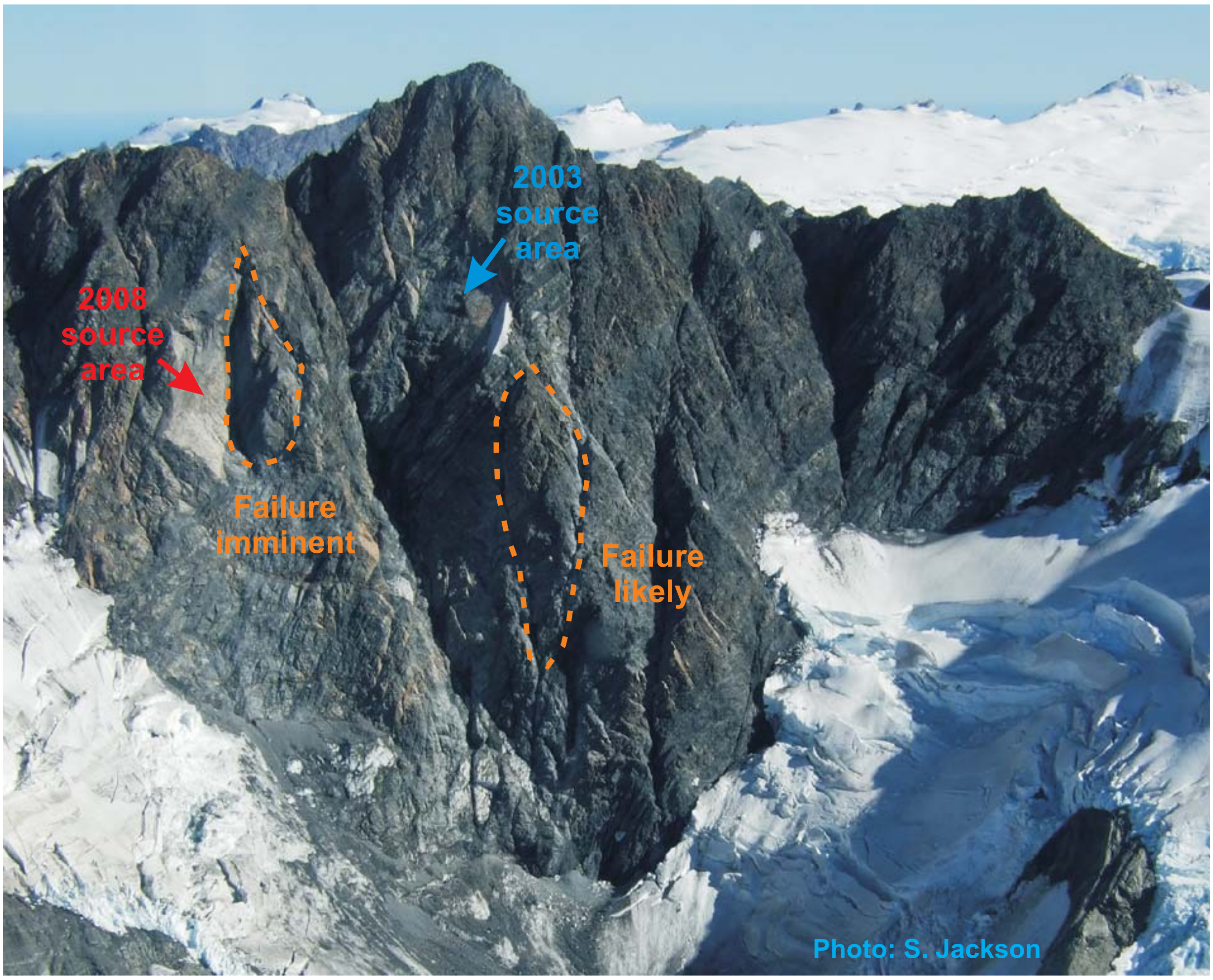


Figure 10 Seismic signals recorded by the GeoNet seismograph FOZ at Karangarua, 27 km to the northwest of Vampire. Times are shown in New Zealand Daylight Time (NZDT) with 2 s time scale divisions.



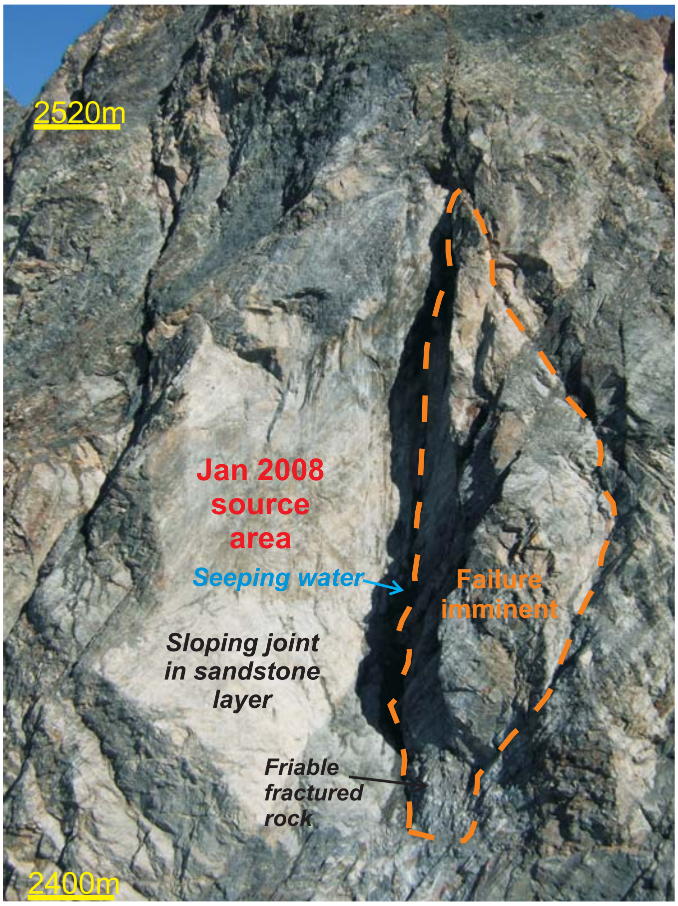


Figure 11

Rock mass failure on the south face of Vampire is not yet complete. A large block lies to the east (right) of the 2008 avalanche source area, with weak crushed rock at its base and with open fractures behind. Failure of this block is imminent. A buttress below the 2003 source area has the same fracture and bedding pattern as the 2003 avalanche source area. Failure of this buttress is likely.
Photographs: S. Jackson, 16 Jan 2008 (top);
S. Cox/GNS Science, 16 Jan 2008 (bottom).

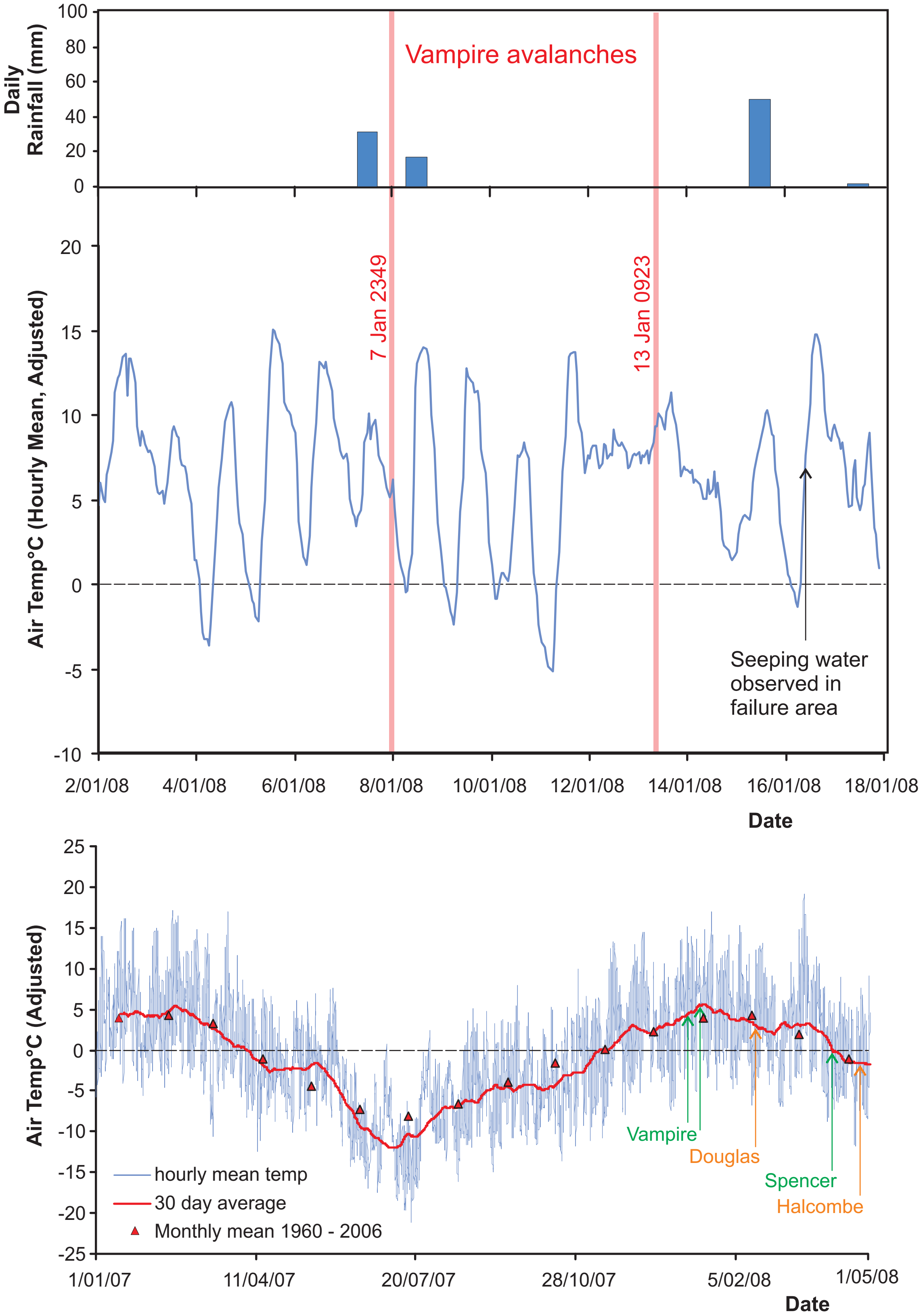


Figure 12 Air temperature data, adjusted to an altitude of 2500 m -see text, from hourly mean temperature recordings made at the Mount Cook Village together with daily rainfall (mm Mount Cook station 18125). Expanded detail of early January 2008 (top) and the 2007-2008 annual variation with the 1960-2006 monthly mean (bottom). (Data supplied by NIWA).

6.0 OTHER RECENT ROCK FALLS

Mt Beatrice 23 November 2004

On the morning of 23 November 2004 some Australian climbers witnessed a rock avalanche from Mt Beatrice (2528 m) engulfing an area they had walked over just 15 minutes previously (Figure 13). Tim Billington's diary describes "*A huge plume of dust was kicked up over the glacier and the land slide tumbled across the glacier like a wave on the beach*". The fall initiated between 1620 and 1700 m, from a 60º sloping area on the east face which had been spalling small amounts of rock for at least two days preceding the avalanche. The final distribution of debris is very clear in the 04 May 2006 Digital Globe (Google Earth) image, which shows two distinct debris lobes reaching 1.2 km from the source area. An earlier lobe was deposited along a trough on the true right side of the glacier. It was cross-cut by a second lobe which spread across the middle of Hooker Glacier. The avalanche dropped a maximum height of 440 m over a 20º angle of reach. The first deposit lobe covers an area of 87,000 m^2, while the second covers 90,000 m^2. Photographs taken in January 2007 (Figure 13) indicate the second lobe is comparatively thick, locally perhaps as much as 10 m. The Beatrice avalanche deposit volume is therefore inferred to be between 10^5 and 10^6 m^3.

Douglas Peak 18 Feb 2008

On 19 Feb 2008 Greg King (Pilot, Helicopter Line) observed a collapse that had occurred from the upper part of Pioneer Ridge, near the summit of Douglas Peak (3077 m) at the head of Fox Glacier (Figure 14). The collapse probably occurred on 18 Feb 2008. Rocks between 2690 and 3010m fell down the North Face over a route not uncommonly used by mountaineers (Palman 2001). The rock fall trajectory was focussed by topography, forming a debris cone at the base of the slope and a debris tongue which flowed out onto the Explorer Glacier to 2530 m. Runout distance was 460 m, with a 46º angle of reach. The resulting deposit has an area of 16,000 m^2. While not a large event by the standards of other avalanches described in this report and McSaveney (2002), it is locally significant for mountaineers. The event occurred during a sequence of warming, possibly as night time temperatures first remained above freezing (Figure 16).

Mt Spencer 6-7 April 2008

On 9 April 2008 Greg King photographed rock fall that had occurred from the upper part of Mt Spencer (2788 m) at the head of Franz Josef Glacier (Figures 14, 15). The collapse from a 49º slope between 2680 and 2720 m probably occurred on 6 or 7 April 2008. Most rocks fell down a gulley to the east of the North West Pinnacle (Palman 2001), but some either made their way down a path to the west of the pinnacle or were part of a second, smaller, collapse. Debris cones formed at the base of the slope and a larger, but thin, debris tongue flowed out across the Explorer Glacier down to about 2340 m. The total drop of the larger tongue was 380 m and runout distance 560 m, giving a 34º angle of reach. The deposits have areas of 1,700 and 36,000 m^2. A small rock fall also occurred from the slopes of Mt Frederic Gardiner, 250 m along the Main Divide to the northeast. The rock fall followed a 24 hour period in which a moderate (31 mm) amount of rainfall was recorded at Mount Cook, while temperatures were probably fluctuating about freezing level at the source area altitude (Figure 16).

Mt Halcombe 24 April 2008

On 24 April 2008 Greg King photographed a collapse of the west face Mt Halcombe (2659 m), also at the head of Franz Josef Glacier (Figures 14, 15). The collapse involved an 80m wide area between 2590 and 2650m altitude, which was still active when he photographed it. The debris covers 15,000 m^2 and includes some very large blocks of sandstone, estimated to be >10 m across. Debris is spread out 200 m from the face, down to 2510 m altitude. The maximum drop was 140 m, giving a 35º angle of reach. No significant rainfall had been measured in the week leading up to the rock fall, which occurred in a period when temperatures were probably fluctuating about freezing level (Figure 16).

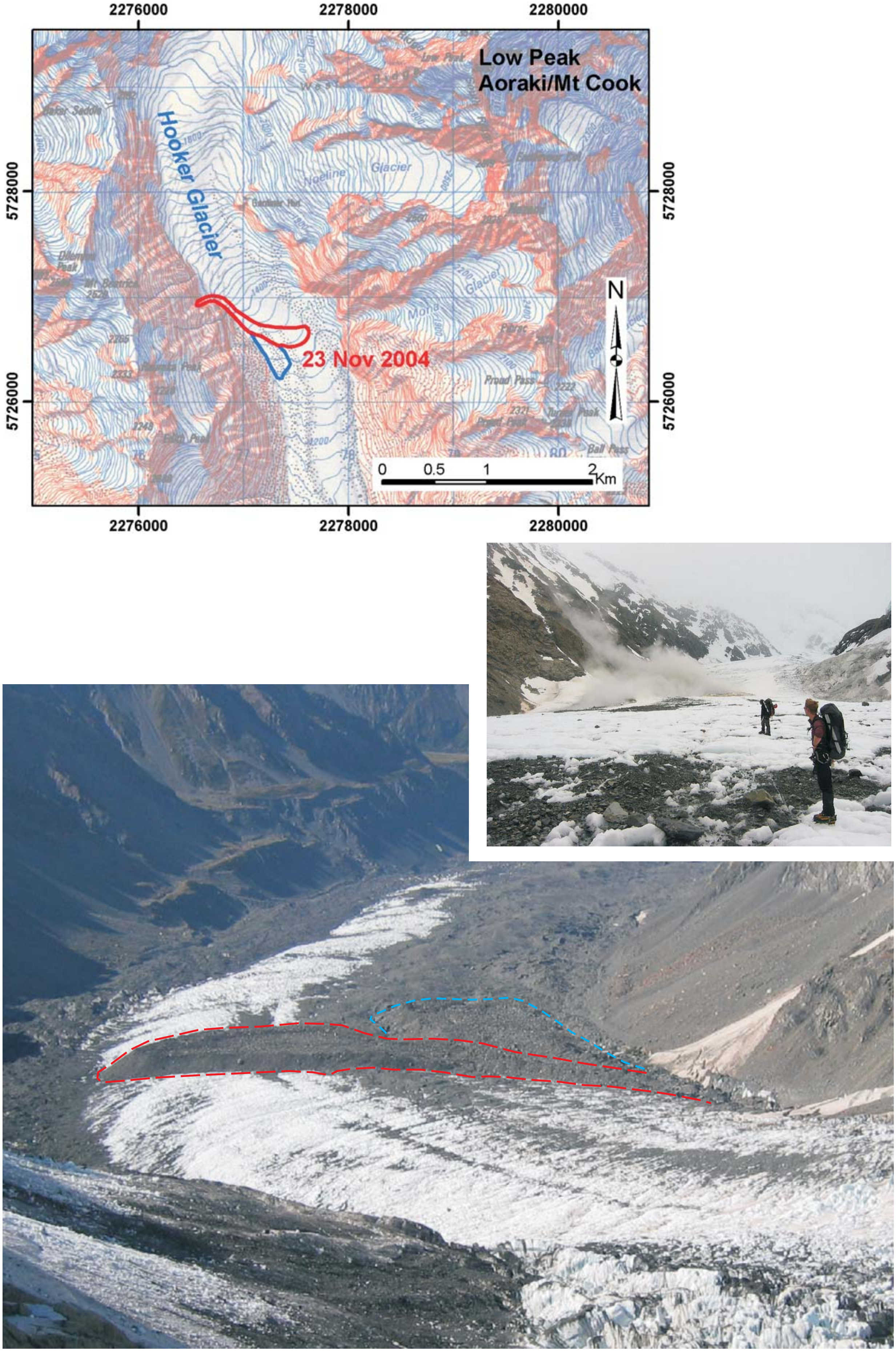


Figure 13 Beatrice rock avalanche. Map, photograph of the event, and two-lobe deposit. Photographs: Neil Monteith (middle), 23 Nov 2004; S. Allen (bottom), 19 Jan 2007.

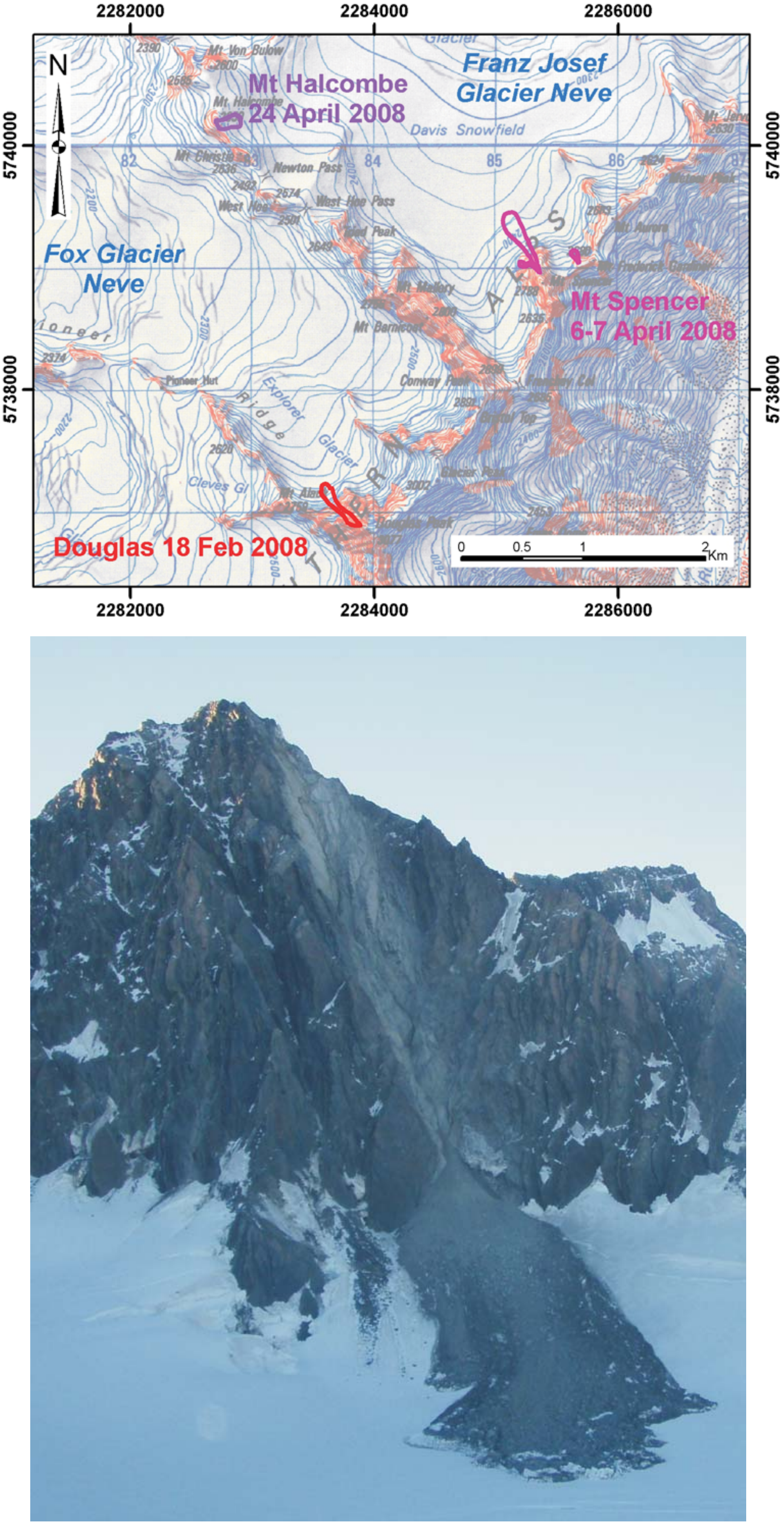


Figure 14 Map of rock falls in the Franz Josef and Fox Glacier neves during February and April 2008 (top). Photo of Douglas Peak rock fall of 18 Feb (bottom). Photograph: Greg King, 19 Feb 2008.

Figure 15 Rockfalls from of Mt Spencer (top) and Halcombe Peak (bottom) at the head of the Franz Josef Glacier. Photographs: Greg King, 9 Apr 2008 (top) and 24 Apr 2008 (bottom).

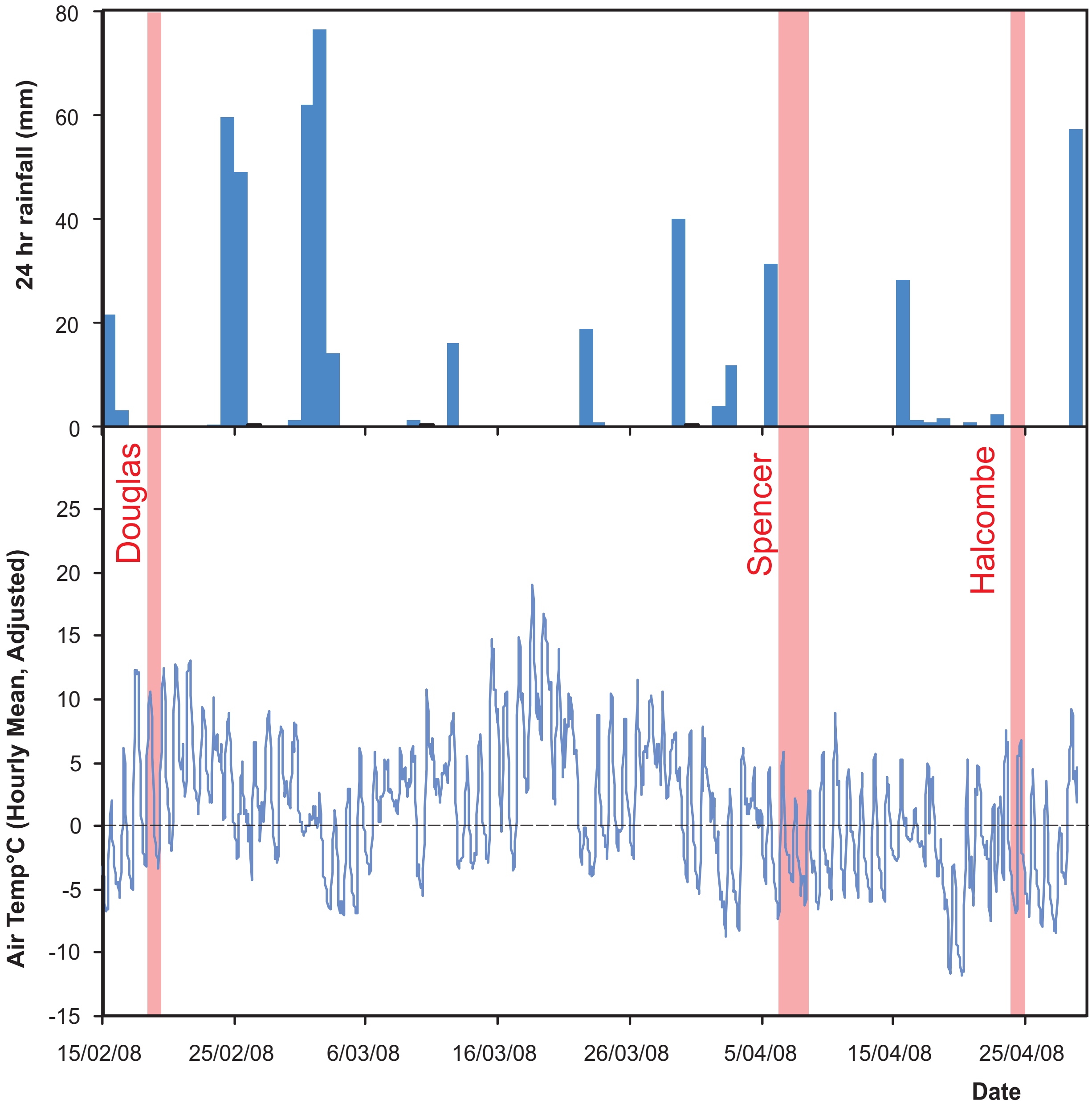


Figure 16 Air temperature data, adjusted to an altitude of 2500 m -see text, from hourly mean temperature recordings made at the Mount Cook Village together with daily rainfall (mm Mount Cook station 18125). The data covers the period mid-February to April 2008, when the Douglas Peak, Spencer and Mt Halcombe rock falls occurred. Note that the Mount Cook weather station is located 20km south of the Franz Josef Glacier neve, and can only be used as an indirect proxy for conditions that may have occurred during the rockfalls (Data supplied by NIWA).

7.0 DISCUSSION AND CONCLUSIONS

There has been ongoing speculation as to whether or not ice retreat and warm weather and a lack of freezing (or freeze thaw) is a causal factor in avalanches from Vampire and other peaks. The mean temperature recorded in Mount Cook Village during January 2008 was 16.1ºC, which was 1.6ºC higher than the January average from 1960-2006 (14.5ºC, std. dev. = 1.4ºC), and the warmest January since 1999 (NIWA National Climate Database - http://cliflo.niwa.co.nz). Temperatures throughout spring 2007-summer 2008 were very warm (Figure 12), and the snow pack retreated so significantly that local residents and climbers were saying as early as January that "the mountains were looking like they normally do in March". Recalculation of Mount Cook Village air temperature measurements to the source area altitude around 2500 m suggests both the 7 January and 13 January 2008 events on Vampire occurred when temperatures had been maintained consistently above freezing during the preceding days and nights. Events on Douglas Peak, Mt Spencer and Mt Halcombe occurred when recalculated temperature measurements suggest air near the source areas may have been above freezing level during the day, but below freezing at night.

As part of this study we looked at the timing of collapses during 2008 cf. modelled air temperature and measured rainfall, but have yet to find any consistencies between events. The known record of large rock falls and rock avalanches in recent time is listed in Table 2. Unfortunately the exact month or season is unknown for many events. There does appear to be an absence of rock avalanches during winter. We believe the record of events is too small, and potentially too incomplete, to draw any firm conclusions on relationships between timing of events and temperature and/or periods of warming. The topic, including rock temperature monitoring and permafrost modelling, is part of an ongoing PhD study at University of Canterbury by Simon Allen. The key contributing factor that should be emphasized is that these events are located in areas of steep topography, in most instances where topography is in excess of 49º.

We conclude that:

1. The Vampire rock avalanches of 2003 and 2008 are part of the natural process of erosion in the Southern Alps. Slopes on the south face are extremely steep, comprised of a relatively weak jointed greywacke rock mass, and therefore prone to failure. Uplift and erosion result in stress-release fracturing and dilation of mountain rock masses. Over time, effects such as rock mass dilation, joint opening, ice wedging, ice thawing, glacier and snow level recession, and the reduction in ice-binding of rock masses have lowered their resistance to failure.

2. Temperatures were probably above freezing temperatures when the 7 January Vampire avalanche occurred, with small quanities of free-flowing water likely to be present in the rock failure volume. However, this was not the first time that temperatures had exceeded zero degrees during spring and summer 2008, and although melting may have been a factor, it is not considered to be a trigger in the collapse of the slope. No other trigger, such as earthquake or rainstorm, has been identified and it should be considered to be spontaneous.

3. The south face of Vampire is still considered to be quite unstable. Collapse of a large block from beside the 2008 avalanche source area appears imminent. A pillar below the 2003 avalanche source area is also likely to collapse. Both appear to be of sufficient volume that they can be expected to form avalanche-like flows that run out across Mueller Glacier. While specifically identified for this site, the hazard is not necessarily greater than beneath many other, steep, fractured slopes within Aoraki/Mount Cook National Park.

4. The recent events on Vampire, Mt Beatrice, Douglas Peak, Mt Spencer and Mt Halcombe continue a trend observed during the past decade of frequent bedrock failures initiating from the steep slopes near the Main Divide, for which all events appear spontaneous with no known trigger recognised. Their destructive paths and debris are “very significant” at a local valley scale.

5. While the observed rock avalanches appear to be spontaneous, similar effects will be much more widespread throughout the central Southern Alps in the event of triggering by a major M7-8 earthquake (Hancox et al. 2002, 2003; Sutherland et al. 2007) on the Alpine Fault.

Table 2 Significant historic rock avalanches and recent, smaller, rock falls in the Aoraki/Mount Cook region.
Where known, dates are shaded by season: spring (green) summer (yellow), autumn (orange) and winter (blue).

LOCATION	Date	Max Elevation (m)	Toe Elevation (m)	Slope Aspect Source	Mean Slope Source	Runout Distance (km)	α º	Source lithology & structure*[3]	Deposit Area (km^2)	Reference
Aoraki/Mt Cook	1873			SW				Greywacke		Barff (1873)
Mt Isobel I	c. 1950-55	2180	1435	SE	49º	1.7	23º	Fractured Greywacke, ss	0.43	McSaveney (2002)
Mt Isobel II	c. 1965	2360	1540	E	59º	1.4	30º		0.14	
Mt Walter-Green	1972			SE				Greywacke, ss		Hancox et al. (1991)
Mt Vancouver	1974 or 75	3300		E	60º			Greywacke, ss		Hancox et al. (1991)
Murchison Glacier	25/12/75 *[1]	1820	1550	NW	43º	1.3	11º	Greywacke, partly ds	0.43	Whitehouse & Griffiths (1983)
Aoraki/Mt Cook	14/12/91	3763	1040	E	54º	8.5	22º	Greywacke, ss	14.1	Hancox et al. (1991), McSaveney (2002)
Mt Fletcher I	2/05/92	2420	1075	SE	56º	3.2	22º	Fractured greywacke, ss	2.2	McSaveney (1992a,b, 2002)
Mt Fletcher II	16/09/92 *[2]									
Mt Thomson	22/02/96	2180	1380	E	66º	0.9	42º	Fractured semi-schist, ss	0.13	McSaveney (2002)
Mt Adams	6/10/99	2130	340	N	57º	2.3	37º	Schist, ss at high angle to schistosity	1.1	(Hancox et al. 1999, 2005)
Vampire	2003	2560	1670	SE	65º	1.9	24º	Semi-schist, jcss	0.28	This report
Mt Beatrice	23/11/04	1720	1280	E	60º	1.2	20º	Fractured greywacke, tss	0.18	This report
Vampire	7-13/01/08	2520	1720	SE	73º	1.7	27.5º	Semi-schist, jcss	0.30	This report
Douglas Peak	18/02/08	3010	2540	NW	58º	0.46	46º	Sandstone, ds	0.02	This report
Mt Spencer	6-7/04/08	2720	2340	NW	49º	0.56	34º	Greywacke, ds	0.04	This report
Mt Halcombe	24/04/08	2650	2510	E	52º	0.14	35º	Semi-schist, ss	0.02	This report

α = Angle of reach from avalanche initiation to the toe of the deposit (Farhböschung).
*[1] *This event was storm triggered.*
*[2] *At the time of avalanche the lake below the peak was frozen, so temperatures at the source were still below freezing.*
*[3] *Type of collapse: ss=scarp slope; jcss= joint controlled scarp slope; tss= toppled scarp slope; ds=dip slope.*

ACKNOWLEDGEMENTS

The authors wish to highlight the outstanding contribution of Greg King (Helicopter Line) who has provided continual reports and photographs of rock fall activity during the summer-autumn 2008. Significantly, this work would not even have begun without his initial observations and efforts to report the Vampire avalanche. The authors would also like to acknowledge the excellent support and cooperation provided by the Department of Conservation in investigating the Vampire rock avalanche. The contributions of Don Bogie, Ray Bellringer (DoC Aoraki/Mount Cook), Neil Monteith and Tim Billington (Climbers), and Mauri McSaveney (GNS Science) were greatly appreciated. We acknowledge the New Zealand GeoNet project and its sponsors EQC, GNS Science and FRST, for providing earthquake data used in this study. Photographic collections of Allen Uren, Colin Monteath (Hedgehog House Photolibrary), Simon Allen, Greg King, Neil Monteith, Trevor Chinn and the New Zealand Alpine Club guidebook were an invaluable resource. We were unable to contact Alex Palman for personal permission to use his photograph, which was kindly supplied by the New Zealand Alpine Club. Air temperature data from Mount Cook Village was obtained from the National Institute of Water and Atmospheric Sciences (NIWA). Field investigations were ably supported by Jamie Scott, Craig Freeman and Sally Jackson, with permissions provided through DoC. This report was reviewed by Graham Hancox and Mauri McSaveney.

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