# Report on the 14-15 October 2016 mass movement event in the Longyearbyen area


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## 1. Introduction

The local authorities asked UNIS on Friday 14 October to provide a report on the mass movements expected due to the forecasted 20-25 mm of rain between the evening of 14 October and morning of 15 October. The request came as met.no/NVE issued an OBS warning about the anticipated heavy precipitation. Following this request, geomorphologists from the Arctic Geology department (the authors), met and decided to 1) deploy rain gauges in the Longyeardalen valley, and 2) observe and record mass movements on 15 and 16 October following the projected rain event. Daylight ended around 17:00 on 14 October, and by this time none of the reported mass movements had been observed. Observations of the mass movements were resumed after 8:00 on October 15, as daylight appeared.

The scope of this report is limited to: 1) pertinent meteorological and geomorphological conditions during the pre-failure stage, which may have contributed to the mass movements on 15 October, 2016; and 2) observations of mass movements (including their classification and spatial distribution). This report documents mass movements on the slopes around Longyearbyen in the Longyeardalen valley, around the airport, along the road into Bjørndalen, and along the road into Adventdalen. Recommendations are provided to improve the assessment of pre-failure conditioning in the future.

## 2. 2016 meteorological situation leading up to the event

The air temperature at Svalbard Airport since June 2016 has been above the average for the previous 30 years, especially in June, July, and September (Table 1). Generally, the air temperature has decreased since August, but there had only been one day with an average temperature below 0°C until 15 October (Figure 1).

Table 1. Monthly air temperature recorded by Svalbard Airport in 2016, compared to the average of the previous 30 years. Source: http://www.met.no/Klima/Varet_i_Norge/

| Air temperature (°C) | June | July | August | September |
|---|---|---|---|---|
| 2016 | 5.0 | 9.0 | 5.8 | 4.1 |
| Average for the period 1986-2015 | 3.3 | 6.6 | 5.8 | 1.6 |

Summer 2016 was relatively wet, particularly in July (Table 2; Figure 1). It is possible that this condition also contributed to the slope instability on 15 October 2016, as the thawed top layer of the ground was generally well supplied with moisture over the summer and autumn.

Table 2. Monthly precipitation values recorded by Svalbard Airport in 2016, compared to the average of the previous 30 years. Source: http://www.met.no/Klima/Varet_i_Norge/

| Precipitation (mm w.e.) | June | July | August | September |
|---|---|---|---|---|
| 2016 | 6.2 | 51.7 | 27.3 | 27.4 |
| Average for the period 1986-2015 | 9.1 | 18.0 | 21.8 | 23.3 |

Due to the warm autumn, the active layer – the layer that freezes and thaws seasonally above permafrost – was largely unfrozen during the event. The ground surface at 464 m experienced freezing in late September and early October, but only for short periods (Figure 1). In combination with the high precipitation amounts in summer 2016, additional moisture added to the active layer during the high intensity event created saturated conditions that allowed mass movements in different forms. Commonly, the ground surface near Longyearbyen will have started to freeze downwards by mid-October, but due to the mild 2016 autumn this freezing had not commenced, and the active layer was close to its maximum thickness on the slopes during the event. Therefore, there was unfrozen ground typically greater than 1 m in depth available for mass movements. On Gruvefjellet, the active layer was about 1 m thick, indicated by the 1 m ground temperature at or just below 0°C (Figure 1).

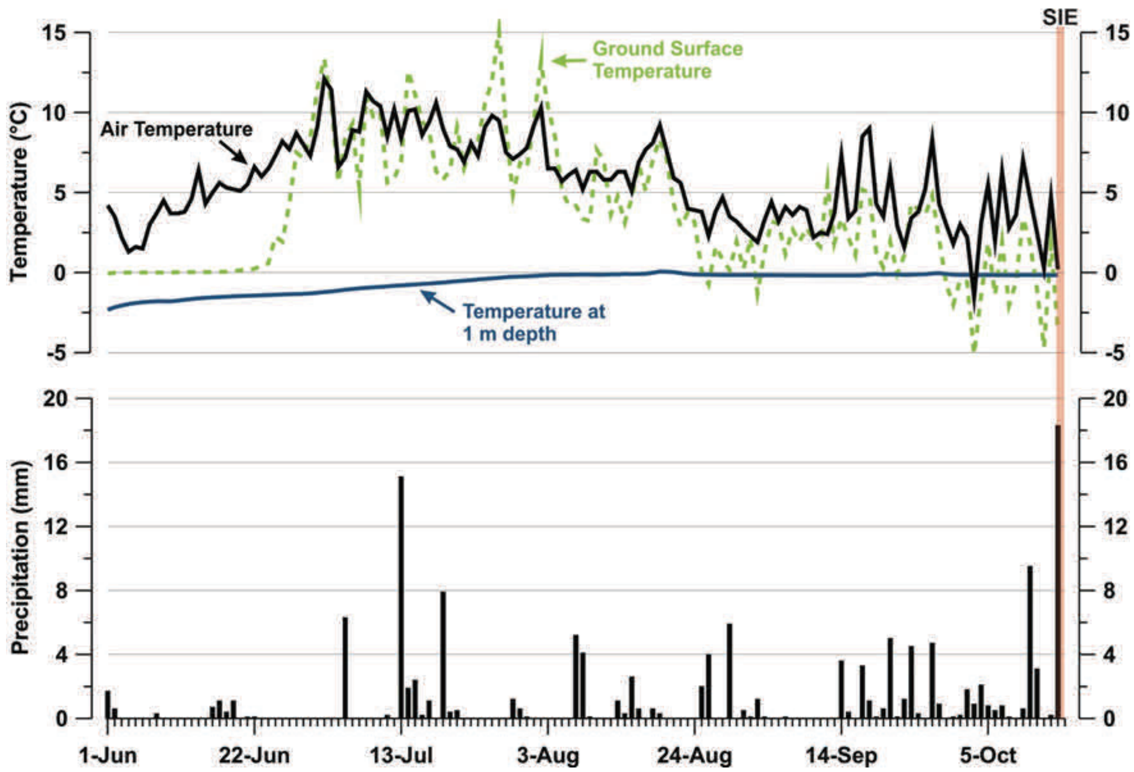


Figure 1. Daily meteorological conditions leading to the observed slope instability event (SIE) on 15 October, 2016. Mean daily rainfall and air temperature are recorded at the Longyearbyen Airport (28 m a.s.l.) from eklima (met.no). Ground temperatures are from the Gruvefjellet meteorological station at 464 m a.s.l. (UNIS online meteorological station).

## 3. Northern Hemisphere meteorological overview, 15 October 2016

On 15 October, 2016, the main jet stream in the upper troposphere (7-10 km altitude) over the North Atlantic sector was characterised by a meridional pattern, with a large northerly deviation towards Svalbard (Figure 2, left). This resulted in relatively high temperatures in the lower troposphere (near sea level), indicated by the northerly position of the freezing isotherm at 1000 m altitude in the Atlantic sector (Figure 2, centre). Consequently, air masses with high moisture content flowed into the Arctic over Svalbard (Figure 2, blue colour on the right diagram), creating the conditions for high precipitation over Longyearbyen during the day and evening of 14 October and in the night to October 15.

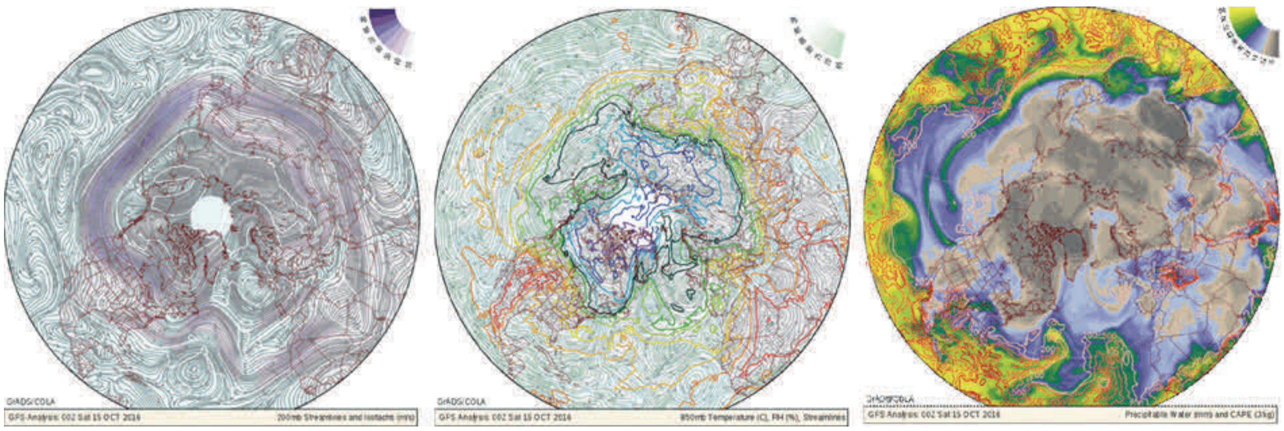

Figure 2. Northern Hemisphere weather, 15 October 2016. Left diagram shows upper troposphere circulation with jet streams shown in purple, central figure shows circulation and temperature at 1000 m altitude, and right figure shows distribution of precipitable water in the atmosphere. Source: http://wxmaps.org/pix/hemi.00hr.html.

### *3.1. Regional meteorological systems near Svalbard 14-15 October 2016*

During 14 October 2016 at 12:50 local time, a major weather system was moving across the Greenland Sea towards Svalbard (Figure 3). As this system moved NE across Svalbard, precipitation fell as rain at low altitudes.

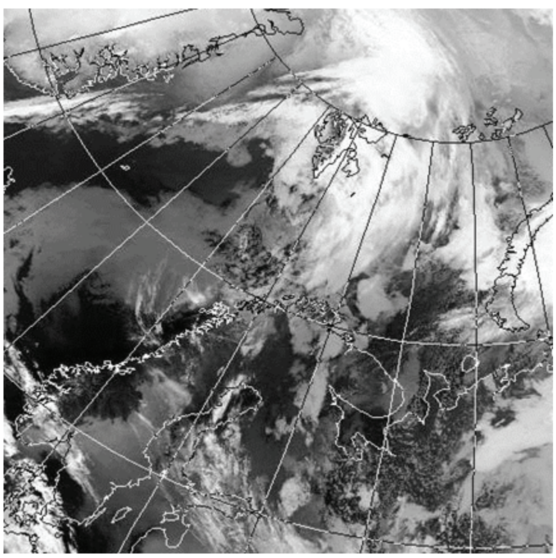

Figure 3. Dundee satellite picture showing part of the Northern Hemisphere on 14 October 2016, 12:50 local Svalbard summer time (thermal infra-red, 10.3-11.3µm). Source: http://www.sat.dundee.ac.uk/.

*3.2. Precipitation 14-15 October 2016*

We established simple beaker rain gauges on the ground in Nybyen, on Elvesletta, and on the roof platform at UNIS on Friday afternoon. The one at Elvesletta was blown over; the two on the UNIS roof recorded 13 and 14 mm, respectively, while the one in Nybyen recorded 21 mm from 14 October at 16:00 to 15 October at 12:30.

At Isfjord Radio, 42 mm of precipitation was recorded in the entrance to Isfjorden on the west coast of Svalbard, while 18 mm was recorded at the Longyearbyen airport (eklima, met.no).

We also installed two precipitation gauges in the middle of Longyeardalen (at about 45 m altitude) in the late afternoon, 14 October. The instruments were programmed to record the amount of precipitation every 5 minutes (Figure 4).

A previous investigation (Larsson, 1982) suggested a rain intensity of 2 mm/hour as a critical value for the release of active-layer detachment slides, debris flows and mudflows in the permafrost environment around Longyearbyen. This result was based on another major precipitation event on 10-11 July 1972, where 30.8 mm of rain fell within 12 hours, and a high number of slides and mudflows were released on both sides of lower Longyeardalen valley. The precipitation measurements from 14-15 October 2016 lend support to Larsson's conclusion based on the 1972 event, but the question about critical precipitation intensities clearly requires additional observations and analysis before any concrete conclusions may be drawn.

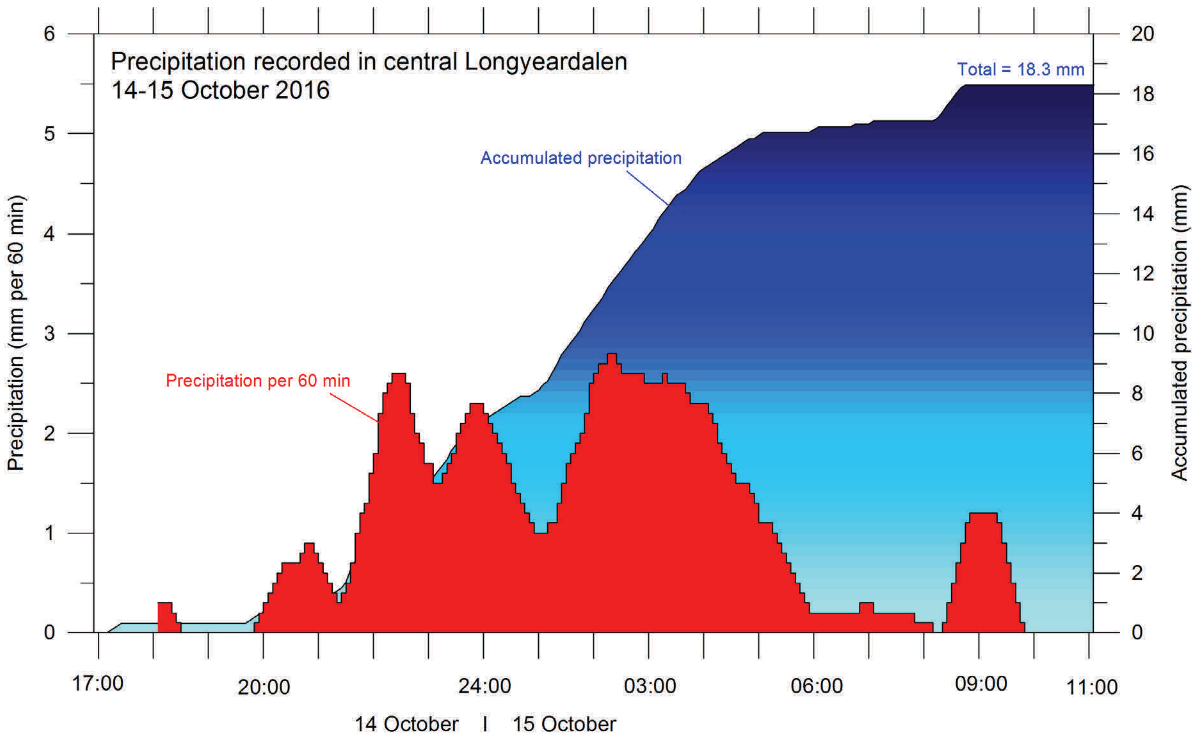


Figure 4. The red region shows the calculated 60-minute intensity (the amount of precipitation during the previous 60 minutes, plotted in 5-minute steps) of precipitation from Friday 14 October at 17:00 to Saturday 15 October at 11:00. The blue shaded region shows the accumulated amount of precipitation during the same period. In total 18.3 mm precipitation was recorded in this period by the data logger. The highest 60 minutes (1 hour) intensity recorded was 2.8 mm/hour, at around 2:00 October 15.

### *3.3. Air temperature 14-15 October 2016*

Near sea level, air temperature in the afternoon of 14 October was about +5°C, while on Gruvefjellet (464 m altitude) it was about +3°C. During the night to 15 October the temperature at these locations increased to about +7 and +5°C, respectively (Source: http://www.unis.no/resources/weather-stations-and-web-cameras/). Therefore, all slopes around Longyeardalen were affected by positive air temperatures during the rainstorm, when the release of the reported slides and flows occurred. As the preceding period since August 2016 had also been characterised by warm conditions, the uppermost ~1-1.5 m of the valley slopes were probably unfrozen at the time of the failures.

Ground temperatures from the slopes are not available from Longyeardalen, but it is likely that several of the slope failures took place at the interface between the active-layer and top of permafrost, which is known to be ice-rich at places in Adventdalen. However, direct observations on the amount of ice in the uppermost part of the permafrost on the slopes of Longyeardalen are not available.

During the morning of 15 October air temperatures rapidly dropped to below zero at all elevations in Longyeardalen, but this happened after the slope failures occurred. However, this drop in temperature may have contributed to some stabilisation of the slopes. This inference requires further data and observations to be substantiated.

## 4. Mass movements in the Longyearbyen area

All visible mass movements that occurred in the areas with road access around Longyearbyen were mapped on 15 and 16 October (Figure 5). The observed mass movements included slumps, slides, and flows. In several places minor slumps occurred, consisting of moving rotational masses that did not slide or flow (Figure 8 & 9). In addition, active-layer detachment slides and debris flow were observed (Figure 6, 7, 9 and 10). Adjacent to the Longyearbyen cemetary, a large active-layer detachment slide occurred, moving sediment downslope into 3 depositional areas, with the lowermost reaching within 50 m of the road leading up to Huset, just 10-15 m from the cemetery. Following the detachment slide, a debris flow initiated in the slide path, continued further down the slope over the road, and towards the river system, covering the road in mud and rocks (Figure 5, 6 & 7). During late morning on 15 October when sliding was still occurring, we observed blocks up to 25 cm moving quickly in the debris flow down onto the fan that crossed the road. Higher up on the slope, larger blocks were moving in waves of sediment downslope in the slide path that formed the debris flow. At around 13:00 most of the movement had ceased and the debris fan crossing the road started to freeze as the air temperatures dropped below 0 °C. As air temperatures decreased to below freezing during the early afternoon 15 October, water started accumulating in the lower slopes as frozen overland flow (Figure 8).


Figure 5. Mass movements (yellow) recorded on 15 and 16 October following the 14 -15 rain storm event. The mass movements were in the form slumps, active layer detachment slides and debris flows, and combinations of these.

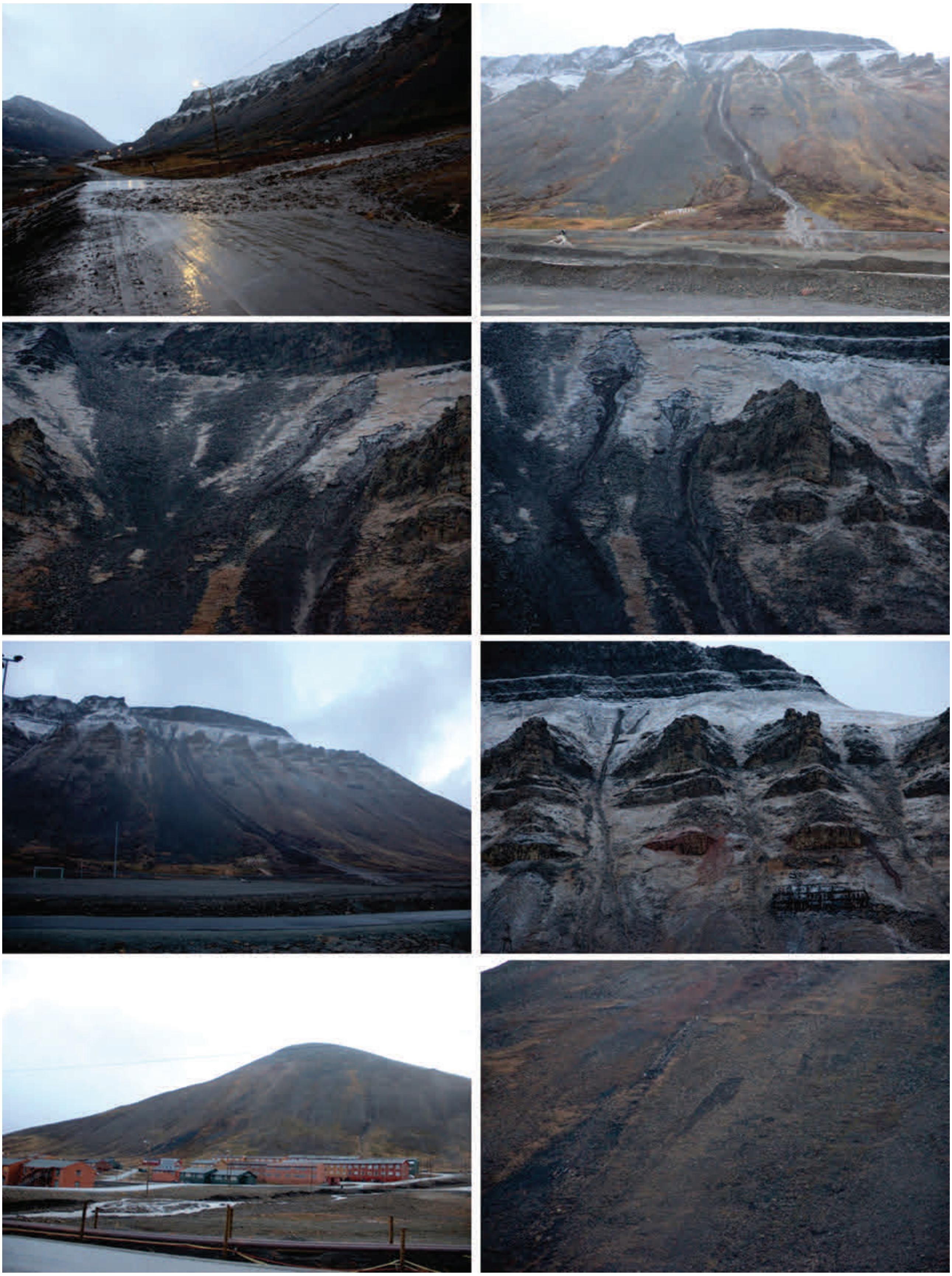

Figure 6. Overview and details of the active-layer detachment slide and debris flow in Longyeardalen valley at the cemetery, and a small slide on the opposite site of the Longyeardalen. Photos: Wesley Farnsworth, 15 October 2016.

Figure 7. Details of the release area of the Longyeardalen valley cemetery slide and flow area. Lower 3 photos are from the debris flows in Adventdalen at the eastern end of Isdammen. Photos: Wesley Farnsworth, 16 October 2016.

Figure 8. Overview (upper left) and detail (upper right) of slump in the upper Longyeardalen valley (opposite to the school). Frozen overland flows in the lower valley sides in both lower (lower left) and middle (lower right) Longyear-dalen. Photos: Hanne H. Christiansen, 16 October 2016.

Figure 9. Overview and details of active-layer detachment slides and debris flows from the area below the Svalsat road next to the airport. Photos: Wesley Farnsworth, 15 October 2016.

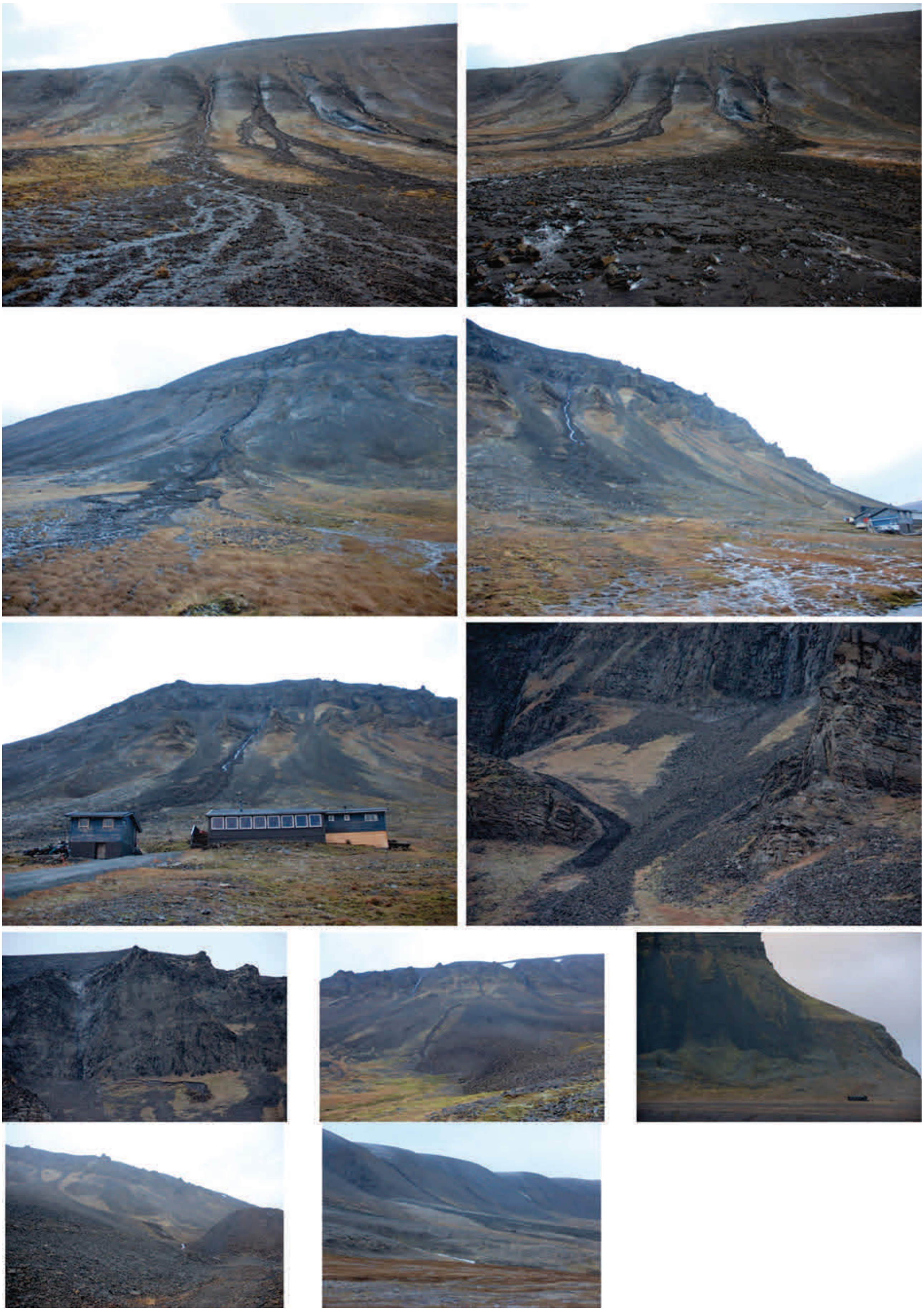

Figure 10. Debris flow further along the road towards and in Bjørndalen. Photos: Wesley Farnsworth, 15 October 2016.

## 5. Volume of the largest slide and flow, located at the cemetery

UNIS uses a high resolution laser scanner for hazard assessment and can survey all surface changes near Longyearbyen, such as snow avalanches, rock fall, and other mass movements. Change detection of the largest active-layer detachment and debris flow event at the cemetery was completed using a laser scan of the area from 16 September 2016 (before event scan) and from 18 October 2016 (after the event scan) with a resolution of the surface models of 10 cm. With this method, the two surfaces can be compared and an accurate determination of the volume change can be calculated (Figure 12). In total, an area of 23000 $m^2$ was covered by the debris flow, and a volume of 5000 $m^3$ of material was displaced. It is possible to identify both the eroded areas in the release zone and the depositional areas below the slide path (Figure 12). The deposits of this slide and flow are up to 5 m thick, and the associated eroded areas are up to 2-3 m deep (Figure 12).

Figure 11. Alexander Prokop laser scanning the cemetery slide Tuesday 18 October, 2016. Photo: Holt Hancock.

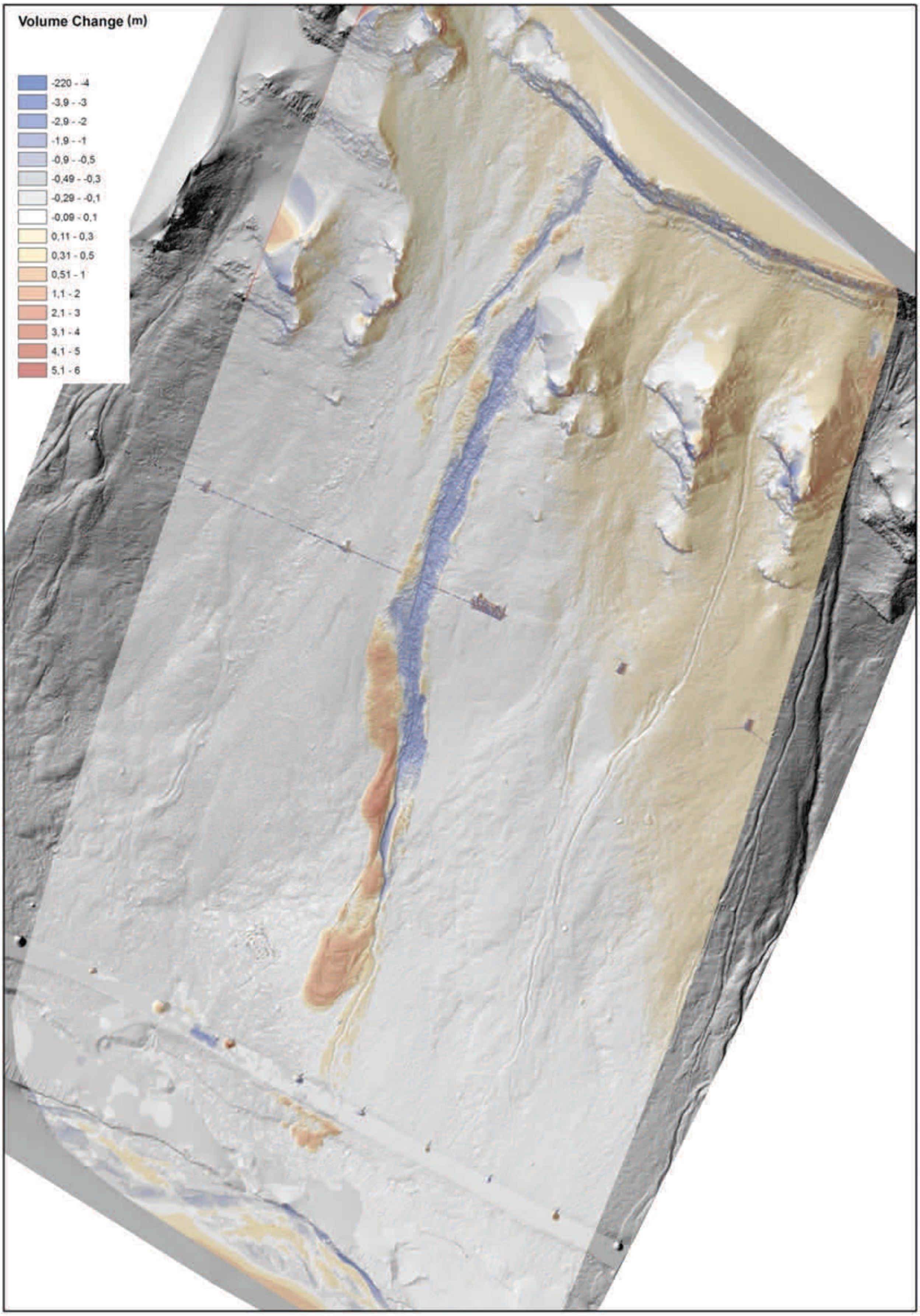


Figure 12. Volume changes of the surface between 16 September and 18 October 2016 in the area of the cemetery slide and flow area. Data obtained by repeated laser scanning. Blue colours showing erosion and red colours showing deposition. The scan was made the day after the debris masses that covered the road were removed, which is why they do not appear.

## 6. Recommendations for future improved observations

Based on this event and the need for access to observations to help determine the potential development of mass movements near Longyearbyen, we suggest installing online slope stations to measure rain precipitation, snow depth, water content, and ground temperatures through the active layer and into the top permafrost. In addition, ground ice content, sediment grain size and other basic geotechnical and geological data should be obtained from cores drilled at the sites. It would also be useful to have access to a terrestrial laser scanner (like the one UNIS presently leases) to enable quantification of snow accumulation and mass movement volumes on a regular basis to monitor longer-term changes, and to assess events like the one reported here.

The lack of continuous, automated precipitation measurements at the elevations of primary concern for mass wasting and snow avalanche hazard assessment is currently a critical limiting factor in the development of accurate and reliable hazard forecasts for the Longyearbyen area. While precipitation data, which is publicly available from the Svalbard Airport meteorological station, can serve as a basis for rough post-event precipitation estimates, this station's location near sea level is insufficient to adequately characterize spatially variable precipitation patterns across the regional vertical and horizontal precipitation gradients of concern for hazard management. Furthermore, the 12-hour temporal resolution of the publicly available precipitation data from the Svalbard Airport is far too coarse to be of use for hazard monitoring purposes and is further limited by the lack of real-time data availability. Establishing infrastructure to take automated, high temporal resolution (hourly to sub-hourly) rain precipitation and snow accumulation measurements at elevations relevant to slope failure is an essential next step in the continued development of reliable hazard forecasts and community warning systems.

At present, little knowledge exists regarding the amount and vertical distribution of ground ice in the slopes surrounding Longyearbyen. However, the presence of permafrost indicator landforms such as solifluction lobes and sheets, and rock glaciers, in addition to rock-fall deposits, debris-flow deposits and snow avalanche deposits, all indicate that an appreciable amount of ground ice is likely present in the substrate.

We would like to provide more detailed information at a later stage to suggest positioning of potential online slope instrumentation and the frequency of laser scanning of mass movement prone slopes, and to discuss ways to collect, process and share data both publicly and for educational and research use. This may allow the development of a system to predict different types of slope events based on observations, modelling, and evaluation, which can be used for decision making regarding the safety of the inhabitants in Svalbard.

## 7. Conclusion

Local mass movements in the form of slumps, slides, and flows in and around Longyearbyen on 15 October 2016 are attributed to a high-magnitude precipitation event, during which around 18 mm of rain fell with an intensity of up to 2.8 mm/hour over a period of about 12 hours. This intense precipitation caused the failures at a time when the thaw depth of surface materials had reached a maximum, following a summer/autumn with higher than average precipitation and warm air temperatures. A large slope failure near the Longyearbyen cemetery displaced 5000 $m^3$ of sediment. Improved measurements of precipitation, ground ice, ground temperatures, sediment properties, and slope topography may enable a better understanding of these slope failures and improved forecasting of events.

## Appendix A: The slope failure continuum

The temporal subdivision of slope failure into three discrete categories provides a starting point from which to study the factors contributing to slope instability and the impacts of mass wasting on Arctic slopes (Figure A). During the *pre-failure* conditioning of a slope, meteorological, geological and geocryological factors – primarily precipitation (rate and magnitude), sediment properties, ground ice content and thaw depth – are of primary importance. These variables contribute to the slope-stability thresholds during the *failure stage* due to the influence of soil moisture and sediment properties on pore-water pressure and the shear stress along potential failure surfaces. Shear strength, the intrinsic resistance of the slope-material to failure, additionally varies as a function of slope steepness and cohesion, at a soil-particle level. Slope failure is initiated once shear stress exceeds shear strength. During the *post-failure stage*, the area impacted by the mass movement varies due to rheological properties of the earthflow material, the release volume and the flow mechanics (Malet et al. 2005). Improved knowledge of these factors together with the analysis of observed events can be back fed into models to estimate risk zones for different mass-movement types with different rheologies and release volumes.

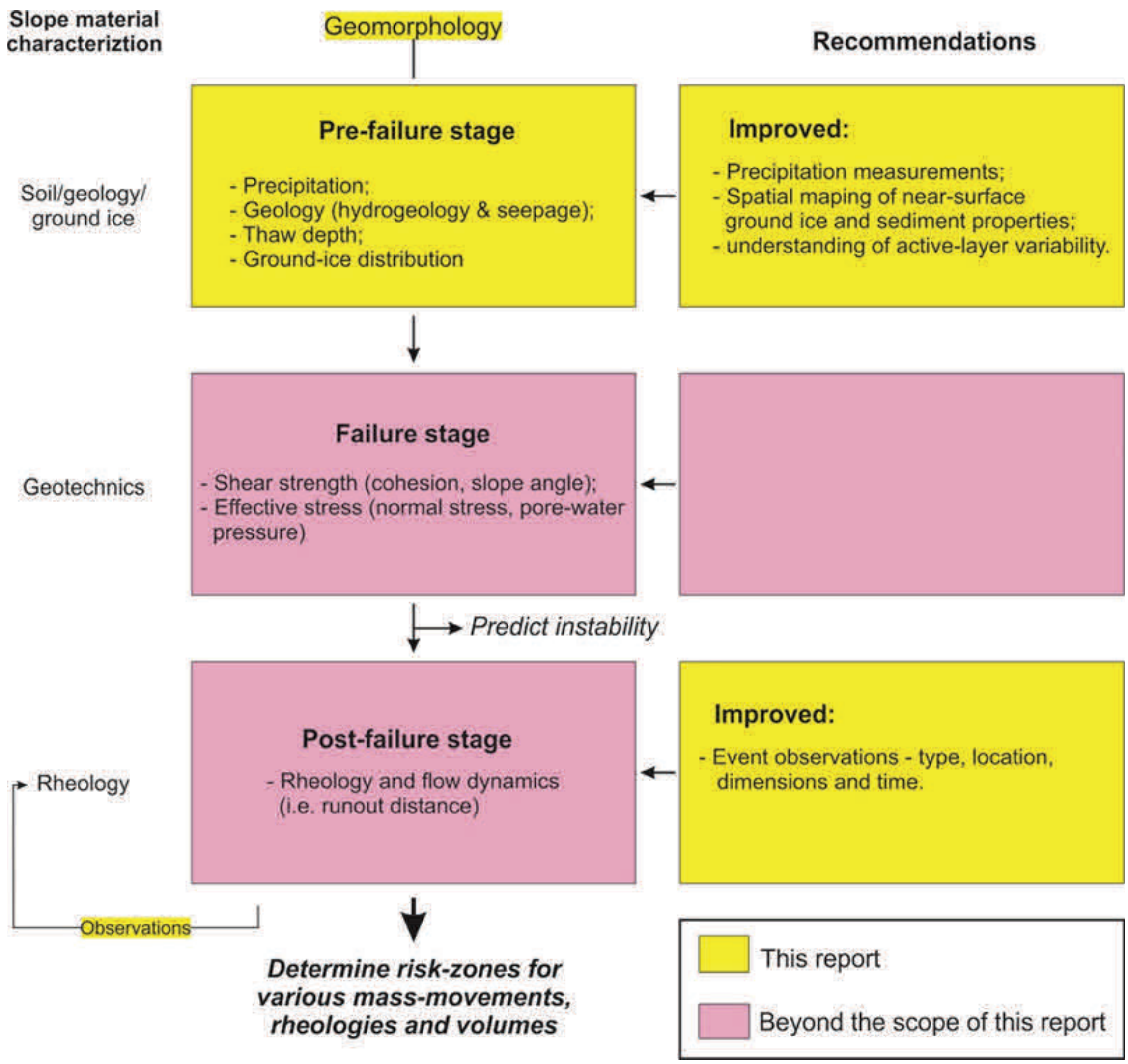


Figure A. Defining the contributing factors in the slope-failure continuum. Three-stage event subdivision modified from Malet et al. (2005).

## Appendix B: Background on slope instability of permafrost slopes

Slopes in Arctic permafrost settings are particularly vulnerable to mass-movement at the end of the summer season, as this period coincides with the maximum thaw (active-layer) depth. The active layer develops during summer months due to downward thawing from the ground surface in response to the summer warming. The maximum thickness of this layer may be upwards of 2 m in steep rocky slopes, where energy is readily transferred to the thaw table by water flow or exposed towards insolation for longer periods. Immediately below the active layer, the top of permafrost is characteristically rich in ground ice – providing a significant source of moisture upon thawing. Throughout the Arctic, large magnitude precipitation events in the late-summer are correlated with slope failure due to accumulation of meteoric water (seeping through the unfrozen active layer) and ground water (primarily sourced from melting ground ice in the active layer) at the thaw table – resulting in increased pore-water pressure and effective stress.

The period of maximum-thaw depth is crucial as it is also the time which the maximum volume of earthflow material is available for release. As the release volume shares a positive relationship with the runout and depositional area, slope failures at the end of summer pose the greatest risk in terms of impacting infrastructure and inhabitants.