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Potential dry slab avalanche trigger zones on wind-affected slopes in central Svalbard

Markus Eckerstorfer [a,b,*], Wesley R. Farnsworth [a,c], Karl W. Birkeland [d]

[a] Arctic Geology Department, University Centre in Svalbard, Norway
[b] Earth Observation, Northern Research Institute (Norut), P.O. Box 6434, Tromsø Science Park, 9294 Tromsø, Norway
[c] Department of Geosciences, University of Oslo, Norway
[d] USDA Forest Service National Avalanche Center, Bozeman, MT, USA

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ABSTRACT

Experience suggests that shallow, steep zones on slopes are potential dry slab avalanche trigger points. However, a scientific understanding of this common knowledge is not well quantified due to the spatial variability of snowpack stability, which is governed by various internal and external processes. Currently, the best way to investigate these processes is through point stability testing on small slopes. We thus performed Compression and Extended Column Tests (CTs and ECTs) on three small, wind-affected alpine slopes in central Svalbard. While one study slope (Gangskaret) had smooth ground topography, the other two (Fardalen and Larsbreen) exhibited irregular, rugged ground topography. Our results show that weak layer reactivity was largely influenced by the ground topography, as snow depth is a function of terrain on wind-affected slopes. Slab thickness determines weak layer sensitivity where the ground topography is rugged. Thus, the most unstable spots on these slopes coincided with the shallower zones characteristic of steeper ground surfaces inclinations where the snowpack is thin and the weak layers are close to the surface. This was not as pronounced on slopes with smooth ground topography. However, as snowpack develops and thickens to a "snow depth threshold X", the ground irregularities are leveled out and their influence diminishes. Thus, knowing the terrain is crucial. Moreover, it is crucial to follow the seasonal snowpack development and extreme weather events that influence it. We found inverse relationships between stability and slab thickness for weak layers that developed early in the season. These early instabilities displayed discontinuity due to melt out over topographic highs during rain-on-snow events, but were left in a preserved state in topographic lows that became overlain by shielding refrozen meltform layers.

1. Introduction

About 250 people are killed by avalanches every year in Europe and North America (Etter et al., 2004; Schweizer, 2008). In about 90% of all accidents, the avalanche victims triggered the slab avalanche in which they were caught (McCammon and Haegeli, 2006). Clearly, an understanding of the snowpack processes involved in artificial slab avalanche release is crucial. Therefore, variability in snowpack stability should be studied, especially focusing on the cause of variability at various scales.

Slab avalanches release when a cohesive slab of snow detaches due to the fracture of a weak snow layer (Schweizer et al., 2003a). Fracture can be described as mixed-mode anticracking, which results in weak layer collapse (Heierli et al., 2008). The dominant limiting factor for weak layer fracture is the snow stratigraphy, where layers might not be continuous (Gauthier and Jamieson, 2010). Thus, it is important to understand how snow layers spatially interact with the terrain, as a means of interpreting weak layer depth and distribution. The spatial variability of the snow cover as a function of topography has been highlighted as a key zone of uncertainty (Haegeli and McClung, 2004). Schweizer et al. (2008) concluded that studying terrain-correlated patterns of weak layer formation is crucial. Furthermore, slab avalanche release is prone to areas of low stability, sometimes called deficit zones (Conway and Abrahamson, 1984). Such areas may be located on steep rollovers, around rock outcrops or topographic highs (Birkeland et al., 1995). Crown profiles and fracture lines often run along such features (Birkeland et al., 1995), as they interfere with snow stratigraphy. It is however, difficult to verify the existence of such zones on a slope, making the study of the spatial variability of snowpack stability highly challenging, yet relevant (Kronholm and Schweizer, 2003).

While the majority of snowpack stability studies are from the Alps and North America, our study is unique in that our field area is the High Arctic. Numerous studies have investigated variability in snowpack stability on different scales from slopes to mountain ranges, mainly using point stability tests. A comprehensive review of previous work is given by Schweizer et al. (2008). The authors identify external and internal causes during snow layer formation. While wind is the most important external factor (Sturm and Benson, 2004), terrain topography is the most important internal factor (Schweizer et al., 2008).

* Corresponding author at: Earth Observation, Northern Research Institute (Norut), P.O. Box 6434, Tromsø Science Park, 9294 Tromsø, Norway. Tel.: +47 92678797.
E-mail address: markus.eckerstorfer@norut.no (M. Eckerstorfer).

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Since terrain is relatively constant at the temporal scales of interest, it is likely the best tool for predicting slope-scale variability (Campbell and Jamieson, 2007). Regardless, the majority of studies have been carried out on sheltered slopes with minor wind influence and smooth ground topography. Only recently, Hendrikx et al. (2009) assessed changes in spatial variability over time on windy slopes. Guy and Birkeland (2013) introduced a spatial variability study from steep couloirs, showing a relationship between weak layer occurrence and wind direction as a function of topography.

In this study, we investigate the spatial variability of snowpack stability on three different, highly wind-affected slopes in central Svalbard. We hypothesize that snow stratigraphy and consequently weak layer formation is highly affected by wind loading, scouring, and redistribution. We further expect the continuity of the snow stratigraphy to be largely a product of the wind activity and the process of snowpack development around irregular ground topography. Therefore, the in-fill process of snow is influential in weak layer development, suggesting that shallow zones tend to correlate with lower stability and thus potential artificial trigger points.

2. Study area and sites

2.1. Study area

Longyearbyen, Svalbard's main settlement, is located in the center of the main island Spitsbergen at 78°N, 15°E (Fig. 1). The region around the settlement consists of deglaciated U-shaped valleys and small cirque glaciers, underlain by continuous permafrost (Humlum et al., 2003). Mountains display generally a plateau shape, where the southeasterly prevailing winter wind direction (Christiansen et al., 2013) forms cornices on the leeward edges. Cornice falls are the most commonly observed avalanche type, exceeding 50% of the avalanche activity (Eckerstorfer and Christiansen, 2011c). Slab avalanches constitute 32% of the total, typically releasing in avalanche cycles as direct action avalanches induced by passing low-pressure systems (Eckerstorfer and Christiansen, 2011b). These lows bring warm and moist air to Svalbard, resulting in large air temperature fluctuations and mid-winter rain events. As a consequence, ice layers are characteristic of the maritime influenced snow climate in the Longyearbyen area (Eckerstorfer and

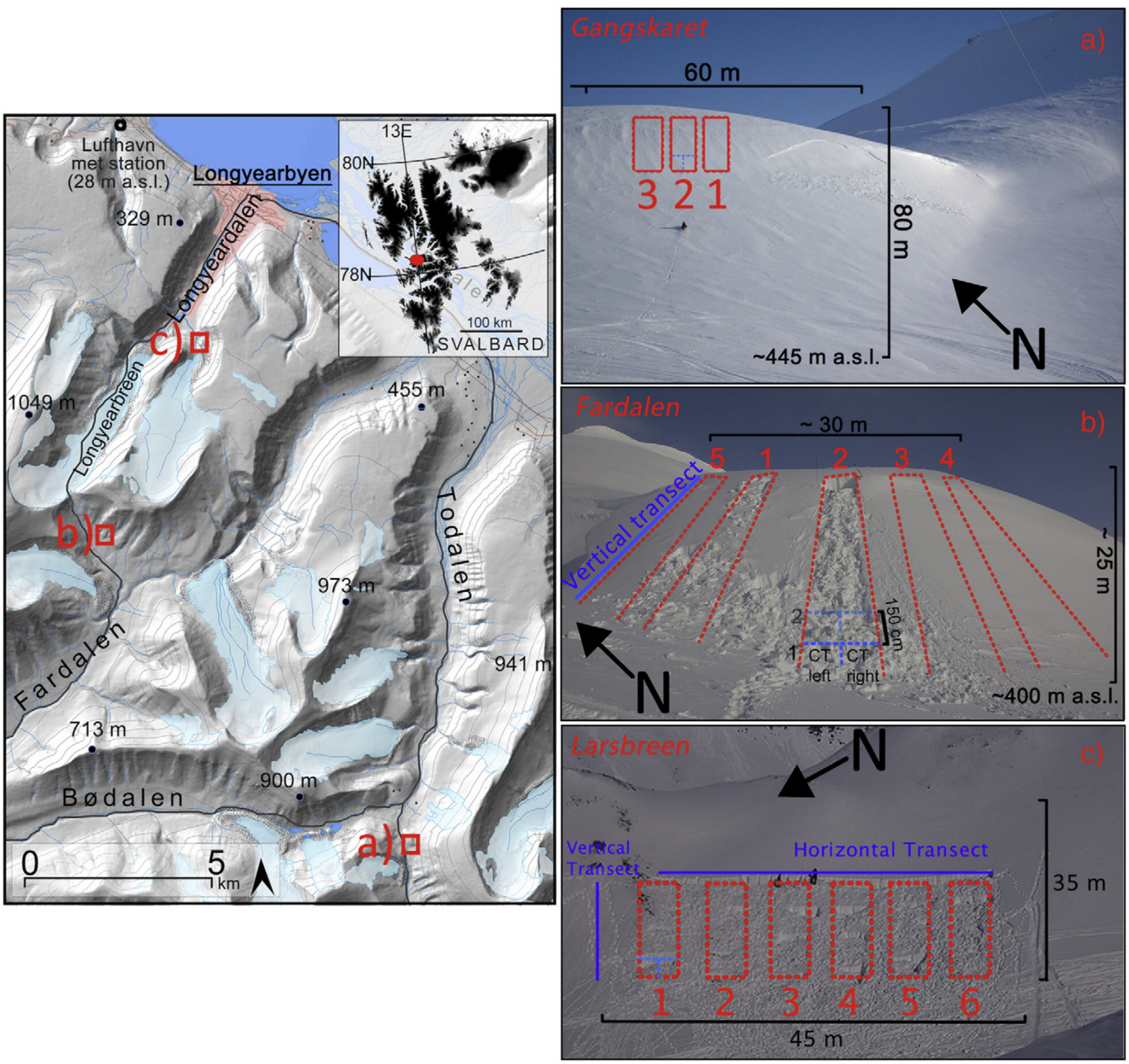

Fig. 1. Study area and sites. The topographic map shows the area around Svalbard's main settlement Longyearbyen. The inset map shows the location of Longyearbyen marked with a red dot. The three study slopes are marked by red squares. a) Gangskaret study slope, b) Fardalen study slope and c) Larsbreen study slope. Note that the picture of Gangskaret was taken before fieldwork, since afterwards visibility did not allow for a picture. Note also, that the trenches are numbered according to the sequence of excavation.

Christiansen, 2011a). Subsequently facets form around these ice crusts, building a commonly observed weak layer and bed surface interface. The highly stratified and cold snowpack consists of numerous wind slabs and refrozen melt layers. At the base of the snowpack, depth hoar is usually found on most slopes due to the slow onset of snow in autumn, providing a high temperature gradient between atmosphere and ground (Eckerstorfer and Christiansen, 2011a). The thin snowpack is due to a low mean annual precipitation rate of around 190 mm (Met.no, 2013), and exhibits high spatial variability due to the lack of any high vegetation and constant wind activity interacting with the complex terrain. The snowpack's maximum depths are reached in April and the seasonal snow cover persists for up to 10 months per year, with higher elevations holding snow year round.

Snowmobilers, dog sledders, and skiers extensively use the study area. During the three-month period March–May 2009, we counted the snowmobile traffic in the valley Fardalen with a traffic counting radar. Over 7300 snowmobiles passed the radar, with a daily maximum of over 300 snowmobiles (Eckerstorfer et al., 2009). In the last 12 years, avalanches caused four fatalities in Svalbard. These accidents were all snowmobile-triggered slab avalanches.

2.2. Study slopes

All three study slopes – Gangskaret, Fardalen, and Larsbreen – are near Longyearbyen, with the furthest, Gangskaret, being about 20 km away (Fig. 1). The study slopes' locations exhibit a horizontal climatic and vertical elevation transect, with Gangskaret being at the highest elevation, thus having the coldest climate, with most amounts of precipitation. The 2012 mean annual temperature at sea level in Longyearbyen (Lufthavn meteorological station, Fig. 1) was −2.0 °C (Met.no, 2013). Data from a meteorological mast at Gangskaret generally display air temperature values that are roughly 2 °C colder. However, these air temperatures follow each other closely in their daily fluctuations, suggesting that air temperatures in central Svalbard are bound to synoptic scale conditions (Hallerstig, 2010). Humlum (2002) modeled the late 20th century precipitation for the Gangskaret area to be around 500–700 mm, roughly 2 to 3 times more than at sea level. No meteorological data are available from Fardalen, where we assume median meteorological conditions between the extremes at sea level and Gangskaret.

3. Methods

3.1. Field data

The Gangskaret and Larsbreen study slopes were both sampled within roughly 30 h, while Fardalen was sampled over a month period. At Gangskaret and Fardalen we dug vertical trenches from top to bottom, conducting two stability tests per pit with roughly 150 cm spacing (Fig. 1a, b). At Larsbreen, we dug a grid of pits vertically as well as horizontally ordered or aligned (Fig. 1c). We tried to account for the spatial scale triplet by choosing slopes with a minimum horizontal extent of about 30 m, spacing between the stability tests of 150 cm and partly by taking account for the support by using ECTs (Simenhois and Birkeland, 2009; Skøien and Bloeschl, 2006). However, our emphasis was to a large degree on sampling simplicity and efficiency.

CTs were performed at Gangskaret and Fardalen (Jamieson, 1999), while ECTs were conducted at Larsbreen (Simenhois and Birkeland, 2009). For both tests, fracture propagation or non-propagation were noted, as well as shear quality. A fracture propagated if it ran across the entire column, effectively detaching the slab from the cut column (for ECT we denoted ECTP). The main reason for using two different stability tests lies mainly in problems with practically performing the ECT. The generally hard snowpack, intersected by meltform and ice layers (Fig. 2) makes it difficult to completely isolate the back of a 90 cm wide column. We were unable to fully cut the back wall with a Rutschblock cord at some sites. However, at the Larsbreen site we successfully isolated our ECTs with a self-made, heavy-duty snow saw. Another reason for favoring CTs in our work was that they took less time and we had little available field help.

To minimize variability only one person conducted the stability tests, two in each pit. Following Jamieson (1999), we isolated the columns only to a depth of 150 cm if the total snow depth in the pit exceeded such value. In each pit, we recorded snow depth and slope inclination of the left and right flanks of each stability test column. Slab thickness of each fractured weak layer and the sliding plane angle (bed surface angle) were measured. We measured both snow depth and slab thickness vertically at the front wall of the CT/ECT column. The weak layer's structural properties were also recorded like layer thickness, grain shape, grain size and hardness, according to the observation guidelines by the American Avalanche Association (Greene et al., 2010). Each weak layer was assigned a letter and consequently traced from pit to pit. At Fardalen, we continuously tracked weak

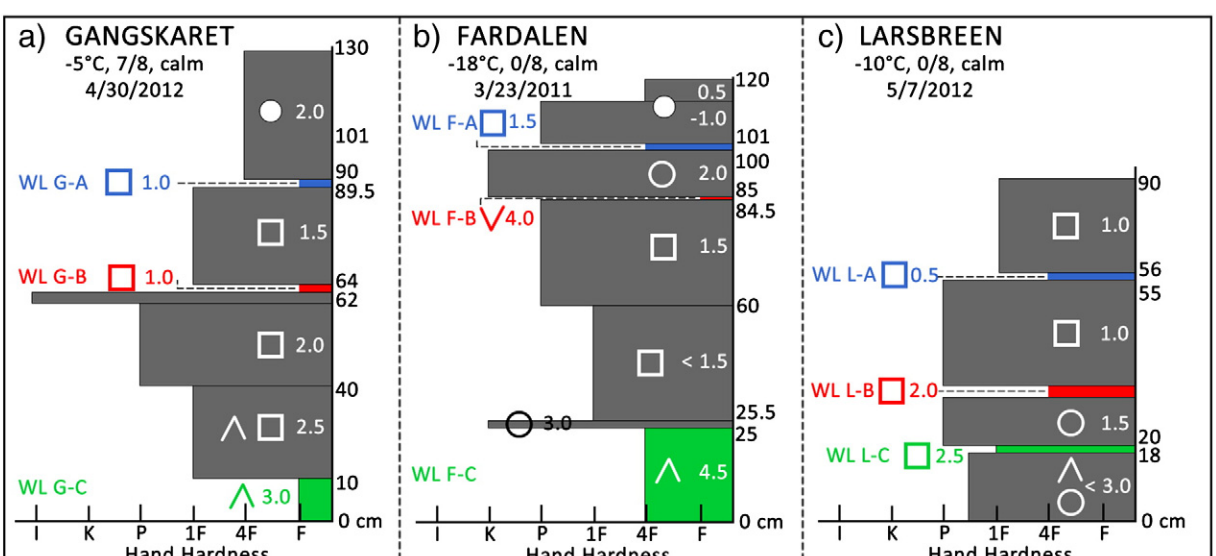

Fig. 2. Simplified snow profiles on the day of sampling for all three study slopes.

Table 1
Topographic characteristics of the three study slopes.

Study slope	Gangskaret	Fardalen	Larsbreen
Slope dimensions (width × length)	60 × 80 m	30 × 25 m	44 × 35 m
Aspect and elevation	180°, 464 m a.s.l.	200°, 400 m a.s.l.	285°, 150 m a.s.l.
Slope curvature	Convex	Convex	Convex
Wind exposition	Top-loading	Top- and cross loading	Top- and cross loading
Slope angles	23–32°	23–50°	32–58°
Ground topography	No vegetation, fine-grained shales, smooth	No vegetation, fine-grained shales, rugged. Towards the northern edge, a 1 m high almost vertical cliff is exposed.	Coarse-grained debris with particle size of up to 40 cm.

layers and their bed surface angles with 50 cm spacing up the left flank of the slope (Fig. 1b). The same was performed at Larsbreen at 1 m resolution, with an additional horizontal transect excavated above the trenches (Fig. 1c).

3.2. Data analysis

Only CT and ECT results where fracture propagation took place are analyzed. However, weak layer fractures of all three shear qualities (Q1–Q3) were included to ensure a large enough dataset. Both the Gangskaret and Larsbreen datasets were analyzed as one dataset, as the excavation and testing took place in one continuous working effort, roughly 30 h. Both datasets were also divided by trenches, which we dug from bottom to top vertically up the slopes (Fig. 1). The trenches at Larsbreen consist of separate pits, vertically lined up, each about 200 cm upslope from the last. The Fardalen dataset was collected over a period of a month, thus each trench is analyzed and discussed separately.

We calculated the correlation coefficient using (Pearson's r) (Spiegel and Stephens, 1999) where $+0.2$ and higher are positive relationships and -0.2 and lower are negative relationships. We used a significance level of $p < 0.05$ to reject the null hypothesis.

Table 2
Trench characteristics for all three study slopes. CT's were used at Gangskaret and Fardalen, ECT's at Larsbreen. The column "CT/ECT" indicates the number of CT's or ECT's conducted in each trench. Gangskaret and Larsbreen were sampled in 2012, Fardalen in 2011.

Trench	Date of excavation	Mean	Mean	CT/ECT
Gangskaret (2012)				
N		Snow depth (cm)	Surface angle (°)	*N*
1	29 April	91	28	22
2	29 April	87	28	22
3	30 April	91	28	20
All trenches		87	28	64
Fardalen (2011)				
1	18 Mars	142	37	26
2	23 Mars	170	39	22
3	7 April	193	38	20
4	13 April	219	40	20
5	18 April	95	38	20
All trenches		161	38	108
Larsbreen (2012)				
1	7 May	186	32	10
2	7 May	160	33	10
3	7 May	145	34	10
4	7 May	136	34	10
5	7 May	111	38	10
6	7 May	94	38	10
All trenches		148	34	60

4. Results

4.1. Trench characteristics

Snow depths varied widely at all three study slopes, highly governed by the interactions between topography and wind exposure. All study slopes experienced downslope winds, which scoured the upper parts of our slopes (where minimum depths were found) and loaded the lower parts (where maximum depths were found). The surface angles varied largely on all three slopes, as they have convex slope curvatures (Table 2). In Table 2 we show the total number of CTs or ECTs we performed at each study site, with the majority on the Fardalen study slope. At all study slopes, we could induce fractures in a number of weak layers and interfaces. For further analysis, we chose the three most reactive instabilities, called WL A, B, and C (with an additional G for Gangskaret, F for Fardalen and L for Larsbreen).

4.2. Weak layer characteristics

At all three study slopes the snowpack had comparable structure, with persistent and weak depth hoar bases overlain by refrozen melt layers and/or layers of faceted crystals (Fig. 2). These refrozen melt forms and faceted crystals created a structure of generally hard layers intersected by the three tested weak layers. The three persistent weak layers with high failure rates in all three snowpacks were mainly faceted crystal layers, as well as a layer of surface hoar at the Fardalen study slope. Weak layers A and B at Gangskaret (WL G-A, B) and Larsbreen (WL L-A, B) are the same layer in that they were formed by the same meteorological events, but WL G-B formed over an ice crust (Fig. 2a). Since the snowpack at Fardalen was formed during a different season, the meteorological conditions leading to the layers differed from the other two sites, but the general layering structure was similar. Due to a persistent cold and sunny period in March and April 2011, the snowpack at Fardalen did not change much within the four-week sampling period.

At Gangskaret and Larsbreen, the two uppermost weak layers were on average the most reactive (as measured by the percentage of propagating fractures), while the depth hoar at Fardalen, WL F-C, was most reactive on average at that site (Table 3). However, the most reactive weak layers did not necessarily produce the largest number of shear quality 1 (Q1) fractures (Table 3). At the trench scale, the relative amount of Q1 fractures ranged between 0 and 100% of the total, with the most reactive weak layer being WL F-C (Table 3). At Gangskaret and Fardalen, the average percentage of Q1 fractures of the total in weak layers G-C and F-C were the lowest, as fractures occurred at the snow-ground interface and were often rough.

Bed surface slope angles and slab thicknesses varied more at the Fardalen and Larsbreen study sites than at Gangskaret as shown by the larger standard deviations (Table 3). This would imply that at Gangskaret a much more regular snow in-fill process took place with uniform layering, due to smoother/regular ground topography

Table 3
Weak layer characteristics divided into study slopes and trenches. CT's were used at Gangskaret and Fardalen; ECT's were used at Larsbreen. Bed surface angle is the angle of the fracture plane; the slab thickness is measured above the fracture plane. Propagating fractures of total is the percentage of time that a given weak layer was reactive in conducting CT's and ECT's. Q1 fracture character of total is the percentage of time that a given weak layer fractures with good shear quality (Q1). Significant correlations between bed surface vs. slab thickness and slab thickness vs. CT/ECT at $p < 0.05$ are in bold.

WL	Trench	N of fractures	Propagating fractures of total	Q1 fracture character of total	Bed surface angle (°)	Slab thickness (cm)	CT/ECT scores	Bed surface vs. slab thickness	Slab thickness vs. CT/ECT
		N	%	%	Stdv.	Stdv.	Median	Correlation	Correlation
Gangskaret									
WL G-A	1	20	48	65	3	8	12.5	**0.45**	−0.05
	2	21	48	100	2.8	8	13	**0.56**	**0.40**
	3	14	61	71	2	8.5	15.5	**0.27**	**−0.81**
WL G-B	1	11	26	82	3.7	10	23	**0.86**	**−0.26**
	2	15	34	87	3	10.8	20	**0.56**	**0.56**
	3	9	39	89	2.7	8.5	15	0.15	0.26
WL G-C	1	7	17	29	2.4	12	27	0.17	−0.22
	2	1	2	100	0	0	13	–	–
	3	0	0	–	–	–	–	–	–
Fardalen									
WL F-A	1	9	24	67	4.4	40.8	12	**−0.88**	**0.63**
	2	7	23	29	3.6	19.9	18	**−0.92**	**0.74**
	3	4	11	0	4.7	28.3	27	**−0.99**	**0.60**
	4	7	18	71	2.9	26	24	**−0.54**	**0.38**
	5	5	17	100	2	21.3	11	**−0.13**	**0.80**
WL F-B	1	3	8	100	3.2	18.2	14	**−0.80**	**0.80**
	2	5	17	100	1.5	27.4	17	**−0.93**	**0.76**
	3	6	14	67	2.7	21.6	21	−0.04	**0.15**
	4	3	8	100	2.1	10.4	19	**−0.97**	**0.93**
	5	3	10	34	6.7	41.3	21	–	–
WL F-C	1	20	53	100	5.4	17.5	11.5	**−0.75**	**0.36**
	2	18	60	78	4.3	37.2	16	**−0.46**	**0.71**
	3	11	31	11	2.4	24.7	18	−0.10	0.02
	4	15	38	27	2.6	17.0	23	0.13	**−0.54**
	5	15	52	60	9.3	9.3	13	0.04	**0.14**
Larsbreen									
WL L-A	1	8	80	63	1.78	4.4	1.5	**−0.45**	**0.13**
	2	10	100	60	3.5	5.9	5.5	−0.04	**0.38**
	3	10	100	90	2.7	7.4	5	**−0.23**	**0.66**
	4	8	80	50	2.8	6.1	19.5	**−0.58**	**0.62**
	5	9	90	63	2.4	11	21	**−0.79**	**0.42**
	6	10	100	100	0.8	8.4	0	**−0.45**	**0.36**
WL l-B	1	3	30	34	1.2	2.6	21	**−0.98**	**0.76**
	2	7	70	58	3.1	4.7	13	**−0.18**	**0.52**
	3	7	70	43	2.5	16	22	**−0.44**	**0.61**
	4	4	40	50	3.5	7.3	15.5	**−0.33**	**0.81**
	5	5	50	60	3.9	18	24	**−0.17**	**0.96**
	6	3	30	100	3.7	5.2	0	**−0.67**	–
WL L-C	1	0	0	–	–	–	–	–	–
	2	2	20	100	1.4	6.4	14.5	**−1**	**1**
	3	3	30	100	0.5	3.6	27	**−0.97**	**0.96**
	4	3	30	100	2.0	9	16	−0.064	**0.41**
	5	1	10	–	–	–	–	–	–
	6	3	30	100	1.3	5.3	0	**−0.14**	**0.32**

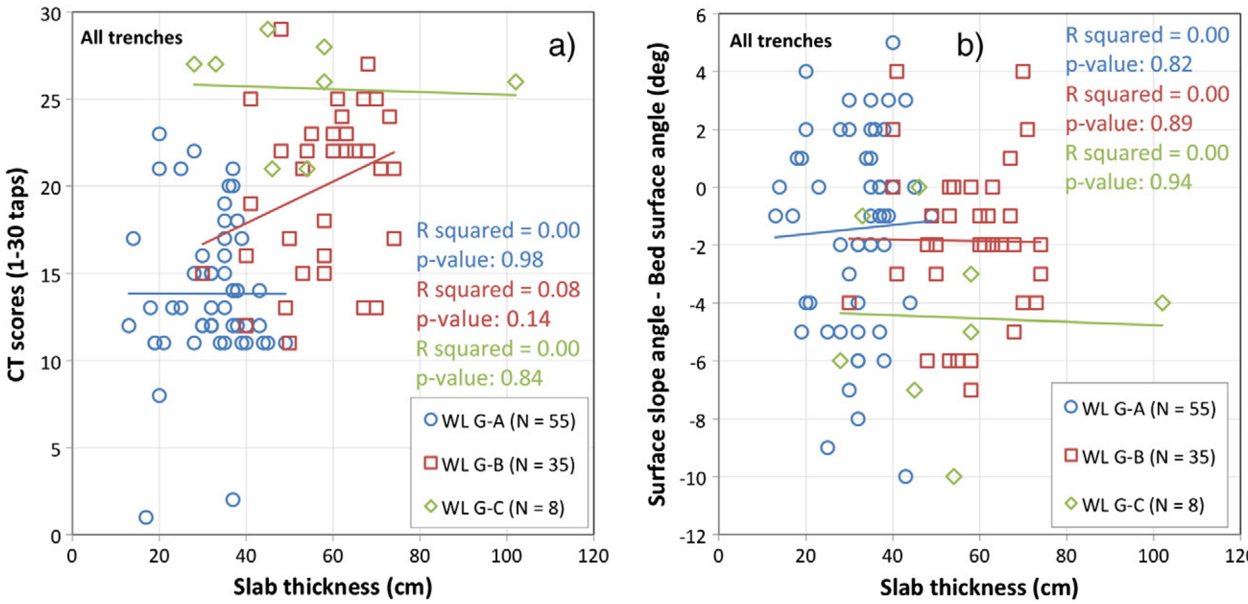

Fig. 3. Snowpack stability data from Gangskaret a) Slab thickness versus CT scores. b) Slab thickness vs. Surface slope angle–Bed surface angle. Significant correlations at $p < 0.05$ are written in italic.

(Table 1). We therefore tested the correlation between bed surface angles and slab thicknesses for each layer in each trench at Gangskaret and found mostly statistically significant positive correlations (significant at $p < 0.05$ in bold). This means that bed surface angles were steeper in deeper sections of the snowpack since the layering more closely followed the ground topography. In contrast, the relationship between bed surface angles and slab thicknesses showed mostly strong statistically significant negative correlations at Fardalen and Larsbreen, demonstrating that steeper bed surfaces coincided with thinner slab depths at these sites (Table 3). This is logical for the Fardalen and Larsbreen study slopes because they are underlain by much more rugged ground topography, where snow layers initially closely mimic terrain, but smooth it out gradually during the snow in-fill process. These correlations were significant with minor exceptions. For example in trenches 3 to 5 at Fardalen, the bed surface angles of WL F-C (depth hoar) did not correlate significantly with slab thickness. This is probably because bed surface angles were measured at the rugged ground surface.

This sharp difference in results is also displayed in the correlation between slab thicknesses and CT/ECT scores (Table 3). We found positive correlations at Fardalen and Larsbreen, indicating lower stability scores in areas with thinner slabs (Table 3). It also shows the influence of slab thickness on the stability scores, displaying consistently higher scores (more compressional taps) necessary to induce fracture in any of the three weak layers where the slab thickness was greater. At Gangskaret, we found a mix of both positive and negative correlations. The negative correlations suggest lower CT scores in areas with thicker slabs. However, the slab thickness standard deviations are low at Gangskaret, which suggests there are other more important determining factors for stability at this site, such as the weak layer properties themselves.

4.3. Snowpack stability and its variability at Gangskaret study slope

The small dataset from the Gangskaret study slope displays rather inconclusive results concerning how instabilities relate to topography (Table 3). Due to the smooth ground topography, devoid any topographic irregularity, wind activity had not created sizable differences in slab thicknesses. The slope is therefore somewhat comparable to more wind-sheltered slopes that have been used in past snowpack stability studies. Fig. 3a confirms data from Table 3, showing that slab thickness is rather unlikely to control snowpack stability, as the CT scores for WL G-A, B and C are not significantly correlated to slab thickness at the trench scale. Fig. 3b shows that with a deeper burial depth, the differences between bed surface and surface slope angle

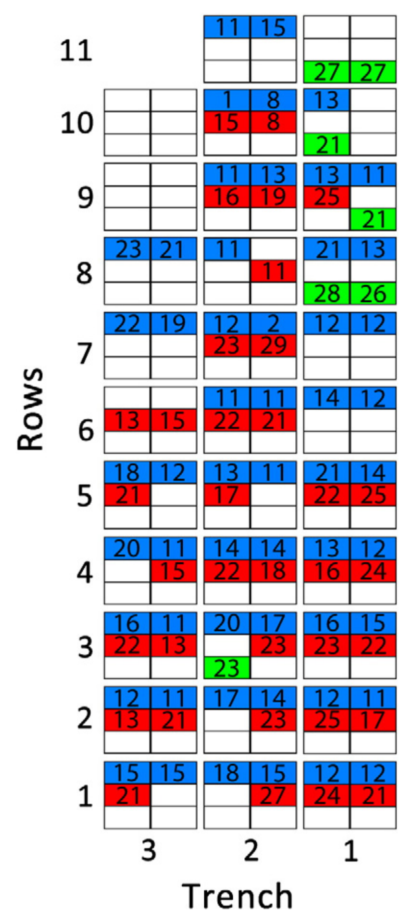

Fig. 4. Spatial variability of reactive weak layers in all three trenches dug at Gangskaret within roughly 30 h. Each rectangle represents one study pit. These rectangles are divided into six smaller rectangles, where the three left ones represent results from the left CT and the three right ones represent results from the right CT. The reactive weak layers for each CT are colored, where blue is WL G-A, red is WL G-B, and green is WL G-C. White rectangles indicate no CT result. The numbers indicate the CT scores.

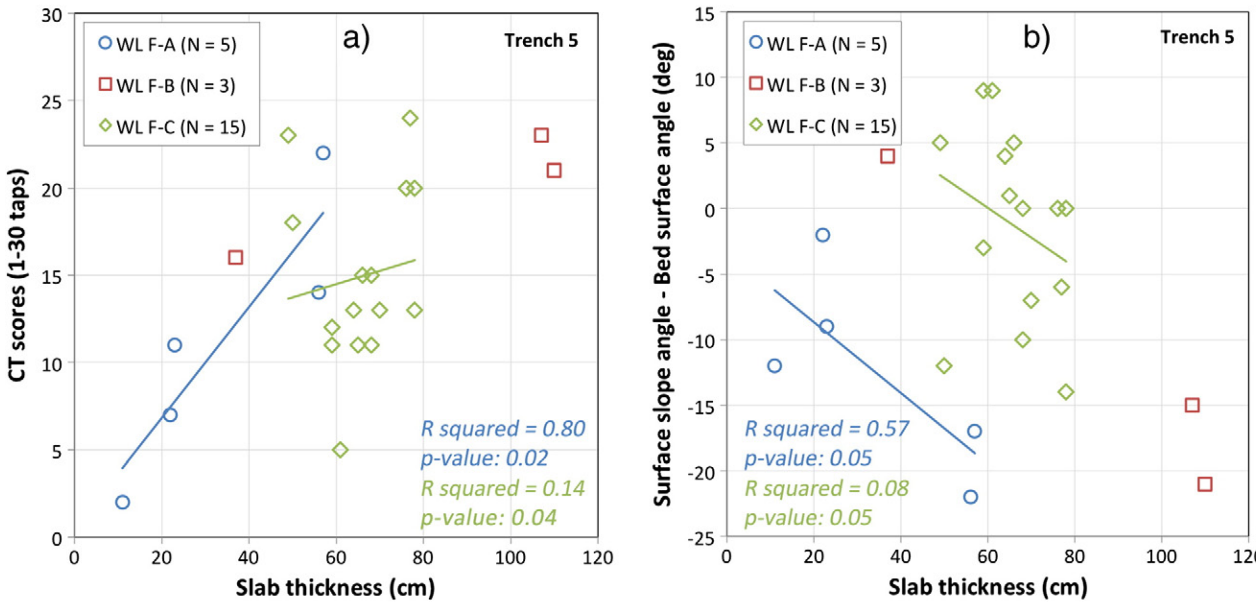

Fig. 5. a) CT scores versus slab thickness and b) slab thickness versus surface slope angle–bed surface angle for all three weak layers, divided in trench 5 at the Fardalen study slope. Significant correlations at $p < 0.05$ are written in italic. We do not draw a line or do significance testing for layer B because the sample size is so small. Our other sample sizes are also relatively small so our results should be viewed with appropriate caution.

did not become larger. This suggests that the ground topography had overall only a minor effect on snowpack depths at Gangskaret. Ultimately, our data at Gangskaret show no statistically significant relationships when all the data are considered for each weak layer (Fig. 3).

Fig. 4 shows the weak layer distribution across the three trenches dug. It shows that WL G-A was the most shallowly buried and the most reactive, followed by WL G-B. WL G-C became reactive only in the uppermost pits in trench 1 (Fig. 4). This is where we found the shallowest snowpack in all three trenches. The combination of WL G-A and G-B was reactive in 65% of all pits, clustering mainly in the lowermost pits in trenches 1 and 3, but being more consistent in trench 2. Significant positive correlations between slab thickness and CT scores were found for both WL G-A and G-B in trench 2 (Table 3), which means that fewer compressional taps induced fracture where slab thicknesses were low. Additionally, bed surface inclinations were steep, shown by the significant positive correlations between bed surface inclination and slab thickness for trench 2 in Table 3.

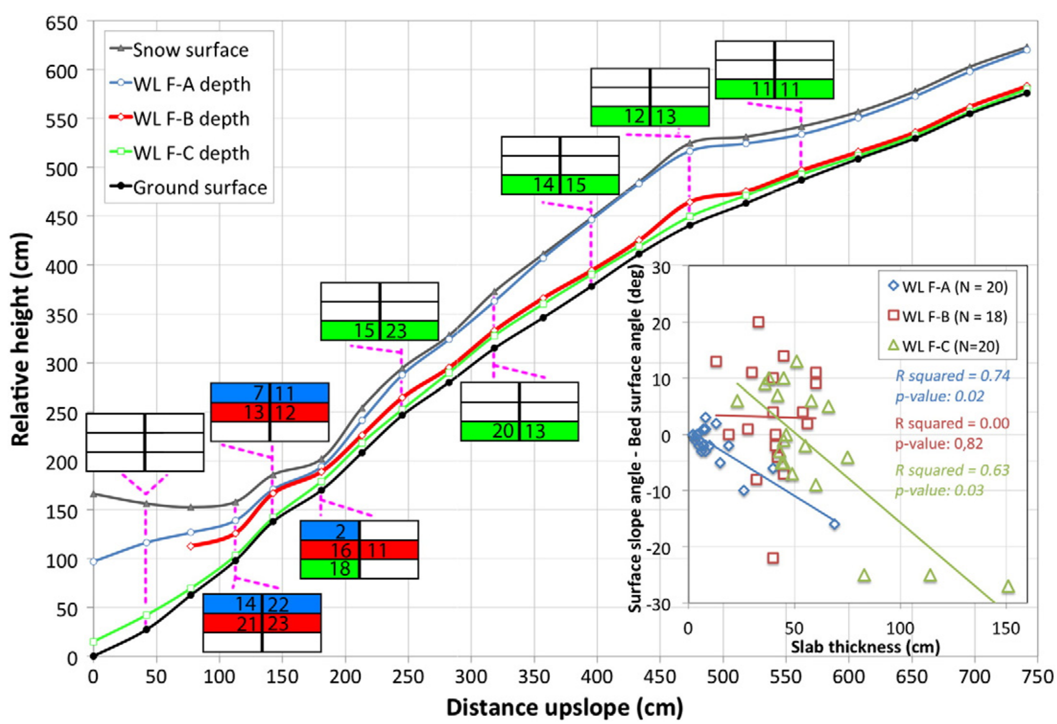

Fig. 6. Layer trace of the three weak layers WL F-A, B, C in trench 5 at Fardalen study slope. The charts show the CT scores, two in each pit, colored according to which weak layer fractured. The inset diagram shows slab thickness vs. surface slope angle–bed surface angle for the three weak layers in trench 5, collected with 50 cm spacing from bottom to top. Significant correlations at $p < 0.05$ are written in italics.

4.4. Snowpack stability and its variability at Fardalen study slope

From Fardalen, we only present correlations for trench 5 since we performed a detailed weak layer tracing in this trench. Correlations from the other four trenches are summarized in Table 3. Though our results must be viewed with caution since some of our datasets are quite small, the significant positive correlations between CT scores and slab thickness show that compressional taps necessary to induce fracture increased with increasing slab thickness in trench 5 at Fardalen (Fig. 5a). Fig. 5b shows data from trench 5 as well, demonstrating the relationship between the difference between surface slope angle and bed surface angle versus slab thickness. The significant negative correlations indicate that the deeper any of the three weak layers were buried, the larger the difference between the bed surface angle and the surface slope angle. Snow surface and ground topography did not resemble each other on wind-affected slopes with complex terrain (Fardalen and Larsbreen) as seen in data from Fig. 5 and the dominantly significant, positive correlations between slab thickness and CT scores in Table 3. These relationships are not only true for trench 5 at Fardalen, but also for the other 4 tested trenches, as the correlations in Table 3 indicate. Exceptions again are the correlations for WL F-C in trenches 3 and 4 at Fardalen.

These results thus suggest that the most unstable spots on this wind-affected slope with irregular ground topography were where the snowpack was the thinnest, coinciding also with the steepest spots. In Fig. 6, all three weak layers fractured in one CT at 180 cm upslope, where the total snow depth was only 32 cm. No fractures could be induced in the first pit, where the snow depth was 166 cm. In the upper part of the slope, fractures were only induced in WL F-C, which was the most reactive. WL F-B was just above WL F-C and more strongly bonded and WL F-A was just below the snow surface, overlain only by some recently fallen, soft snow. The insert diagram in Fig. 6 reinforces data from Fig. 5b, where it shows that when WL F-A and F-C were buried more deeply, the difference between the bed surface angle and the surface slope angle became significantly larger as well. It also displays that the bed surface angles of WL F-C at great depths mimicked the ground surface inclination.

Another potential weak spot on the slope was found in trench 2, pit 3, were all three weak layers fractured in the left pit (Fig. 7). Fig. 7 also confirms visually that WL F-C was the most prominent weak layer, fracturing in 79% of all pits. WL F-C fractures furthermore clustered primarily in the upper, shallower parts of the study slope, with significant positive correlations between slab thickness and CT score (Table 3).

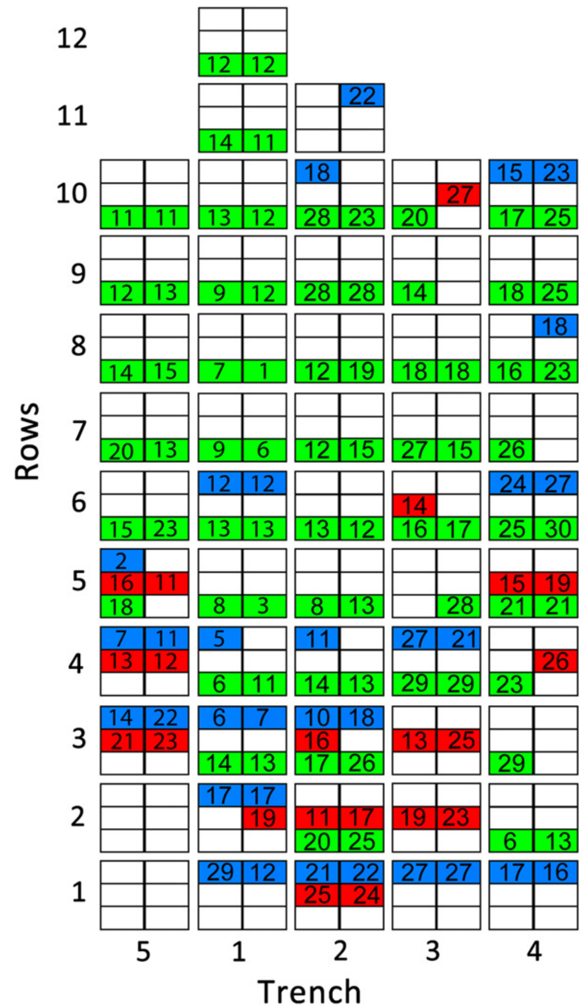

Fig. 7. Spatial variability of reactive weak layers in all five trenches dug at Fardalen within roughly 30 h. Each rectangle represents one study pit. These rectangles are divided into six smaller rectangles, where the three left ones represent results from the left CT and the three right ones represent results from the right CT. The reactive weak layers for each CT are colored, where blue is WL F-A, red is WL F-B, and green is WL F-C. White rectangles indicate no CT result. The numbers indicate the CT scores.

4.5. Snowpack stability and its variability at Larsbreen study slope

Results from WL L-A at Larsbreen agree with the results from Fardalen, where stability increased significantly as slab thickness increased (Fig. 8a). In addition, the deeper WL L-A and B were buried (larger slab thickness), the larger the difference between surface slope angle and bed surface angle (Fig. 8b). However, WL L-C showed significant inverse correlations for both relationships. WL L-C's stability decreased with slab thickness (Fig. 8a). This weak layer developed early in the season of 2011/2012, and was then influenced by a rain-on-snow event at the end of January 2012 which stabilized it in thinner areas due to the refreezing of percolating melt water or by completely melting it out over topographic highs. Nevertheless, in deeper sections – such as in topographic depressions – the early season weak layer was protected from melt water and was therefore more reactive during our stability testing. It is important to note that although the inverse relationship exists for WL L-C stability scores, those values are generally much higher, and overall the weakest zones on the slope are still found in shallower regions (Fig. 9). In 9 pits in all but trench 1, all three weak layers fractured during one ECT, which is significantly more than at the other two study slopes. However, this could be not only due to generally more unstable conditions during field work at Larsbreen compared to the other two slopes, but also due to the technique used in cutting the back of the ECT column. The snow saw used bent slightly during sawing, potentially putting more-than-intended strain onto the column. This might also explain the high number of ECTV's. Strikingly, WL L-A fractured in all pits and in all but three ECT's (Table 3), making it the most reactive weak layer tested in this study.

5. Discussion

5.1. Differences between all three study slopes

In this study from central Svalbard, we sampled three different small slopes to identify their weakest spots and thus potential artificial trigger points for dry slab avalanche release. Since all three slopes are wind-affected, we hypothesized that the interplay between ground topography and wind activity would determine the variability in snowpack thickness, which correlates with snowpack stability. While the Gangskaret study slope displays smooth, regular ground topography, both the Fardalen and Larsbreen slopes exhibit very complex, irregular ground topography. Therefore, the determining factors of snowpack stability are different at Gangskaret compared to Fardalen and Larsbreen. Compared to the

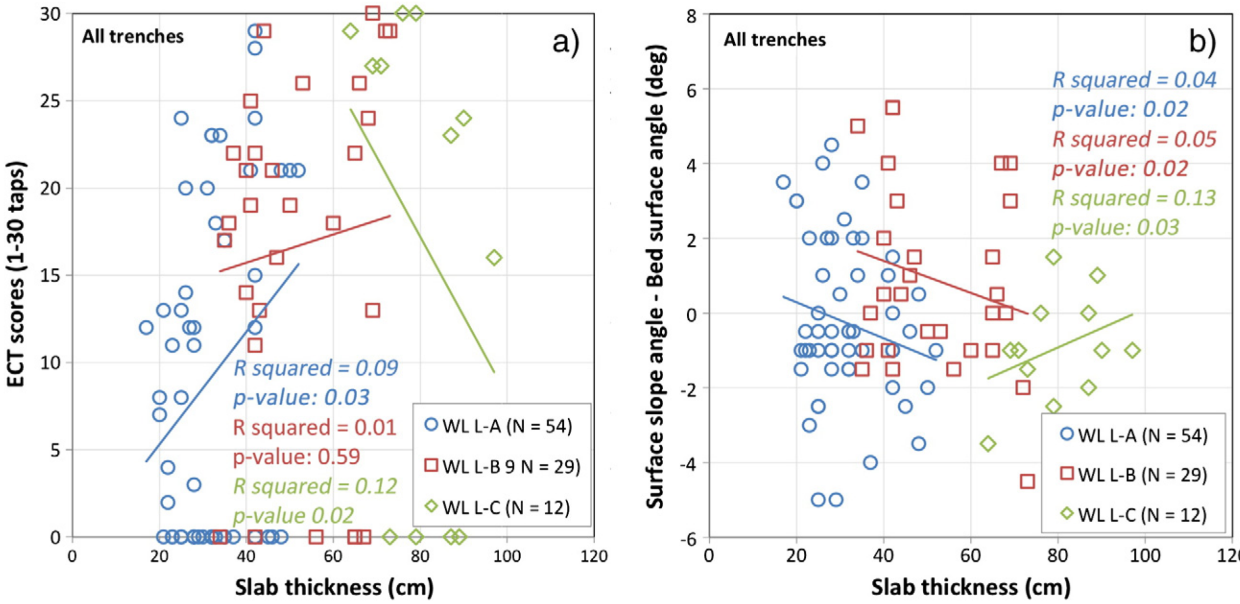

Fig. 8. a) ECT scores versus slab thickness and b) slab thickness versus surface slope angle–bed surface angle for all three weak layers, at the Larsbreen study slope. Significant correlations at $p < 0.05$ are written in italic.

other slopes, the Gangskaret study slope is more comparable to wind-sheltered, uniform slopes, where the variability in slab thickness is low and is therefore a less important factor for stability. Due to the smooth ground topography, the snow in-fill process has no significant terrain to develop around and flatten out. Thus, the snow surface largely resembles the terrain surface and leaves stratigraphy generally consistent across the slope. The rather constant slab thicknesses for each weak layer resulted in CT scores with a low median; their correlation to other measured variables remained rather elusive. We think therefore the main snowpack stability-determining factors were the weak layer properties and largely the slab properties. Both weak layer and slab properties could probably be better assessed using ECTs instead of CTs at this site.

In contrast, at both Fardalen and Larsbreen slab thickness was a primary determining factor of snowpack stability. The weakest zones on both slopes were found where the snowpack was the shallower over steep slope sections. This is in line with findings by Logan (1993) and Jamieson (1995) who give examples of increased skier triggering potential where the slab is locally thin. Referring to these studies, Schweizer and Jamieson (2001) state that where a weak layer and slab are present, skier triggering is more likely where the slab is thin and soft. Schweizer and Jamieson (2003) showed that unstable profile locations have in general shallower snow depths, which means also thinner slabs. This result agrees with the findings by Schweizer and Camponovo (2001), Schweizer et al. (2003b) and Campbell and Jamieson (2007), whom found increasing stability results as slab thickness increased. While data from the Fardalen slope suggested the shallowest zones to be the least stable, data from the Larsbreen slope display a minimum threshold value, governed by the burial depth of the refrozen meltform layer. Larsbreen results displayed a general trend of shallower zones decreasing in stability but not the shallowest zones, suggesting that weak layer characteristics as well as slab properties need to be better understood to gain insight as to these minimum thresholds. The strong, hard slabs (1 F – P hardness) at Larsbreen and Fardalen must influence our stability test results. It is likely that such hard slabs are not representative of actual snow conditions concerning artificial slab avalanche release. Therefore, test results are potentially overestimating the stability. This is good for using stability tests for conservative decision-making and hopefully avoiding being caught in an avalanche, but this is not beneficial for research purposes. We therefore think that while it is harder to induce fracture underneath a hard slab, once it starts, it is more likely to propagate further (Schweizer et al., 2003a).

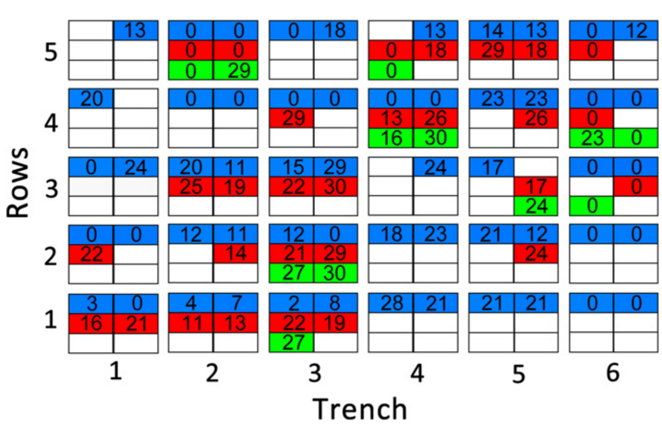

Fig. 9. Spatial variability of reactive weak layers in all six trenches dug at Fardalen within roughly a month's period. Each rectangle represents one study pit. These rectangles are divided into six smaller rectangles, where the three left ones represent results from the left ECT and the three right ones represent results from the right ECT. The reactive weak layers for each ECT are colored, where blue is WL F-A, red is WL F-B, and green is WL F-C. White rectangles indicate no ECT result. The numbers indicate the ECT scores.

5.2. Snow in-fill process around irregular ground topography

In the early days of snow science, snow was regarded as a sedimentological substratum, with its accumulation and redistribution comparable to sand, loess and gravel (Welzenbach, 1930). Welzenbach (1930) further recognized that the development of sedimentological units, such as the snow cover on a slope, cannot be determined by its outside-form, but only by analyzing its inner structure. Since then, field studies of snow were largely built on snow profiles and internal measurements of the snow's physical structure. Moreover, Welzenbach's observations are especially true for wind-affected slopes with rugged, irregular ground topography, where the snow surface does not resemble the terrain. In this study, this holds true for the Fardalen and Larsbreen study slopes. Without knowledge of the underlying terrain, it is difficult to recognize potential slab avalanche trigger zones over large boulders and outcropping rocks, where the snowpack is thick enough to cover them and the bed surface angles of potential weak layers are steep.

During the seasonal snow in-fill process on a slope, governed mainly by wind activity in arctic and alpine terrain, the snow cover at first mimics the slope and its irregularities (Fig. 10a). As in-fill progresses further (Fig. 10c), these irregularities are smoothened out and any local complex terrain, like large boulders or rock outcrops, is leveled out (Fig. 10d). After a certain threshold value is surpassed, ('snow depth x') these ground irregularities do not interfere with the snow stratigraphy or appear on the snow surface, hiding potential slab avalanche trigger zones (Fig. 10d). Snow depth x is a value governed by the scale of the complex terrain as well as the seasonal development of the snow.

However, this seasonal snowpack development can be influenced by extreme weather events. Such an event occurred during the period 26 January–3 February 2012, with air temperatures reaching 4 °C and 25.9 mm rain on 30 January (Met.no, 2013), influencing the snowpack in several ways. The snowpack warmed, became wet, and then refroze, forming a layer of melt–freeze crystals. Snowmelt destroyed the continuity of the seasonal snowpack that had developed up to that point, and most early weak layers either melted out or stabilized due to the refreezing of the melt water within the snowpack (Fig. 10b). In some locations such as topographic depressions, thicker deposits of snow were significantly deep enough to protect lower stratigraphy from the stabilizing effects of the melt water.

Our results suggest generally that the older the persistent weak layer (deeper buried), the greater the discontinuity and the lower the reactivity. While WL L-A was the most reactive and spatially continuous, more deeply buried weak layers displayed less continuity (Table 3). In addition, each subsequently buried instability displayed diminishing variation in slab thickness range (ex. WL L-C), indicative of the in-filling around ground topography. WL L-C exhibited a lower slab deviation value than expected, due to its low failure rate across the slope (as a result of melting out and stabilizing during the extreme event).

5.3. Possible errors and uncertainties

The majority of correlations calculated for the relationships between slab thickness and CT/ECT scores or difference between surface slope and bed surface angle are significant. However, there are a few exceptions, some of the significant correlations are rather low, and some of our datasets are small. Further, even with the significant correlations,

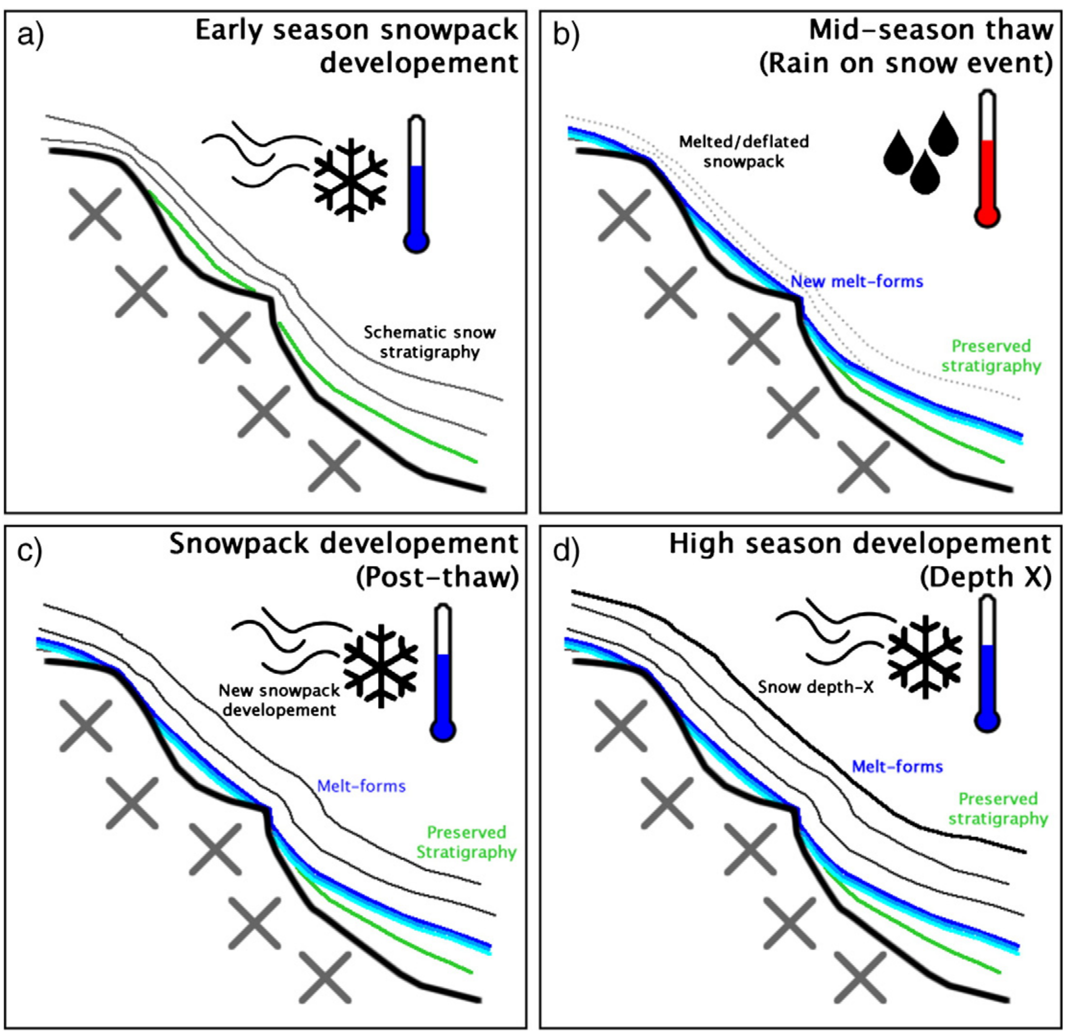

Fig. 10. Model of snowpack development over irregular ground topography. a) Initial snow in-filling around terrain. Depressions hold more snow, and thus have more stratigraphy. b) Thaw and rain-on-snow event causes snow depth decrease and melt out, hindering stratigraphic continuity. Significant stratigraphy melts or stabilizes, except in deeper areas where weak layers may persist. Upon refreezing, melt-form layers are formed. c) Snowpack continuously develops post-thaw once again in-filling around irregularities. Melt forms persist as well as the possibility for preserved instabilities in the old stratigraphy beneath. d) Snow depth threshold X is reached when development has surpassed the influence of topographic features. Threshold value is a function of terrain feature size as well as exposure to wind and weather. The knowledge of snow-free terrain becomes crucial as snow development masks potential trigger points.

there is a great deal of scatter in our data. While the data display some clear general trends, a slight change in some of the data points could easily reverse the trend. However, using our field observations and general process understanding, we suggest that the trends found are real. In general, the large uncertainties are not unexpected since many studies have documented a great deal of variation in stability test data, even on slopes that were relatively uniform and unaffected by the wind (Landry et al., 2004; Schweizer et al., 2008). Given the variability of past studies and the variable nature of the weather and substrate at our study sites, it is encouraging we found so many significant relationships. However, with our work we did have several sources of possible error that may have masked some of the relationships at some sites or in some trenches. These include:

1. Error in slope angle measurement. We used a standard inclinometer to measure slope angles and we think that there is a consistent error of slope surface and bed surface angles of +/− 1–2°. The error measuring ground surface is probably on the scale of +/− 3–4° due to the irregular ground topography.

2. Problems with performing the stability tests. The maritime influenced snowpack with its ice layers and meltforms made it hard to isolate a test column without any disturbance. Isolating an ECT column was especially difficult, resulting in a number of ECTV's. By excluding those ECTV's the correlations in Fig. 8 would improve.

3. Sample size. In some trenches, we only got 3 to 5 results per weak layer, so the sampling size for those trenches was insufficient to test the significance of any observed relationships.

6. Conclusion

In summary, topography and a general understanding of the seasonal development of the snowpack, which is influenced by weather (such as rain events and wind activity), are key in understanding depth and distribution of instabilities on small slopes. To a large extent weak layer stability is influenced by topography since snow depth is a function of terrain in windy environments. Slab thickness strongly influences stability where the ground topography is rugged. This trend is not as apparent in areas with smooth ground topography; in these areas, other factors such as weak layer properties and slab characteristics are more important. Further, the influence of ground topography on snow stratigraphy diminishes as snow depths increase until a snow depth threshold X is reached. The snow depth threshold X is a function of the roughness of the topography and the exposure to wind and extreme events. In snow climates with a thin snowpack, small terrain features such as boulders and stones might influence snow stratigraphy, while in deep snowpacks such features might have to be several meters in diameter or more to have an influence.

The most unstable spots on our study slopes and thus potential slab avalanche trigger zones tended to be where the snowpack was thin. At these locations, the weak layers emerge closer to the surface and are more likely to fracture (Simenhois and Birkeland, 2008). This is due to the fact that the skier-induced stress strongly decreases with depth (Föhn, 1987; Heierli et al., 2011; Schweizer and Camponovo, 2001). These results are consistent with past observations (Logan, 1992) and studies (Birkeland et al., 1995) and are a piece of common knowledge that we were able to better quantify in a High Arctic environment. For practitioners and winter recreationists it is thus essential to know the terrain they are working and travelling in, as well as to be aware of the seasonal development of the snowpack.

Based on our results, further work should emphasize the temporal aspect of weak layer evolution, as studied by Hendrikx et al. (2009), focusing on rugged, wind-affected terrain influenced by extreme weather events. An interesting point would be to focus on the scale and depth of variability as large rocks serving as early-season anchor points could change to trigger points later in the season as the snowpack thickens.

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