

SPATIAL VARIABILITY OF SNOWPACK ON SMALL WIND AFFECTED SLOPES, CENTRAL SVALBARD

Wesley R. Farnsworth^{1,2} Markus Eckerstorfer^{1,2} and Hanne H. Christiansen^{1,2}

¹ Arctic Geology Department, University Centre in Svalbard, Norway

² Department of Geosciences, University of Oslo, Norway

Abstract:

Spatial variability studies of snowpack stability have predominantly been conducted on sheltered uniform slopes despite mountains and avalanche starting zones being dominantly rugged wind-affected terrain. This study strives to correlate trends in ground topography with trends in snow stability to better understand spatial variations across wind-affected irregular slopes in the high-relief landscape of central arctic Svalbard. The expected outcome of this research is to gain insight of seasonal snowpack development and how the geomorphological and meteorological snow in-fill processes influence weak layer evolution and reactivity.

A small wind-affected slope (45 x 35 m) with irregular terrain and variable slope inclinations (32°–58°) was monitored and analyzed. 60 extended column tests were conducted in a grid of 30 snow pits across the slope as well as two stratigraphic profiles (horizontal & vertical) were excavated bordering the grid.

Previous research suggests that the weakest zones on slopes for artificial trigger points coincide with the shallowest snow and steepest sections. Results from this small data set suggest that not only is there a minimum threshold value regarding shallow trigger points, but in some cases depending on seasonal snowpack development it is possible to have the inverse relationship between stability and slab thickness. Also deeper zones present a greater number of potential instabilities, but often in a more stable/protected state. In summary, topography and a general understanding of seasonal snowpack development (rain events or wind activity) are key to understanding depth and distribution of instabilities.

1 INTRODUCTION

Snow depth is generally a function of topography, especially in environments devoid of vegetation and with persistent wind activity. The spatial variability of the snow cover as a function of terrain topography was highlighted as a key zone of uncertainty in avalanche forecasting (Hägeli & McClung, 2004). Also Schweizer *et al.* (2008) concluded in reviewing spatial variability of the snowpack that “research to understand and analyze terrain-correlated patterns of weak layer formation is important”.

Snow stratigraphy is the limiting factor in fracture propagation within a weak layer (Gauthier and Jamieson, 2010). It is important to understand how snow layers spatially interact with the terrain as a means of interpreting weak layer depth and distribution. Kronholm and Schweizer (2003) identify artificial slab avalanche release as prone to areas of less than average stability, called deficit zones. Such deficit zones are generally in shallower zones, located on rollovers, around rock outcrops or topographic peaks especially in windy regions.

**Corresponding author address:* Wesley Farnsworth, Dept. of Arctic Geology, University Centre in Svalbard, Norway; wesleyf@unis.no

Crown profiles and fracture lines often run along such features (Birkeland *et al.*, 1995). These topographic features disturb and largely influence snow stratigraphy.

This research was conducted on a small wind affected slope with irregular, complex topography in central Svalbard. It is expected that snow stratigraphy and weak layer formation will be largely a product of the wind activity and the process of snowpack development in-hand with the irregular topography. If the in-fill process is truly influential in weak layer development, there should be indirect trends between topography and stability.

2 STUDY SITE AND AREA

The study site is a small slope, roughly 45 m wide and 35 m high (Figure 1). The slope is the steep forefront of the Larsbreen rock glacier located in the southeastern corner of the Longyeardalen valley. The slope is located roughly 3 km south of Svalbard's main settlement Longyearbyen. The terminus of the rock glacier is located 150 m a.s.l. The slope is moderately wind affected both by top loading and cross loading. The slope inclination ranged

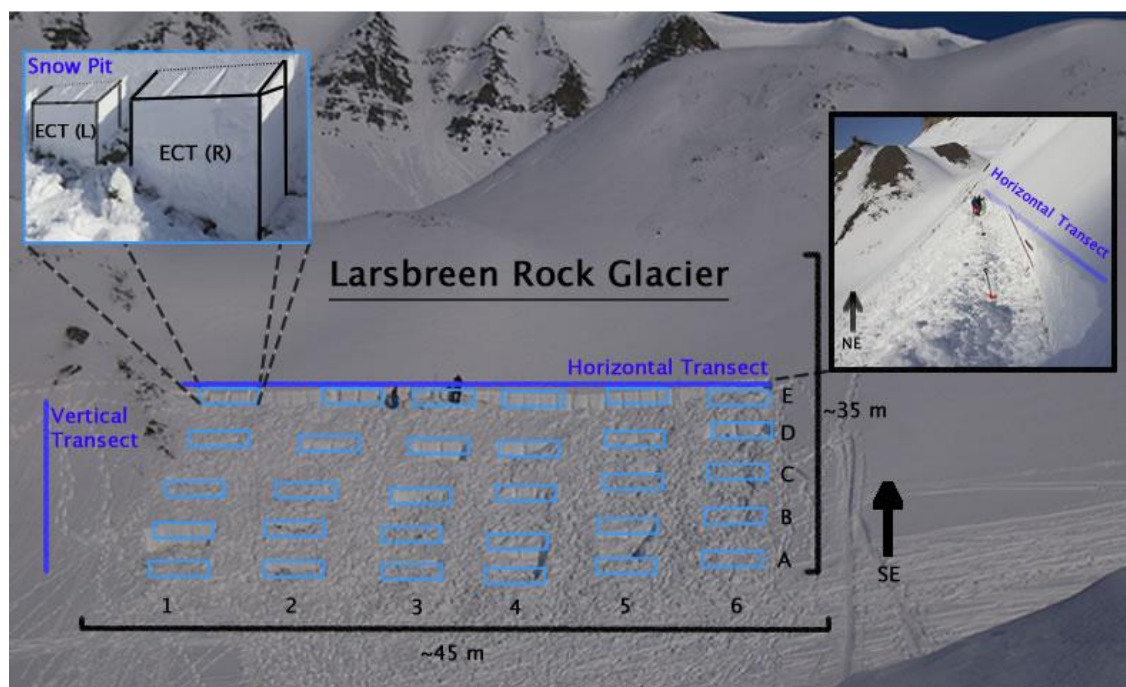


Figure 1: Study slope with the 30 pits and 2 transects. Inset photos show the two ECTs in a snow pit (left) and view across the horizontal transect (right).

from 32 ° to 58 ° (avg. 44 °) exhibiting large variation in vertical convexity and concavity. The slope has an aspect to the northwest (285 °) exhibiting minor cross slope curvature. The regional snow climate has been defined by Eckerstorfer and Christiansen (2011) as a high arctic maritime snow climate. But the snowpack at the site displays continental characteristics, being generally thin, highly stratified with a persistent depth hoar base. Snow depths exhibit high spatial variability driven by the interplay of the persistent winds interacting with the irregular slope topography. Due to the close proximity of the slope to the sea (6 km) the maritime influence is significant, forming ice crusts and melt-forms from mid-winter rain-on-snow events (Eckerstorfer and Christiansen, 2011). The Larsbreen rockglacier front is dominated by relatively coarse debris, with particle sizes up to 40 cm, creating large pore space and a relatively shallow active layer above the permafrost.

3 METHODS

The slope excavation took place within roughly 60 hours (stability tests within 36 hrs.) from May 6-8, 2012. A total of 30 snow pits were excavated across the slope as well as two transects, one horizontal (36 m) and one vertical (20 m) bordering the snow pit grid. Two Extended Column Tests (ECT; Simenhois & Birkeland 2006) were conducted in each snow

pit, whereas transects allowed for stratigraphy profiles to be conducted at a 1 meter resolution.

The snow pits were roughly 3 m wide and excavated in a grid form (6 x 5) across the slope (Figure 1). The 5 rows of pits were alphabetized from bottom-up. The pits are roughly 3 m apart from one another horizontally and spaced vertically ever 2 meters up-slope from each other. Following Jamieson (1999), ECT columns were only cut down to a depth of 150 cm, in the cause of snow pits exceeding such depth.

In each pit, snow depth and slope inclination of each ECT column were recorded. The bed surface inclination and slab thickness of each fractured weak layer were also recorded. The weak layer's structural properties were recorded according to industry standards (Greene et al., 2004). Each weak layer was assigned a letter and consequently traced from pit to pit and throughout the two transects.

The two transects allowed for the continual tracing of weak layers across the slope both horizontally (36 m) across the top and vertically (20 m) up the left flank. Slab sizes, weak layer thickness as well as bed surface inclinations were measured for each prominent weak layer. The profiles also provide exposure to measure depth hoar thickness and the depth of a main melt-freeze boundary.

4 RESULTS

4.1 *Snowpack Characteristics*

Snow depths recorded at each Extended Column Test across slope ranged from 30 to 300 cm with a mean value of 148 cm (Table 1). Snow cover thickness decreased towards the upper extent of the slope, while snow surface inclination angles increased from the base of the slope upwards (Table 1). Snow surface inclination values ranged from 30 °- 40 ° and averaged 34 ° (Table 1). The steepest and shallowest zones were found in Row-E (top) and the deepest values and gentlest slope angles were found in Row-A (bottom) (Table 1). This snowpack distribution is indicative of

Table 1: Test slope snowpack characteristics divided into Rows A–E and slope sum.

Row	Snow Depth (cm)			Surface Angle (°)		
	Mean	Max.	Min	Mean	Max.	Min
A	186	300	74	32.4	34	30
B	160	270	35	32.8	34	31
C	145	280	48	33.7	36	31
D	136	230	30	34.4	36	31
E	111	143	55	37.5	40	33
All	148	300	30	34.2	40	30

top loading and minor cross loading during the in-fill process.

4.2 *Weak Layer Properties*

Stability results among the 60 Extended Column Tests highlighted three persistent weak layers (WL A-C) and one active interface (Int-A) (Table 2). WL-A was a bed of small grained facets (.5 – 1 mm) with a range in slab thickness of 17 cm to 48 cm (avg. 31 cm). WL-A exhibited the shallowest burial as well as the greatest rate of failure (92%) across the slope (Table 2). WL- B was made up of roughly 2 mm facets with a slab ranging from 34 cm to 73 cm in thickness (avg. 52 cm) (Table 2). The facets displayed the second largest failure rate of 47%, and overlaid and icy bed surface. This ice bed formed during an extreme weather event between January 26 and February 3 2012, when air temperatures reached 2°C at an elevation of 464 m a.s.l. and substantial precipitation fell as rain. WL-C was buried the deepest of the four highlighted instabilities with a slab ranging from 64 cm to 97 cm in thickness (avg. 79 cm) and also displayed the lowest failure rate of 20% (Table 2). WL-C was

Table 2: Weak layer characteristics divided into the Rows A-E and summed together across the

WL	Trench	Count	Fail. Rate	Mean	Min	Max	Stdev	Mean	Min	Max	Stdev	Mean	Min	Max	Stdev
		(n)	(%)	Bed surface angle (°)				Slab thickness (cm)				ECT scores			
WL-A	A	12	100	32	30	35	1,5	34	20	52	12,6	10	0	28	10,2
	B	12	100	34	31	36	1,3	33	17	48	9,3	9	0	23	8,8
	C	10	83	35	32	37	1,6	33	21	42	8,3	14	0	29	10,9
	D	11	92	35	32	36	1,2	31	25	35	2,9	6	0	23	2,9
	E	10	83	39	33	42	2,8	24	17	29	3,8	7	0	14	6,5
	Slope	55	92	35	30	42	1,7	31	17	48	7,4	9	0	29	7,9
WL-B	A	6	50	33	32	35	1,7	42	37	47	3,4	18	11	22	4,3
	B	5	42	34	33	35	0,9	47	40	68	11,9	22	14	29	5,4
	C	5	42	33	31	35	1,8	54	35	69	14,2	19	0	30	10,3
	D	5	42	34	31	39	2,9	63	53	73	8,6	19	0	29	12,2
	E	7	58	39	36	42	2,2	54	34	72	15,9	9	0	29	12,1
	Slope	28	47	35	31	42	1,9	52	34	73	10,8	17	0	30	8,9
WL-C	A	1	8	34	34	34	x	71	71	71	x	27	27	27	x
	B	2	17	34	33	35	0,8	73	69	76	4,9	29	27	30	2,1
	C	2	17	33	31	35	2,1	90	89	90	0,7	12	0	24	16,9
	D	4	33	35	31	37	2,3	86	79	97	8,5	17	0	30	12,8
	E	3	25	39	36	40	1,6	75	64	87	11,6	10	0	29	16,7
	Slope	12	20	35	31	40	1,7	79	64	97	6,4	19	0	30	12,1
Int-A	A	4	33	31	30	34	1,7	21	20	23	1,5	12	12	13	0,5
	B	4	33	32	30	34	1,4	27,5	23	32	5,2	13	0	18	8,5
	C	6	50	35	34	37	0,8	26	24	31	2,8	9	0	16	7,3
	D	1	8	33	33	33	x	22	22	22	x	12	12	12	x
	E	x	0	x	x	x	x	x	x	x	x	x	x	x	x
	Slope	15	25	33	30	37	1,3	24	20	32	3,2	11	0	18	5,4

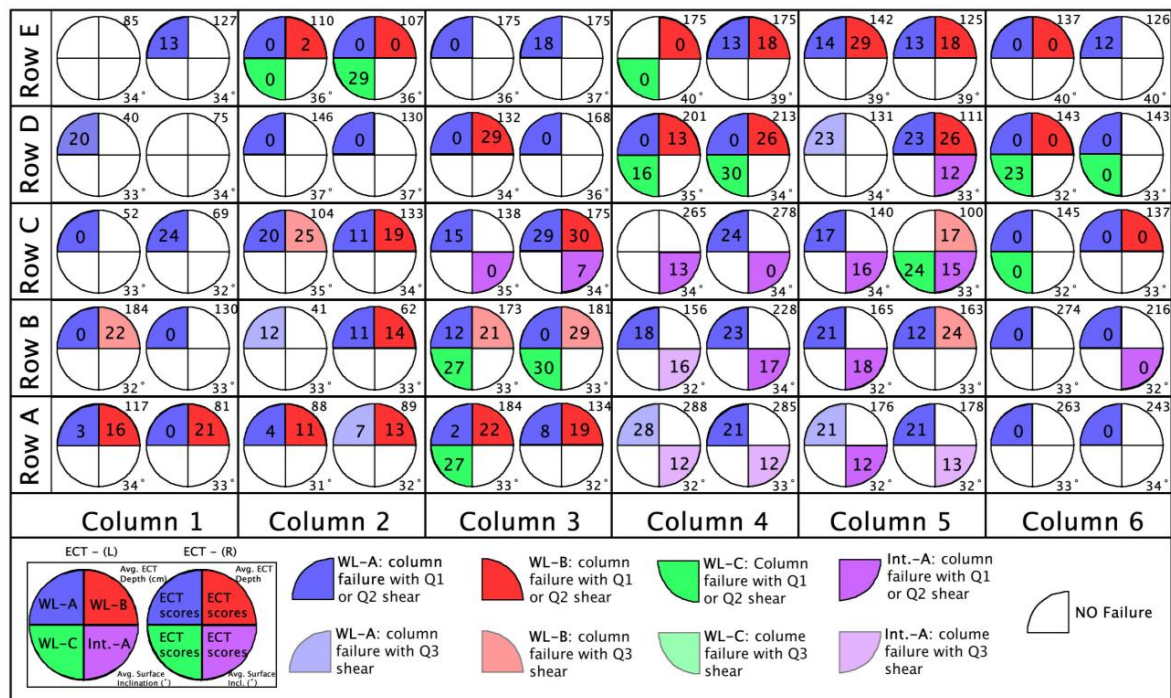


Figure 2: Weak layer distribution across test slope. Pie charts represent ECTs; colored slices represent weak layer failure with numeric stability scores. Faded pie slices correspond with low shear quality (Q3). For each ECT: average snow depth, top right; snow surface angle, bottom right.

present under the January melt-form contact and consisted of a thin, dense, bed of facets (2 – 4 mm) resting on an older ice bed surface. Depth hoar, although the most common weak layer in the regional snowpack (Eckerstorfer and Christiansen 2011) did not prove reactive to the ECT during the fieldwork. The goblet shaped crystals ranged from 10 - 35% of snowpack in the profiles, but only failed in 1 of the 60 extended columns. Int.-A was present in a shallow new snow / old snow interface formed during two minor wind loading periods. Int.-A displayed the thinnest slab ranging from 20 cm to 32 cm in thickness (avg. 24 cm) and had a 25% failure rate (Table 2).

Bed surface angles were consistent for all persistent WLs averaging 35°, but proved slightly lower for Int.-A, 33 ° (Table 2). Similar to the trend seen in the snow surface inclinations, bed surface angles increased from row A–E across the slope (Tables 1 & 2). Relative stability scores for the three different weak layers increased with burial depth. Failure occurred in WL-A after an average of 9 compressional strikes, where WL-B and C averaged ECT-17 and ECT-19 respectively (Table 2). This trend was not seen in Int.-A test scores, where the instability averaged 11 compressional strikes despite exhibiting the thinnest slab.

4.3 Depth and Distribution

The distribution of weak layer activity across

the slope displays a complex sorting of instabilities. WL- A (blue) is clearly the most dominant weak layer highlighted in the ECT scores, leaving merely 5 out of 60 tests where failure was not induced through compressional strikes. Many of the failures also occurred while freeing the backside of the column (ECTPV), totaling 21 of the 55 failures.

The subsequent weak layers display greater variation in their spatial distribution. WL-B (red) failed in roughly half of the stability tests and displayed more consistent activity in the upper most and lower most rows (Figure 2). The middle three rows (B-D) display small pockets or deficit zones where WL-B failed (ex-Col. 2 & 3 Row B & C). WL-B was active in snow pits that ranged in depth from 62 to 278 cm. WL-B was nonexistent in the upper three rows of column 1, where the snowpack was thinnest. WL-C (green) is the least continuous of all yet always failed in clusters with relatively consistent stability scores (Figure 2) (ex. Col. 3, A & B). WL-C was active in pits that ranged from 100 to 213 cm deep. These pits generally correspond with the deep snowpack zone on the slope, but not the deepest.

Int.-A (purple), like WL-C, only failed in a small percentage of the ECTs (25%), but the 14 failures where almost completely all clustered. This cluster centered over the deeper section of the slope where in-fill had doubled average snow depth values seen across the rest of the slope. Int.-A reacted in

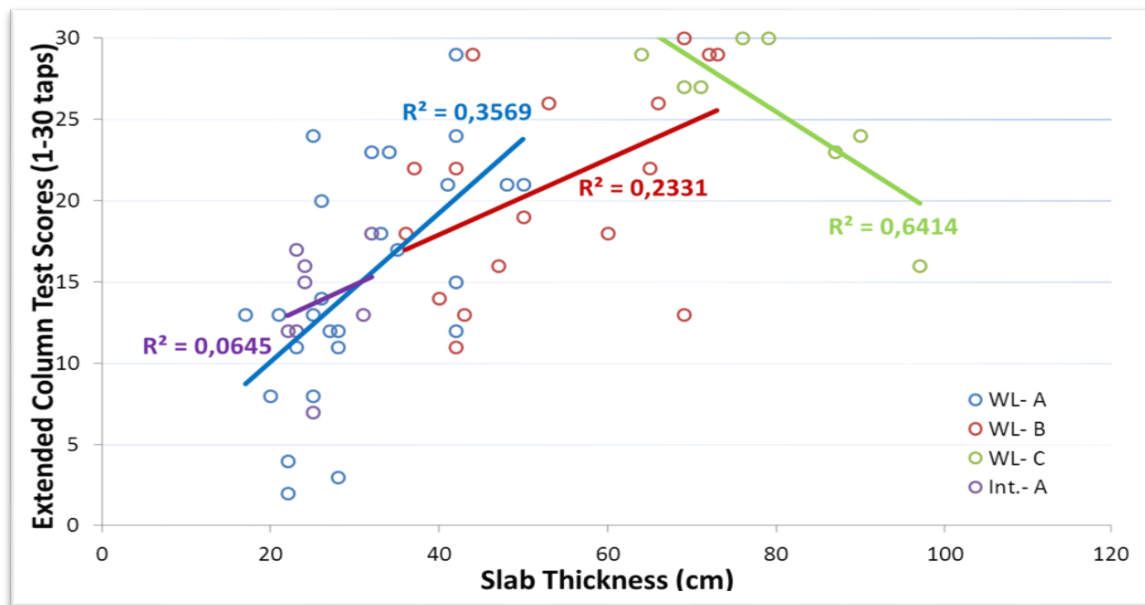


Figure 3: ECT score compared to slab thicknesses overlaying by instability. Q3 shears and ECTPVs excluded.

ECTs where WL- A would subsequently fail, but rarely would failure occur in columns with WL- B or C (except ECT-R, in pit 5c).

Results suggest that the older the persistent weak layer (deeper buried), the greater the discontinuity and the lower the reactivity. WL-A was the most reactive and spatially continuous and each subsequent weak layer displayed less continuity and required more compressional force to initiate failure (Table 2 & Figure 2). Also, each subsequently buried instability displays diminishing variation in slab thickness range (ex. WL-C), indicative of the in-filling around ground topography. WL-C exhibits 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).

The highly reactive WL-A failed at ECTPVs in 38% of the 55 ECTs and detracted data from the sensitive, unstable range of the stability spectrum. This has diminished the range and resolution of the data set. The large number of ECTPVs is also reflective of the difficulty of freeing ECT column in a cold hard maritime snowpack.

Despite relatively low r^2 values, WL-A, B and Int.-A all display a similar trend, where increasing slab thickness increases stability score results (Figure 3). WL- C displays the inverse relationship. As a means for focusing failure results on propagation propensity quality 3 shear failures were excluded (Johnson & Birkeland 2002) (Figure 3). This presented the same trends as excluding the extended column tests without propagation (ECTX), but allowed for a larger data set. ECTPVs were also disregarded due to the sensitive reactivity. The poorest r^2 correlation

is found in Int.-A (0,0645). This is reasonable as it is not a persistent weak layer but a temporary instability during the time of the field work.

5 DISCUSSION AND CONCLUSION

Warm temperatures and rain during the period January 26 to February 3 influenced this year's snowpack in several ways. During the extreme weather event slopes were active and unstable. Two key things happened as the snowpack warmed, saturated and then refroze; significant snowmelt deflated the continuity of the seasonal snowpack development and most early persistent weak layers melted out or stabilized with the refreezing of melt water (ex. WL-C, DH). This event was also when the melt-forms developed. This indicates that during the warm event, while a lot of the snowpack melted out and became isothermal, thicker deposits of snow (in depressions) were significantly deep enough to protect lower stratigraphy from melt water, and stabilization during refreezing.

Results from WL-A, B and Int.-A agree with research presented by Schweizer and Camponovo (2001) where stability results increase as slab thickness increases. However, WL-C the deepest of the highlighted instabilities did not follow such a trend. WL-C persisted in the deeper zones where melt and rain was not as effective in stabilizing the weak layer. This is displayed nicely in Figure 3, where WL-C stability decreases with slab thickness. It is possible that a similar effect could have stabilized the depth hoar and only in the deep zone (if the ECT column was cut deep enough) would failure have occurred.

Results from this small data set suggest that not only is there a minimum threshold value regarding shallow trigger points (Schweizer and Camponovo 2001), but in some cases depending on seasonal snowpack development, it is possible to have the inverse relationship between stability and slab thickness (as seen in WL-C).

Deeper zones present a greater number of potential instabilities, but often in a more stable/protected state. There is a clear correlation with the shallower zones presenting lower ECT score results, but there is a minimum threshold value, as the triggering of an avalanche needs not only a weak layer but a slab. This was clear as shallower zones on the slope did not have the lowest ECT scores as well as Slab A exhibited a minimum thickness of 17cm. It is unfortunate that time did not allow for more flexibility with the field day selection. The highly reactive WL-A reduced the resolution and influenced the range of the sensitive, unstable stability spectrum. It is possible that if time was provided for a day or two of settlement and bonding, results would have shifted into an ECTP 1-7 range, providing a better range and resolution to the comparison of stability versus slab thickness and the minimum threshold value.

The zone where Int.-A presented its activity (Columns 4 & 5, A-C) is a clear example of how snow will drift in and in-fill around topography, which seems to influence potential instabilities from earlier in the season. The exclusive failure of WL-A and Int.-A at that one zone reflects the padding and protection that the new wind slab provided for the deeper instabilities. It is not that WL-B and WL-C were not present in that one zone, rather they were buffered by the compressional forces of the test strikes being absorbed by the upper slab of Int.-A and WL-A. If time allowed to perform deep slab stability tests to better understand weakness buried in the depressions, results would probably show activity in WL-B and WL-C as well as expose other weak layers that formed early in the season with even less continuity.

In summary, topography and a general understanding of seasonal development / meteorology (rain events or wind activity) are key in understanding depth and distribution of instabilities. To an extent weak layer (re) activity is influenced by topography as snow depth is a function of terrain in windy environments. Results display the influence of ground topography on snow stratigraphy diminishes as snow depths increase. It would be interesting to study the temporal aspect of

weak layer evolution like Hendrikx *et al.* (2009) on rugged, wind-affected terrain influenced by extreme weather events. Would WL-A stabilize completely or organize itself into deficit zone clusters related to topography? Studies should also focus on the scale and depth of variability as anchor points could transform to trigger points from one storm to another.

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