METEOROLOGICAL AND SNOWPACK PROPERTIES ASSOCIATED WITH CRUST-ADJACENT PERSISTENT WEAK LAYERS PART 1: A REVIEW OF PRIOR RESEARCH

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ABSTRACT: Previous research has explored the mechanisms - in theory, field studies, and lab experiments - that explain the formation of faceted grains at crust/snowpack interfaces. Additionally, numerous case studies have described operational challenges that crust-adjacent persistent weak layers have presented to avalanche forecasting operations, accompanied by the meteorological and snowpack conditions that contributed to long-term avalanche issues. Recently, avalanche forecasting frameworks and decision support tools have been crafted to help operations identify indicators for when persistent weak layers may be activated, producing persistent slab or deep persistent slab avalanches.

This paper reviews and connects theory, field studies, lab experiments, case studies, and forecasting tools to identify a set of meteorological and snowpack indicators that may be specifically associated with long-term, crust-adjacent, persistent weak layer instability. These indicators may assist avalanche forecasting operations as they sort through a myriad of data points in attempts to anticipate the longevity of crust-associated dry slab avalanche issues. A companion paper then tests select indicators against two groupings of substantial crusts in Turnagain Pass, Alaska, USA: (1) those with a weak layer that produced long-term avalanche problems, and (2) those with short-lived or no reactivity.

KEYWORDS: crusts, melt-freeze layers, persistent weak layer, deep slab, avalanche forecasting

1. INTRODUCTION

Avalanche forecasting operations are often challenged by anticipating dry slab instability on crust-adjacent facets, and whether specific layers of concern will remain an issue for a period of days, weeks, or months. This can be especially challenging during long periods of weak layer dormancy despite nearly continuous loading (Morin, 2012), or because of subtle structural changes to a crust-adjacent weak layer — occurring over weeks to months — as crust-adjacent facets develop and then start to round (e.g., Jamieson, 2006; Sharaf and Janes, 2014). With natural and human triggered avalanches potentially occurring 2-3 months after an early season crust is buried, the bulk of a season's snowpack can be involved in highly destructive persistent and deep persistent slab avalanches should a failure occur. Yet despite this destructive potential, some stout crusts produce no long-term crust-adjacent instability – a pattern that is investigated by Schauer et al. (2024). Given this uncertainty, identifying indicators that could help practitioners anticipate signs of long-term, crust-adjacent dry slab instability would be of utility for avalanche forecasting operations.

Fortunately, a great body of prior research is available to help understand crust-adjacent instability. This paper analyzes 18 case/field studies, three laboratory studies, and four theoretical papers to better understand how crust-adjacent instability causes dry slab avalanches. Additionally, seven forecasting frameworks and decision support tools evaluate methods for forecasters to anticipate persistent and deep persistent slab avalanches. While this last set of papers is not exclusively focused on crust-adjacent instability, they all relate to anticipating the avalanche problems — persistent slab and deep persistent slab — that crust-adjacent weak layers can create. A companion work (Schauer et al., 2024) then tests some of the proposed indicators, applying them to ten substantial crusts — some with long-term instability, and some with no instability — that were observed over nine years in the Turnagain Pass forecast area of the Chugach Mountains, Alaska, USA.

2. CRUST FORMATION AND THE INITIAL FACETING PROCESS

Key to understanding crust-adjacent instability is understanding how a crust forms in the first place. Jamieson (2006) notes that wet layers can be introduced to a winter snowpack through

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a variety of mechanisms, including through temperature warming events, solar radiation, and rain. At a regional scale, each mechanism has potential to introduce more or less water to a snowpack at any specific location, with aspect, elevation, slope angle, and even wind direction potentially producing variation. As key examples, Jamieson (2006) notes that warming events are often variable by elevation, with thick crusts forming at lower elevations where temperatures are generally warmer, and thin or no crusts forming at higher elevations (though a temperature inversion can produce the opposite.) Solar radiation preferentially warms steeper slopes that are closer to perpendicular to the path of incoming solar radiation, introducing both slope angle and aspect into the equation. Prevailing winds also have the potential to deposit more rain on a windward slope, leaving a thinner crust on leeward slopes. Finally, Jamieson (2006) reminds us that two or more of these mechanisms are often at play in any given crust formation scenario, potentially contributing to spatial variability across a region.

Generally, when a wet layer is introduced to a winter snowpack, it freezes over the course of hours or days, releasing latent heat that can drive vapor transport and fuel facet formation (Colbeck and Jamieson, 2001). While facets near crusts have long been observed, the terminology used today was proposed by Birkeland (1998). He described a variety of faceting processes, including melt-layer recrystallization, where a temperature gradient drives vapor flow through a layer of new, dry snow that has fallen on a wet melt-layer prior to it refreezing. Lab studies have observed the formation of small facets in such a scenario in a matter of just hours (Jamieson and van Herwijnen, 2002), though often several days or longer is required for facets to form (Jamieson, 2004).

Unfortunately, faceting processes do not halt once a melt-layer has refrozen. Colbeck and Jamieson (2001) hypothesized that crust-adjacent facet grain growth was likely initially driven by latent heat release from a refreezing layer of wet snow, but that once initiated, facet growth could be enhanced by the lower thermal conductivity of a facet layer in comparison to a well bonded melt-freeze crust or ice layer. They suggested this could create possible ‘feedback mechanism,’ where future faceting would be enhanced after initial crust-adjacent facets form. One decade later, a lab study confirmed enhanced temperature gradients at the dry snow/ice interfaces around a crust, revealing hyper-localized temperature gradients that were many times greater than the bulk temperature gradient affecting the snow sample (Hammonds et al., 2015). This lab study aligns with field observations that note continued facet growth weeks after a melt-layer has refrozen (e.g., Sharaf and Janes, 2014).

Persistent weak layers can also form and grow near crusts through mechanisms that don’t inherently require a crust. Birkeland (1998) also described diurnal recrystallization, where day and night temperature swings introduce a temperature gradient to surface snow. Later works cite melt-layer recrystallization as a primary driver of faceting near crusts but acknowledge that the latter also can play a role (Jamieson, 2004). Additionally, surface hoar can also form either directly on a crust, or on layers of dry snow over a crust. Depth hoar grains have even been observed on top of a mid-snowpack crust (Sharaf and Janes, 2014), the likely result of a combination of faceting processes described in this section. Coupled with the potential of a stout crust to produce a hard, continuous bed surface that extends across terrain features — and potentially above any surface roughness that can interrupt or anchor a slab — these crust/persistent weak layer combinations can be a perfect recipe for very large avalanches and long-term instability.

Most studies related to crust-adjacent facets have focused on facets over a crust, but prior research has also acknowledged problematic weak layers in between and below crusts (e.g., Jamieson, 2004; Jamieson, 2006; Schauer et al., 2023). Multiple crusts have been observed near the snow surface immediately following a crust formation event, the result of surface water percolating down into the snowpack and preferentially saturating fine grain layers through capillary action (Jamieson 2006), or the result of temperature fluctuations during one or more storms. Additionally, Jamieson (2006) notes field observations of “crust laminations” forming within what initially appeared to be a uniform, thick crust. He hypothesized that this might be caused by slight density differences within a thick crust layer, where that slight variation then concentrates a temperature gradient and results in vapor transport/facet formation over time. Put simply, a lot is happening at a crust/snow interface, and persistent weak layers adjacent to a crust can continue to change for months after crust formation.

While the processes above can lead to crust-adjacent instability, the time it takes for a weak layer to heal varies greatly. During this time, additional loading events may stress a weak layer, resulting in avalanche activity. The remainder of this literature review is focused on indicators that may be of utility when attempting to anticipate the longevity of instability, after a crust-adjacent weak layer forms.

3. POTENTIAL INDICATORS OF CRUST-ADJACENT WEAK LAYER LONGEVITY

Predicting dry slab avalanche release on crust-adjacent persistent weak layers is notoriously difficult. While many examples exist of slab avalanche activity occurring months after crust formation, the mere presence of a crust does not guarantee long-term issues, where a weak layer, slab, bed surface, and suitable trigger come together to produce natural or human triggered avalanches.

While no one indicator is definitive in this section, prior research — including field studies, lab experiments, case studies, and forecasting frameworks — suggests that avalanche practitioners keep the following in mind when evaluating whether and where long-term crust-adjacent instability may be present in a forecasting region.

3.1 <u>The Crust Formation Event</u>

Starting at the most basic level, a crust-adjacent persistent weak layer must exist in an avalanche start zone if it will produce future instability that leads to an avalanche. This requires avalanche practitioners to track the specifics of a crust formation event, which includes consideration of the mechanism(s) that introduced water to the snowpack — a warming, solar, and/or rain event (Jamieson, 2006). Considering the crust formation not only provides a sense of where a crust may be found but also assists in painting a picture of anticipated wet layer variation in the region. For instance, prior research has found that crust-adjacent instability may be localized to select elevation bands (e.g., Jamieson and Johnson, 1997; Jamieson and Langevin, 2005; Sharaf and Janes, 2014), with theories for why this may be the case related to regional variation in wet layer thickness and/or initial crust burial (further discussed in sections 3.2 and 3.3 of this paper). Noting these trends and targeting snowpack observations to suspect locations can help practitioners make better predictions of slope scale instability in a region (Brill, 2005).

3.2 <u>Crust Thickness and Hardness</u>

Laboratory experiments not only confirmed the potential of a strong temperature gradient within a thin, dry slab sitting on a wet layer, but also found that thicker wet layers were slower to refreeze and produced facets faster than thinner wet layers (Jamieson and van Herwijnen, 2002). Case studies have noted that facets were less prevalent at elevations that received less rain (Sharaf and Janes, 2014) and persisted longer in locations featuring a thicker crust (Bingaman, 2012).

Conlan and Jamieson (2017) developed a decision support tool for use in western Canada based on survey responses from 31 avalanche professionals, where thresholds of interest were provided for a variety of meteorological and snowpack observations that may precede deep persistent slab avalanche cycles. A threshold of note was whether a crust - if present as a bed surface - was pencil hard or harder. This suggests that identifying the specific locations that feature a stout crust should be of particular interest to practitioners just after crust formation.

3.3 <u>Initial Crust Burial – Timing and Depth</u>

A review of prior research suggests that clear and cold weather, coupled with shallow initial crust burial, may be one of the best early indicators for crusts that have the potential to support long-term crust-adjacent instability. A lab study by Jamieson and van Herwijnen (2002) found that temperature gradients were stronger in thinner dry slabs versus thicker dry slabs over wet snow. Nine of the case studies reviewed in this paper — and 100% of case studies that made any note of temperature or initial crust burial depth — noted clear and/or cold weather, along with thin snow coverage over a crust, in the days to weeks just after crust formation. Case studies described these weather trends in a variety of ways, ranging from how a region was exhibiting “Continental” characteristics for months (Sharaf and Janes, 2014), had a “below average early snowpack” (Stethem, 2004), or featured “extended periods of dry conditions” (Johnson and Reardon, 2023). Some case studies also included specific observations of the days to weeks featuring thin coverage (often less than 30cm of snow) over a crust (e.g., Jamieson, 2000; Schauer et al., 2023).

Practitioners should be careful to track variation in initial crust burial depth across a region. Jamieson and Johnson (1997) note in a case study how longer-term instability was observed in an area of a region that had observations of thinner dry snow coverage in the days just after a crust formation. Variation may also be found across a region based on elevation. Jamieson and Langevin (2004), for instance, describe how “dry-on-wet” (DW) faceting may be constrained to specific elevation bands where cooling temperatures lower a rain/snow line, allowing for dry snow to fall on a wet layer that recently formed by a rain event. In their review of a facet/crust combination in the North Columbia Mountains of Canada, they observed more advanced facets near treeline than at higher elevations, where less latent heat was available from a thinner crust. At lower elevations below treeline, moist snow or rain continued to fall on the already wet snow surface, thus not producing the conditions necessary for DW faceting.

Finally, an avalanche forecasting framework for deep persistent slabs proposed by Schwartz and Anderson (2016) — piloted in Central Sierra Nevada Mountains of California, USA — noted that near crust facets are most likely to form after a rain or warming event saturates the snow surface, and less than 30 cm of new snow covers this layer before a dry period ensues. The authors include the caveat that this is not the only weather pattern that produces near crust facets, but that it is the most common. As a result, it is the “first part” of their deep persistent slab forecasting framework.

3.4 Weak Layer Grain Size, Type

The literature suggests that large facets are more likely to produce long-term crust-adjacent instability than smaller facets. In a sample of 39 facet-on-crusts avalanches and whumpfs in the Columbia Mountains, Jamieson and Langevin (2004) found that failures occurred 6-70 days after the burial of crust-adjacent facets, with an interquartile range of approximately 15 - 27 days. They noted that older failure layers tended to have larger grain sizes. In a later work, Jamieson (2006) found that facets below .7 mm in size didn’t produce failures for long in stability tests but that the median failure age for 2.3+ mm facets was 67 days.

The literature suggests that practitioners be wary of faceted grains, rounding facets, buried surface hoar, or depth hoar when attempting to anticipate long-term crust-adjacent instability. When performing a series of stability tests targeting .8 - 1.7 mm faceted grains adjacent to a specific crust, Jamieson (2006) consistently observed fractures with little difference in persistence or result between sharp cornered facets and rounding facets. Case studies note both sharp cornered and rounding advanced facets in natural and human triggered avalanches (e.g., Schauer et al., 2023; Morin, 2012). This suggests that evidence of rounding may not be definitive when ruling out future instability, particularly for larger faceted grains.

3.5 Weak Layer Thickness

Melt-layer recrystallization and ongoing localized temperature gradients at a crust/dry snow interface can produce thin (<5-10 mm) weak layers (Jamieson and Langevin, 2004). Greene (2007) observed very localized changes to the crust/dry snow interface within a grain or two of the crust in a laboratory setting. Hammonds et al. (2015) successfully measured very large temperature gradients at the sub-millimeter scale immediately above and below crusts, describing how such thin faceted layers may form. While thicker persistent weak layers are also responsible for long-term crust associated instability - thicker even than the 10 cm lemon threshold as defined by McCammon and Schweizer (2002) - field practitioners should exercise care to not miss thin layers of facets directly adjacent to a crust.

3.6 Weak layer location, in proximity to crust

Instability and avalanche activity has been credited to persistent weak layers above, below, and within crust laminations. Jamieson (2006) noted how, over a period of weeks to months, he has observed facets below a crust retaining their flat edges while facets above the same crust became more rounded. In a laboratory setting, Hammonds et al. (2015) observed a stronger localized temperature gradient directly below an ice lens compared to the gradient above it. Greene and Johnson (2002) analyzed instability around a crust in the Wasatch Mountains of Utah, USA, over the course of a season. They observed that, over time, the facets below a crust became the dominant failing layer, while initial avalanche activity saw failures both above and below a crust. Finally, Schauer et al. (2023) documented avalanche activity failing on persistent weak layers that had formed above and below crust layers. This suggests utility in tracking structure above, below, and within laminations of a crust, and not assuming that the failure layer for crust-adjacent facets will remain the same over time.

3.7 Indicators associated with slab formation

As a persistent weak layer continues to develop and eventually starts to heal, subsequent loading events can build a slab and add stress to the weak layer, which can sometimes lead to avalanche release or unstable stability test results. In other cases, the slab thickness will continue to increase without any indicators of snowpack instability.

Meteorological and snowpack test indicators have been researched through expert opinion surveys, case studies, and regional avalanche reviews for persistent slab and deep persistent slab avalanche problems. Loading events — caused by precipitation and/or wind — are commonly a precursor to natural crust-adjacent avalanches, though slab warming through temperature increases and solar input are also potential precursors to deep slab avalanche activity (Conlan and Jamieson, 2013).

The remaining indicators are for use primarily as a slab builds on an established crust-adjacent weak layer.

3.7.1 Loading Events (Precipitation/Wind)

In instances where multiple, smaller storms add additional stress to the snowpack over multiple days, the literature suggests being mindful of incremental loading over time, with less of a focus on just 24-hour loading totals. This includes numerous case studies that found loading trends over a longer period (3-5+ days) provided better insight into whether crust-adjacent avalanches would occur, when compared to just looking back on 24- to 36-hour snow totals (Jamieson et al., 2000; Savage, 2006; Schauer et al., 2023).

In a paper evaluating meteorological variables that could potentially aid in forecasting deep persistent slab avalanches, Marienthal et al. (2015) found higher cumulative precipitation totals in the seven days leading up to days with deep persistent slab avalanches when compared to days without observed avalanche activity. The dataset — which relied on observed avalanches over 44 years at the Bridger Bowl ski area in Montana, USA — also revealed that new snow loading over a period of 5 days was a better predictor of potential deep slab activity than precipitation totals over shorter periods of time. However, in general they found limited utility in using precipitation loading variables to forecast days with deep slab avalanche activity, in part due to high false alarm rates.

While loading events — driven by wind and/or precipitation — often activate or reactivate crust-adjacent instability, that doesn't mean that every loading event, including large loading events by regional standards, will result in instability. Morin (2012) noted how relatively light precipitation and a brief warm-up produced a destructive natural avalanche, and subsequent explosive triggered R3D3s and an R5D4 on a crust-adjacent weak layer. These very large avalanches occurred after the layer went dormant for 50 days, with no signs of instability as 600cm of new snow was added to the slab. This Morin (2012) case study suggests that the lack of avalanches during prior loading events should not be relied upon to rule out potential future activity on a crust-adjacent weak layer.

The decision support tool created in western Canada by Conlan and Jamieson (2017) identified specific precipitation loading thresholds of interest to avalanche forecasters for 24-hour, 3-day, and 7-day cumulative loading time periods, with those thresholds identified as 34, 59, and 79cm respectively. While these thresholds closely matched observed avalanche activity associated with snow loading events in the Coast Mountains, as reported by Conlan et al. (2013), the decision support tool thresholds were the average of numbers provided by respondents. Conlan and Jamieson (2017) noted geographic differences in threshold values provided by individual survey respondents, which could possibly be explained by variation in usual storm size that each individual experiences based on the snow climate of their home forecasting region.

Finally, wind loading has been credited as an important driver of certain crust-adjacent weak layer avalanches in numerous case studies (e.g., Schauer et al., 2023; Savage, 2006; Sharaf and Janes, 2014). In reviewing the literature, however, there are fewer papers analyzing wind loading, in part due to the difficulties of accurately measuring winds and any subsequent snow transport in avalanche start zones. Conlan and Jamieson (2017) note that wind loading requires "expert estimation" in the discussion about their decision support tool, and that they expect thresholds to be similar to those provided as precipitation thresholds of interest.

3.7.2 Warming/Cooling Events

While changes in air temperature are generally considered an uncommon driver of dry persistent deep slab avalanches (Conlan and Jamieson, 2017), some notable exceptions exist that warrant mention and tracking. Numerous case studies found warming to be the explanation for natural and human triggered avalanches, including warming over the course of hours (Sharaf and Janes, 2014; Morin, 2012) or warming over the course of multiple days (Jamieson et al., 2000; Conlan and Jamieson, 2014). Conlan and Jamieson (2017) found practitioners pay close attention to an increase of 8 -13°C over 24-72 hours, or rapid cooling from near freezing by 14°C within 12 hours as important thresholds. Similarly, Marienthal et al. (2015) detected higher 24-hour minimum temperatures and higher 3-day average daily maximum temperature as two predictors of deep slab avalanches.

3.7.3 Settlement Rates

Wright et al. (2016) propose using settlement rates as an additional indicator of instability when forecasting deep slab avalanches. In their review of 42 seasons of records from the Bridger-Teton National Forest Avalanche Center, Wyoming, USA, they found that settlement rates of greater than 8 cm per day were an indicator of sustained hazard, while low settlement rates (~2.5 cm a day) suggest the snowpack may be gaining stability. While not definitive nor the primary driver of instability, they suggest tracking settlement rates as part of a multivariate approach to hazard assessment.

3.8. Stability Test Indicators

The literature suggests a focus on fracture character in stability tests that involve tapping on a column in the snowpack, including Compression (CT), Extended Column (ECT), and Deep Tap (DT) tests, with less of an emphasis on test scores alone (Conlan et al., 2013).

Case studies confirm the utility of fracture character in stability tests, often citing it as more important than test score. Sharaf and Janes (2014) found fracture character and propagating results to be more correlated to avalanche activity than simple test scores when tracking facets adjacent to a specific crust, with tests rarely failing at low scores. Savage (2006) noted that shear quality or fracture character may be a better indicator of potential current or future deep slab instability. Finally, on the 2012 ubiquitous Martin Luther King Jr. crust in North America, Richardson (2012) noted “amazing consistency in shear quality,” while Nalli (2012) noted high scores and his eventual inclusion of 30+ taps in ECT procedures, and consistent sudden planar fractures in crust-adjacent layers.

Forecasting framework and decision support tool literature also suggests that fracture character should be heavily relied on when anticipating deep persistent slab avalanches. Respondents in Conlan and Jamieson (2017) expert opinion survey weighted “sudden fracture” fracture character as the most important indicator for anticipating future instability, rating this indicator even higher than recent deep slab avalanche observations. Given observed limitations of CTs and ECTs for testing deeply buried weak layers, they also note the utility of the DT test and Propagation Saw Test (PST) to gather this information.

Schwarz and Anderson (2016) evaluated the use of large column tests to forecast future deep persistent slab avalanche cycles in the central Sierra Nevada, CA, USA. After a weak layer is present, they note three precursors to a potential future deep persistent slab avalanche cycle: a) stability tests are producing ECTN results, b) no avalanche activity is currently occurring, and c) Propagation Saw Tests are producing (END) results at less than 50% cut length. Most literature puts a PST (END) result at less than 50% cut length as an unstable result, while an ECTN result is generally considered stable (e.g. Marienthal et al., 2023). For the purpose of predicting future instability, this suggests the utility of a PST, particularly when ECT results aren’t showing propagation potential.

3.9. Recent Avalanches

Several case studies note how instability lingers days after a natural cycle on long-term crust-adjacent persistent weak layers. Savage (2006) noted that deep slab instabilities often remain sensitive for a period of days following a significant loading event. Sharaf and Janes (2014) noted a week and a half of human triggered avalanches following a specific natural cycle on crust-adjacent facets. Finally, the deep persistent slab decision support tool developed by Conlan and Jamieson (2017) noted that forecasters placed great weight on prior deep slab avalanche activity, with a specific interest in activity over the prior four days. Particularly for a deep persistent slab avalanche problem on crust-adjacent facets, these data points suggest being wary of potential lingering instability several days after recent avalanches have been observed.

4. CONCLUSIONS AND FUTURE STUDIES

Given the requirement that a crust, weak layer, slab, and trigger all come together in a specific location at a specific time to produce a crust-associated persistent slab avalanche, it is no wonder that no one meteorological or snowpack indicator is definitive when anticipating long-term regional avalanche issues. Despite that difficulty, the literature suggests indicators and data points – starting at crust formation – which could be useful to keep in mind when tracking persistent weak layers adjacent to a crust.

Specifically, the literature suggests tracking:

- Where a crust is located, how thick it is (including variation in a region), and how much snow initially buries it.
- Whether a crust froze prior to burial, or whether it was buried wet.
- The meteorological conditions in the initial days and weeks after formation, with specific concern for crusts with thin snow coverage during cold, dry periods.

In a snow pit after crust formation, be mindful of:

- Thin, crust-adjacent weak layers that are found above, below, or within a crust.
- Continued changes to weak layer structure, potentially continuing for weeks after crust burial.
- Large persistent weak layer grains, which are more associated with long duration activity than smaller grains.
- Stability tests, even with high scores, that exhibit propagation potential and/or sudden fracture characteristics.

As loading events build a slab over a crust-adjacent persistent weak layer, consider:

- Cumulative wind or precipitation loading totals over a longer period of days, and not just more recent (24-36 hour) totals.
- Warming events that may change slab character, increasing instability and/or leading to natural avalanches.
- The potential of lingering instability for days after an observed avalanche cycle.
- Not relying on a lack of instability during a previous loading event as definitive evidence of stability during subsequent loading events.

The indicators suggested above may not only help practitioners focus on useful data points when evaluating crust-adjacent instability, but they may also help practitioners identify indicators that could have less utility than previously thought. While such reflection is likely personal and institution- or region-specific, an example of this may well be the de-weighting of 'stable' stability test scores, in favor of a focus on fracture character and propagation potential in stability tests. Depending on current personal practices, this may encourage the addition of Deep Tap tests for deeply buried weak layers, or overdrive taps on standard CT or ECTs when weak layer strength is very high, but structure is poor.

On top of tracking change over the course of one season, the same necessity may exist for operations to track year to year in the decades to come. Eckert et al. (2024) note that areas that have seen a historically dry snowpack are seeing increased rain-on-snow events and increased surface melt due to warming. This change is being accompanied by an increase in the presence of crusts in regions where they have not commonly existed in the past. A study focused specifically on Alaska, USA noted a likely general increase of rain on snow events in northern regions of Alaska through 2100, with some potential declines of rain on snow events in select southern areas due to a lack of snow for rain to fall on (Bieniek et al., 2018). Although there has been limited work modelling snow stratigraphy well into the future, there are several studies that predict an increased occurrence of buried crusts as a result of climate change in the decades to come (Rasmus et al., 2004; Bellaire et al., 2016). These changes argue for continued literature review and cross-region discussions, so that practitioners aren't caught off guard as an outlier event in one region becomes a more common occurrence.

While weak layer development has been well studied and documented, further analysis of slab development and slab properties may also prove useful in efforts to anticipate crust-adjacent avalanche activity. This includes a review of circumstances where a crust is not the bed surface for an avalanche but instead part of the slab, when the failure occurs in facets that have formed just below a crust, as described in section 3.6 of this paper.

Finally, absent any one definitive indicator, further research is needed to evaluate whether multiple indicators considered together can provide avalanche forecasting operations with more clarity in situations where long-term crust-adjacent instability is likely. Until that time, relying on a holistic approach – including but not limited to the indicators discussed in this paper – will be necessary when assessing the likelihood of long-term crust-adjacent instability.

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REFERENCES

Bellaire, S., Jamieson, B., Thumlert, S., Goodrich, J. & Statham, G. Analysis of long-term weather, snow and avalanche data at Glacier National Park, B.C., Canada. Cold Regions Science and Technology, 121, 118–125. 2016.

Bieniek, P., Bhatt, U., Walsh, J., Lader, R., Griffith, B., Roach, J., Thoman, R. Assessment of Alaska rain-on-snow events using dynamical downscaling. Journal of Applied Meteorology and Climatology, Vol. 57, 1847-1863. 2018.

Bingaman, D. 2011 MLK rain event: Payette avalanche center. The Avalanche Review, Vol. 20, No. 3., February 2012. 30. 2012.

Birkeland, K. Terminology and predominant processes associated with the formation of weak layers of near surface faceted crystals in the mountain snowpack. Arctic and Alpine Research, 30 (2), 193-199. 1998.

Brill, G. Observations on faceted crusts. The Avalanche Review, Vol. 23, No. 4, 16-17. 2005.

Colbeck, S., Jamieson, B. The formation of faceted layers above crusts. Cold Regions Science and Technology. 33 (2-3), 247-252. 2001.

Conlan, M., Jamieson, B., Case study of a solar triggered persistent deep slab avalanche. Proceedings of Geohazards. 6, 15-18. 2004.

Conlan, M., Tracz, D., Jamieson, B. Measurements and weather observations at deep persistent slab avalanches. Cold Regions Science and Technology. 97, 104-112. 2013.

Conlan, M., Jamieson, B. Weather preceding persistent deep slab avalanches. Proceedings of the International Snow Science Workshop, Chamonix Mont-Blanc, France. 219 – 226. 2013.

Conlan, M., Jamieson, B., A decision support tool for dry persistent deep slab avalanches for the transitional snow climate of western Canada. Cold Regions Science and Technology. 144, 16-27. 2017.

Eckert, N., Corona, C., Giacona, F. *et al.* Climate change impacts on snow avalanche activity and related risks. *Nature Reviews Earth and Environment,* **5**, 369–389. 2024. https://doi.org/10.1038/s43017-024-00540-2

Greene, E., Johnson, G., Characterization of a deep slab instability. Proceedings of the 2002 International Snow Science Workshop, Penticton, B.C., Canada. 491-498. 2002.

Greene, E. The thermophysical and microstructural effects of an artificial ice layer in natural snow under kinetic growth metamorphism. Ph.D. Dissertation, Colorado State University. 2007.

Hammonds, K., Lieb-Lappen, R., Baker, I., Wang, X. Investigating the thermophysical properties of the ice-snow interface under a controlled temperature gradient Part I: Experiments and observations. Cold Regions Science and Technology, 120, 157-167. 2015.

Jamieson, B., Johnston, C., The facet layer of November 1996 in western Canada. Avalanche News, Summer 1997. Vol. 52, 10-15. 1997.

Jamieson, B., Geldsetzer, T., Stethem, C. Case study of a deep slab instability and associated dry avalanches. Proceedings of the 2000 International Snow Science Workshop, Big Sky, Montana, USA. 101-108. 2000.

Jamieson, B., van Herwijnen, A. Preliminary results from controlled experiments on the growth of faceted crystals above a wet snow layer. Proceedings of the 2002 International Snow Science Workshop, Penticton, B.C., Canada. 2002.

Jamieson, B., Between a slab and a hard layer: Part 1 – Formation of poorly bonded crusts in the Columbia mountains. Avalanche News 70, Canadian Avalanche Association. 2004.

Jamieson, B., Langevin, P. Faceting above crusts and associated slab avalanching in the Columbia mountains. Proceedings of the 2004 International Snow Science Workshop, Jackson Hole, Wyoming, USA. 112-120. 2004.

Jamieson, B., Langevin, P. Between a slab and a hard layer: Part 3 – Two field studies of facets growing above wet layers. Avalanche News 72, Canadian Avalanche Association. 2005.

Jamieson, B. Formation of refrozen snowpack layers and their role in slab avalanche release. Reviews of Geophysics, 44, RG2001. 2006.

Johnson, C., Reardon, B. April-fooled in the Flathead: The hazard of late-season persistent weak layers. Proceedings of the 2023 International Snow Science Workshop, Bend, Oregon, USA. 736-740. 2023.

Marienthal, A., Hendrikx, J., Birkeland, K., Irvine, K. Meteorological variables to aid forecasting deep slab avalanches on persistent weak layers. Cold Regions Science and Technology. 120, 227-236. 2015.

Marienthal, A., Chabot, D., Birkeland, K. Comparing the effectiveness of the ECT, PST and CT for assessing snow stability. Proceedings of the 2023 International Snow Science Workshop, Bend, Oregon, USA. 1039-1046. 2023.

McCammon, I., Schweizer, J. A field method for identifying structural weaknesses in the snowpack. Proceedings of the 2002 International Snow Science Workshop, Penticton, B.C., Canada. 477-481. 2002.

Morin, C. The MLK event at Crystal Mountain. Proceedings of the 2012 International Snow Science Workshop, Anchorage, Alaska, USA. 240-243. 2012.

Nalli, N. MLK rain crust, deep slabs & cornice failures in the southern Wasatch. The Avalanche Review, Vol. 20, No. 3., February 2012. 27. 2012.

Rasmus, S., Räisänen, J. & Lehning, M. Estimating snow conditions in Finland in the late 21st century using the SNOWPACK model with regional climate scenario data as input. Annals of Glaciology. 38, 238–244, 2004.

Richardson, M. MLK crust thoughts from Mike Richardson. The Avalanche Review, Vol. 20, No. 3., February 2012. 24. 2012.

Savage, S. Deep slab avalanche hazard forecasting and mitigation: The south face at Big Sky Ski Area. Proceedings of the 2006 International Snow Science Workshop, Telluride, Colorado, USA. 483-490. 2002.

Schauer, A., Johnston-Bloom, A., Smith, A., McKee, M., Kennedy, J. Crusts and facets: A case study of a season with deep issues near Girdwood, AK. Proceedings of the 2023 International Snow Science Workshop, Bend, Oregon, USA. 589-596. 2023.

Schauer, A., Moderow, A., Johnston-Bloom, A. Meteorological and snowpack properties associated with crust-adjacent persistent weak layers Part 2: Applying theory to observed patterns. Proceedings of the 2024 International Snow Science Workshop, Tromsø, Norway. 2024.

Schwartz, B., Anderson, A. Using large column tests to successfully forecast persistent deep slab avalanches in the central Sierra Nevada. Proceedings of the 2016 International Snow Science Workshop, Breckenridge, Colorado, USA. 1298- 1301. 2016.

Sharaf, D., Janes, M. The evolution of the 2014 ‘Damalanche’ facet layer of south-central and southeast Alaska. Proceedings of the 2014 International Snow Science Workshop, Banff, Alberta, Canada. 55-62. 2014.

Stethem, C., Piche, M. Winter in 2003 in southern BC – Perspective, Recognition, Management. Proceedings of the 2004 International Snow Science Workshop, Jackson Hole, Wyoming, USA. 742-746. 2004.

Wright, P., Comey, B., McCollister, C., Rheam, M. Deep slab instability: Loading, temperature, and settlement rate thresholds related to failure – Part II. Proceedings of the 2016 International Snow Science Workshop, Breckenridge, Colorado, USA. 533-540. 2016.