METEOROLOGICAL AND SNOWPACK PROPERTIES ASSOCIATED WITH CRUST-ADJACENT 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 reactivated, 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 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 all 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 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, contributing to spatial variability across a regional scale.

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 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 would be further enhanced by the lower thermal conductivity of a facet layer in comparison to a well bonded melt-freeze crust or ice layer. They hypothesized a ‘feedback mechanism’ where future faceting could be enhanced once initial crust-adjacent facets have formed. One decade later, a lab study confirmed a temperature gradient at the dry snow/ice interfaces of a crust, revealing a hyper-localized temperature gradient that is many times greater than the bulk temperature gradient affecting a snow sample (Hammonds et al. 2015). This lab study aligns with case studies that note 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 2004a). 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 2004a, 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 the 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 the 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 The Crust Formation Event

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 Crust Thickness and Hardness

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 32 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 any locations featuring a stout crust should be of particular interest just after crust formation.

3.3 Initial Crust Burial – Timing and Depth

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), through 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 in 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 falls on 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 one laboratory experiment, 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 both above and below 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, likely 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 a 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 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 these 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 partly be explained by the usual storm size in a practitioner's home forecasting region/snow climate.

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. Conlin 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 (Conlin 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 with 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, the 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 CT 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) propagating 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 instabilities. Savage (2006) noted that deep slab instabilities often remain sensitive for a period of days following a significant leading event. Sharaf and Janes (2014) noted a week and a half of human triggered avalanches following a 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 layer instability 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 has refrozen 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 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 above don’t just help practitioners focus on useful data points when evaluating crust-adjacent instability, but they can also help practitioners identify indicators that may 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. 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.

ACKNOWLEDGEMENT

The authors would like to thank the Chugach National Forest Avalanche Center for assistance throughout this project, and Heather Thamm for her thoughtful review of early drafts.

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