CRUSTS AND FACETS: A CASE STUDY OF A SEASON WITH DEEP ISSUES NEAR GIRDWOOD, AK

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ABSTRACT: During the 2021-22 winter season, the snowpack in the southwest Chugach and northeast Kenai mountains near Girdwood, Alaska, was characterized by two crusts that formed early in the season and were directly related to avalanches that occurred throughout the winter and persisted until the snowpack melted in the spring. Although southcentral Alaska is no stranger to avalanche problems associated with buried crusts, these two layers were noteworthy in their geographic extent, the duration of the period in which they stayed reactive, and their impact on multiple avalanche forecasting operations in the area. The avalanches related to these two problematic layers impacted infrastructure, affected ski resort operations, and led to at least two near-misses with backcountry users. This case study summarizes the weather events that formed the problematic snowpack, documents the avalanche activity associated with these layers, and highlights challenges and lessons learned while forecasting during this difficult season. This case study is a collaboration between avalanche professionals from the Chugach National Forest Avalanche Center (CNFAC), Alyeska Resort, Alaska Railroad, and the Alaska Department of Transportation and Public Facilities. We hope the perspectives shared from this challenging season will improve the ability of forecasters from many different operations to predict similar events in the future.

KEYWORDS: deep slab, crust, persistent weak layer, infrastructure, headache

1. INTRODUCTION

Southcentral Alaska is no stranger to season-long stability issues stemming from faceted snow associated with crusts buried deep in the snowpack. Despite a long history of avalanches related to these crust/facet combinations, avalanches failing on layers associated with crusts remain very difficult to predict. Historically, the seasons with the most impactful avalanche cycles tend to be plagued with problematic crust/facet combinations.

The 2021-2022 season was no exception to this dilemma and stood out as a particularly tricky season operationally. Two different crust layers formed early in the season and produced very large avalanches well into May. This difficult snowpack impacted infrastructure as well as recreation, with natural avalanches leading to highway and railroad closures, destroying portions of power distribution lines, and multiple near misses involving full and partial burials of backcountry recreationists. Challenges impacted the ski resort as well, requiring carefully orchestrated operations to open terrain at the start of the season. This case study documents the weather events that led to the formation of these weak layers, highlights the major avalanche events of the season, and identifies some of the lessons forecasters from multiple operations learned while trying to predict this difficult scenario.

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2. LOCATION

Girdwood is located near the coast of Southcentral Alaska at roughly 60.95 N, 149.16 W (Figure 1). The town is situated along the southwest edge of the Chugach range, just north of the Kenai Mountains. Ridgetops in the area rise from sea level to approximately 900-1400 m (3000-4000 ft) elevation on average near the coast, while the mountains just a little further inland reach 2100-3100 m (7000-10000 ft). Due to

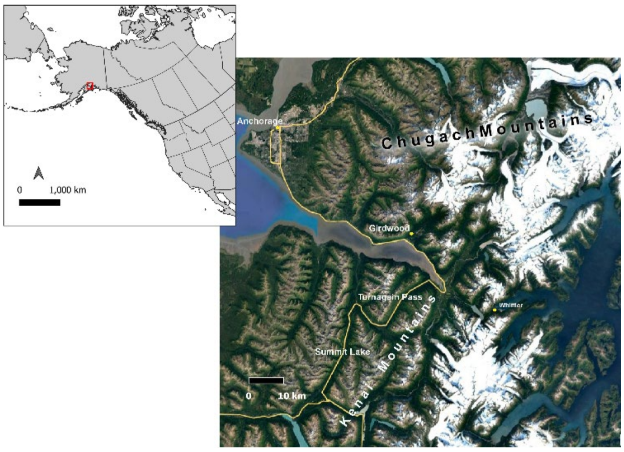

Figure 1: Location map of the study area. Data: Google Earth (2023), World Bank (2020), Nat. Res. Can. et al. (2010).

the proximity to the coast and dramatic vertical relief, the snow climate varies substantially both interannually and over short geographic distances (Wagner, 2012). It is not uncommon to experience a transition from a maritime to a continental snowpack over distances on the order of 30 km (20 mi).

The main infrastructure corridor exposed to avalanche hazard lies along the Seward Highway, which travels between Anchorage and Seward. There are 110 named avalanche paths along the corridor that threaten the highway, powerlines, and train tracks. The highway provides easy access for backcountry skiers and snowmobilers and sees especially heavy use through the Turnagain Pass and Summit Lake areas. In addition to the Seward Highway corridor, the Alaska Railroad also travels along the Placer River and Trail Creek drainages, adding another roughly 25 km (15 mi) of avalanche exposure.

3. FORMATION OF PROBLEM LAYERS

3.1 The 2021/2022 Climate

The 2021/2022 season was characterized by a Moderate La Nina, with an intermountain snowpack based on the snowpack climatology classification developed by Mock and Birkeland (2000) and implemented for this specific region by Wagner (2012) and Champion & Thamm (2018).

3.2 Halloween crust

In late October, an atmospheric river brought a powerful storm to the region that would be named “The Halloween Storm” (Figure 2). Lasting from 10/29-11/04, the storm brought 490 mm (19 in) rain to Girdwood and 710 mm (28 in) rain to Portage, approximately 30 km (18 mi) east of Girdwood. This storm set a national record in Portage as the northernmost location in the U.S. to record two consecutive days of 200 mm (8+ in) rainfall. This included one day that brought 260 mm (10.34 in) rain in 24 hours. Upper elevations saw 6-7.5 m (20-25 ft) of snow in some areas. The system, driven by a slow-moving upper-level low situated just to the southwest of the study area, promoted a strong south to southeasterly flow and pushed a strong jet of moisture directly into our forecast zone. This precipitation event formed what was to become a stout crust in the 450-900 m (1500-3000 ft) elevation band. This Halloween crust would prove to be problematic for months to come.

Following the storm, the month of November was predominantly cold and clear with a few inches of low-density snowfall, leading to the formation of a 25 cm (10 in) thick layer of near surface facets (NSF) and surface hoar (SH) on top of the Halloween crust. A cold storm at the end of the month brought 0.5-1 m (2-3 ft) of very low-density snow. This was the start of the incremental loading that would create the forecasting challenges in the days and weeks ahead.

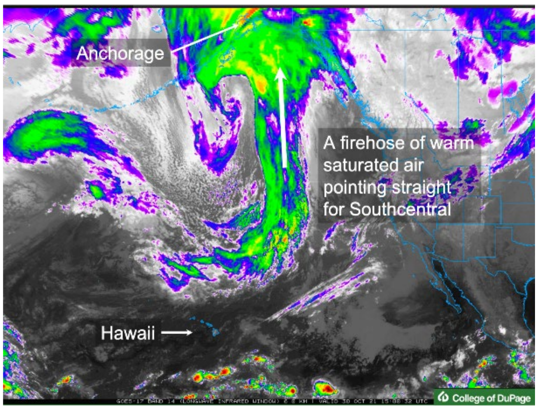

Figure 2: Infrared image of the atmospheric river pointed at Southcentral from the GOES-West satellite. Image taken 10.30.21 at 7:10 am. (CNFAC)

3.3 New Year’s crust

There was a rapid warming event at the end of December that brought above-freezing temperatures up to 2150 m (7000 ft) Ridgetop temperatures reached 2-4 C (35-40 F), driven by a subsidence inversion associated with a persistent upper-level ridge that stuck around the area for the last week of December. A weak southwesterly system moved along the top of the upper-level ridge on Dec. 27, bringing light rain to ridgetops that was not enough to amount to measurable precipitation at weather stations. As temperatures cooled during the following days, this formed another crust that would also be problematic for the rest of the season. The crust was buried by 7-12 cm (3-5 in) snow during a storm on Dec. 31, and a subsequent stretch of high pressure and subzero temperatures in early January formed a layer of near-surface facets on top of the crust. A storm on January 9th ushered in a pattern change, with measurable precipitation on 21 of the next 23 days. During this 23-day period, the Top weather station at Alyeska (938m /2750 ft) recorded 445 cm (175 in) of snow and 370 mm (14.97 in) snow water equivalent (SWE). This crust and weak layer, now buried by a significant slab, would be the second crust/facet issue for all the forecasting operations to deal with.

4. MAJOR AVALANCHE EVENTS

Throughout the season, there were multiple periods of activity on the Halloween and New Year’s crust layers, separated by extended periods without any avalanches despite continued loading (Figure 3). We’ve grouped the periods of activity into four clusters: early winter, mid-to-late January, late February, and the spring meltdown. Additionally, we briefly describe an extraordinary avalanche cycle in late March that we do not believe involved the two weak layers that are the subject of this case study but need to be acknowledged looking back on the 21-22 winter season.

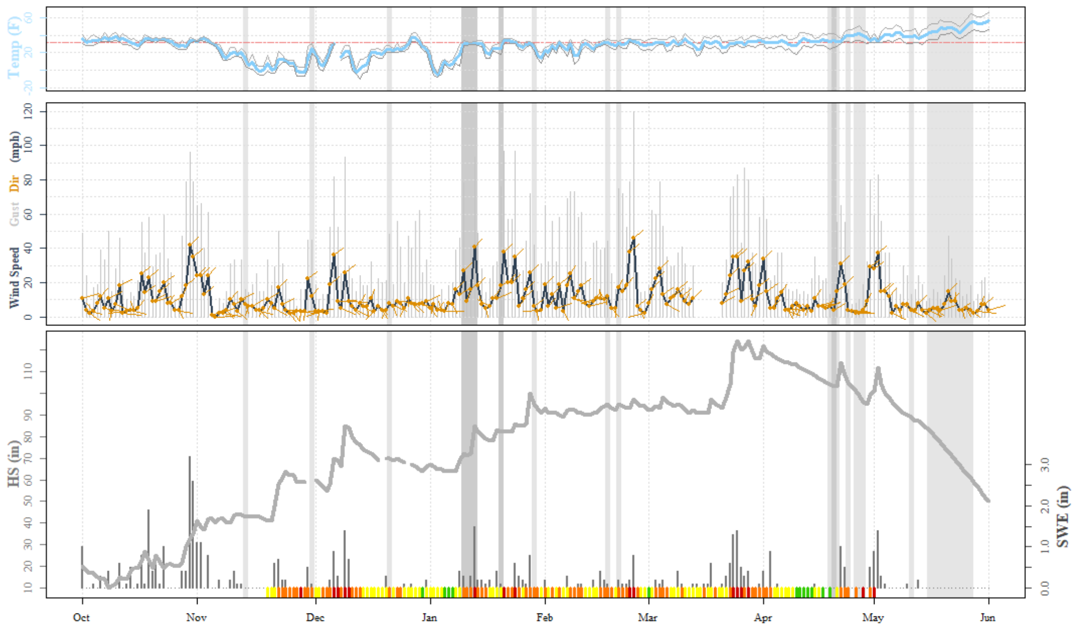

Figure 3: Season weather history for Turnagain Pass. The data includes temperature (top), wind (center), and snowfall (bottom). Wind data come from the Sunburst weather station (el. 1162 m [3812 ft]), while temperature and snowpack data come from the Center Ridge SNOTEL.

4.1 Early winter

Avalanche activity on the facets above the Halloween crust began in late November when a series of storms brought 1-1.2 m (3-4 ft) snow, equaling around 80 mm (3 in) SWE in a little over a week. The snow fell on a thick layer of faceted snow that formed during the previous nine days of clear skies and cold temperatures and sat on top of the Halloween crust. This snow was low density (8.0 % on average) and initially did not act as a cohesive slab. During late November and early December, Alyeska ski patrol triggered several large avalanches during early season control work. The first abnormal avalanche foreshadowing the coming cycles was a D2 avalanche failing on the early November facet layer on November 30. It was initiated from approximately 3/4 of the way down the slope by the fifth skier on slope, after ski patrol had finished ski cuts. The slab was very low density, and the estimated slope angle was 30 degrees on average. During the same day, multiple explosives were deployed on steeper, higher-elevation slopes on the South Face, producing zero avalanches. After more loading, these higher paths would eventually release large avalanches failing on the Halloween layer.

Outside of the ski area, on December 2, there were three large natural avalanches in the Kern Creek area near milepost 86.5 on the Seward Highway south of Girdwood that connected across multiple terrain features. Later that same day, there were seven recorded human-triggered D2-D3 avalanches on Turnagain Pass in both the motorized and non-motorized zones. The biggest of these were two skier-triggered D3 avalanches that were 60-120 cm (2-4 ft) deep and over 300 m (1000 ft) wide. Luckily, in both incidents, the skiers were able to self-arrest before getting carried for the entire path. During this cycle, it is unclear whether the Halloween crust played a significant role because the bed surface was 10-15 cm (4-6 in) above the crust within the recently buried November facet layer, which was 25 cm (10 in) thick. Persistent Slab or Deep Persistent Slab was either Avalanche Problem 1 or Avalanche Problem 2 on the CNFAC public avalanche forecasts from November 26 until December 29, when the New Year's crust formed with cooling temperatures after a rain/rapid warm-up.

Over the following two weeks, ski patrol triggered multiple large, deep avalanches, deploying multiple 11 kg (25 lb.) Ammonium Nitrate Fuel Oil (ANFO) shots in addition to regular control work with artillery and hand charges. They triggered another noteworthy avalanche during control work on the morning of December 10, opening day, when an air blast triggered a 2 m (6 ft) deep crown on the First Point path on the South Face. With strong winds and significant loading the night before, the ski patrol had decided to use explosives on this slope, which is more commonly mitigated with ski cuts. A steeper portion of the slope had been released during previous control work in the preceding weeks, but this lower-angle pocket higher up on the slope still had enough volume to produce a large avalanche.

4.2 Mid to Late January

The first major loading event on the New Year's layer came during January 10-14 with a system that brought 75-90 mm (3-3.5 in) SWE to Turnagain Pass and 100-130 mm (4-5 in) SWE to Alyeska. The storm came in two main pulses, one on January 10 and the second on Jan.13. Heavy precipitation rates were accompanied by sustained easterly winds of 65-100 km/h (40-60 mph) and gusts of 130-145 km/h (80-90) on Jan. 13-14. This storm system led to a widespread D2-D2.5 natural cycle. The Headstone avalanche path below Max's Mtn. at Alyeska was the only known avalanche that stepped down to the November facet layer/Halloween crust, with the majority of the activity failing on the New Year's crust interface. The deeper pocket on the Headstone path was triggered when a shallower storm slab released in a higher start zone and poured over a cliff, impacting the slope below and stepping down to the deeper Halloween layer. The step-down occurred right in the middle of the problematic elevation band at approximately 600 m (2000 ft).

During an artillery mission on Jan. 15, Alyeska ski patrol triggered one D3 avalanche and multiple D2s, with only one avalanche failing on the New Year's crust and the majority of the activity failing on a mid-storm interface. They noted that during the strong winds on Jan. 14, they were able to trigger fresh wind slabs 30 cm (12 in) deep with ski cuts that were reloading every 30 min through the day. The paths along the Seward Highway also saw widespread activity during this cycle, including natural avalanche activity on Jan. 13 on the Kern Creek paths between milepost 86.6 and 86.8 just south of Girdwood where a powder cloud dusted the road. Another avalanche on the Dogleg path (mile 97.8) just north of Girdwood ran to sea level but stopped short of the road on the same day.

Natural and human-triggered activity subsided quickly following the Jan. 10-14 loading event, with the exception of one skier experiencing shooting cracks while touring on Raggedtop Mtn. in Girdwood on Jan. 16, which they suspected were propagating along the New Year's crust. Backcountry skiers began stepping out into higher-consequence terrain during the following week, and on Jan. 20, a group triggered a D2.5 avalanche failing on the New Year's crust on the north side of Tincan Proper in Turnagain Pass while boot-packing up the last steep pitch along the ridgeline. The person was able to step off the moving slab, which was 60-150 cm (2-5 ft) deep, and ran 600 m (2000 ft) through high-consequence terrain all the way to the valley floor. It is suspected that this slope had been recently loaded by strong easterly winds, with sustained speeds of 50 km/h (32 mph) and gusts as high as 156 km/h (97 mph) recorded that day on the nearby Sunburst weather station just one ridgeline to the south of the incident.

The next major weather event came on Jan. 28, when a storm delivered roughly double the predicted precipitation, with 35-55 cm (14-22 in) snow equaling 36 mm (1.4 in) SWE at Turnagain Pass and 60-90 cm (24-36 in) snow equaling roughly 76 mm (3 in) SWE in Girdwood and in the Portage and Placer Valleys. This led to a widespread natural avalanche cycle with D2-D3 avalanches failing at the new/old interface. That day, a natural avalanche on the Dogleg path along the Bird Flats section of the Seward Highway just north of Girdwood produced a natural avalanche that failed 2.5-3 m (8-10 ft) deep. This marked the third time that path had run since the New Year's crust and facets formed. The start zone for the path is very difficult to access, and it is unclear whether this avalanche failed on the New Year's or Halloween layer. Alaska DOT&PF had conducted an artillery mission three days earlier without any noteworthy results.

On Jan. 29, Alyeska ski patrol triggered an avalanche with a 1.8 kg (four lb.) air blast that failed all the way down to the Halloween crust, now 2.5-3 m (8-10 ft) deep and resulted in a D3 avalanche. Patrollers were able to access the crown in the following days and identified the Halloween crust/facet layer at the failure interface (Figure 4). The layer that failed was a 20 cm (8 in) thick, 1F+ hard layer of 2 mm rounding facets sandwiched between P to K hard layers. The New Year's crust layer, along with residue from previous avalanche control missions, was visible in the crown profile. The last avalanche known to have released on this Halloween layer at the ski area had occurred on December 24th.

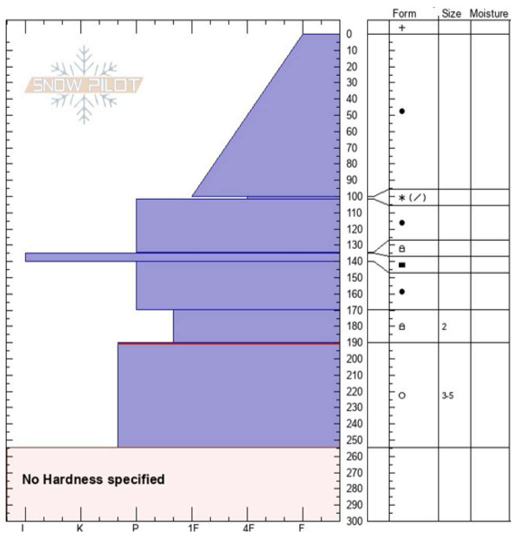

Figure 4: Crown Profile of the Jan 29 avalanche in Alyeska's Christmas Chute. The avalanche failed on the 1F+ hard layer of rounding facets at 170-190 cm. Halloween crust is 190-250 cm, and New Year's crust is 135-140 cm.

4.3 Late February

The weather was quiet for the first part of February, with consistent systems bringing 8-15 cm (3-6 in) snow at a time and light to moderate winds and providing great skiing and riding conditions without producing major avalanche activity for most of the month. The first big storm system of the month occurred during the week of Feb. 11-18, favoring Girdwood over the rest of our forecast zones with 66 mm (2.6 in) SWE recorded at the Alyeska mid-mountain weather station. This ‘system’ actually consisted of five loading events during that week, the largest of which brought 28 mm (1.1 in) SWE overnight on Feb. 17, along with sustained winds of 20 mph with gusts around 40 mph. The storm approached the area from the southwest, favoring the mountains between Girdwood and Anchorage over Turnagain Pass.

At around 3 a.m. on Feb. 18, a natural avalanche at mile marker 91.5 just north of Girdwood hit the Seward highway, putting 3-4.5 m (10-15 ft) debris on the road. A subsequent artillery mission that morning resulted in multiple D3 avalanches, including one on the adjacent path at mile marker 90.8 that crossed a bike path and made it to the road, and two more between mile markers 93 and 94. One of these destroyed a section of a Chugach Electric Association distribution line, and both left debris piles at that same elevation on the bike path measuring 6-9 m (20-30 ft) deep. This was the first artillery mission for that stretch of highway for the season. When the skies cleared on Feb. 19, the Alaska Division of Geological and Geophysical Surveys (ADGGS) was able to execute an airborne lidar survey and obtain high-resolution photos documenting the extent of the cycle (Figure 5). The effort revealed crown depths up to 4.5 m (15 ft) deep and fractures stepping down to multiple deeper layers in the snowpack. Both of these observations indicate the cycle involved new snow as well as both of the problematic crust layers. Crown lines from several avalanches connected multiple terrain features, some of which propagated 450 m (1500 ft) wide or wider.

Although there was a widespread natural cycle north of Girdwood and in Turnagain Pass during this same time, the paths along the Seward Highway near Girdwood were the only paths that produced avalanches stepping down to deeper weak layers in the snowpack. The next major event came three days later, on Feb. 21, when a storm brought 56 cm (22 in) of snow, equaling 50 mm (2 in) SWE to Girdwood. The load triggered a natural D3 avalanche in the Crow Creek area. Debris from the avalanche crossed the creek, and the powder cloud hit a house in the Crow Creek neighborhood. CNFAC forecasters accessed the crown of the avalanche two days later and determined the avalanche failed on facets below the New Year’s crust (Figure 6). The avalanche was an estimated 1-1.5 m (3-5 ft) deep, 200 m (700 ft) wide, and ran 600 m (2000 ft) vertical. There was evidence of a

Figure 5: Photograph of an artillery-triggered avalanche during the Feb. 18 mission. Note the wide propagation connecting multiple start zones and multiple layers involved. Photo: Katreen Wikstrom-Jones/ADGGS, 02.19.2022

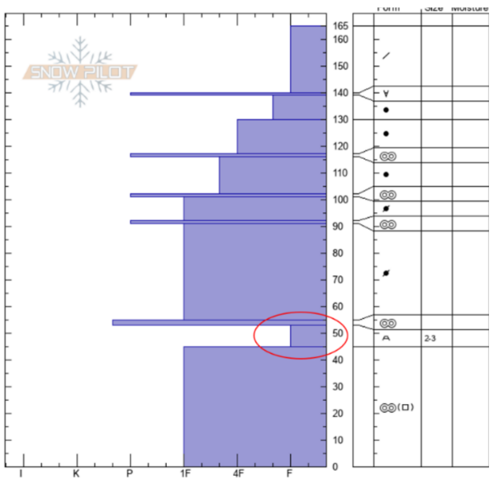

Figure 6: CNFAC crown profile from the Feb. 21 avalanche on Goat Mtn. in the Crow Creek drainage. The New Year's layer, responsible for this avalanche, is circled in red.

larger avalanche in the adjacent Gulch Creek drainage that ran in the middle of the storm and was likely bigger than the avalanche that crossed Crow Creek.

4.4 <u>March Madness</u>

Following the late February cycle, the New Year’s and Halloween layers were to remain dormant until the snowpack began its springtime transition in late April. Although it did not involve either of the layers that are the focus of this case study, there was one cycle during March 22-25 that cannot be overlooked in considering the noteworthy events of this season. A storm that began on the afternoon of March 22 delivered around 100 mm (4 in) SWE in just over three days, including a 24-hour period of 64 mm (2.5 in) SWE, during which we recorded precipitation rates of up to 10 mm (0.4 in) SWE an hour at the Turnagain Pass SNOTEL site. This storm left 1-2 m (3-6 ft) of snow on top of a widespread layer of surface hoar, leading to a natural cycle with multiple D4 avalanches propagating up to 610 m (2000 ft) wide and connecting multiple aspects. Remarkably, in surveying the aftermath of this impressive cycle, we did not observe any avalanches stepping down to the deeper weak layers that are the focus of this study. It seems the more fragile surface hoar layers broke before the crust layers did, and somehow the load was not enough to trigger the deeper crust/facet layers.

4.5 Spring meltdown

A springtime glide cycle began between April 9 and 11, with multiple glide avalanches observed in the area as sunny skies accompanied mild temperatures with daytime highs just above freezing at ridgetop elevations. Despite seeing continued glide activity for several days, it wasn't until April 19 that we began to observe wider-propagating slab avalanches failing on the New Year's and Halloween crust layers. We observed one large wet slab avalanche in the Crow Creek area on Magpie on April 19, followed by a very wide-propagating avalanche on Gulch Creek near Turnagain Pass on April 20, which was followed by another very wide-propagating avalanche on Girdwood's Raggedtop on April 21.

Between April 22 and early in the morning on April 24, the Turnagain Pass SNOTEL station recorded 64 mm (2.5 in) SWE, with observed rain levels as high as 600 m (2000 ft) by the end of the storm. The storm dropped 45-75 cm (1.5-2.5 ft) of snow at elevations above 760 m (2500 ft). Avalanche activity ramped up as warm temperatures were accompanied by clear skies from April 24 to April 28, with above-freezing temperatures to ridgetops. We observed widespread D3-D4 wet slab activity from Girdwood through Turnagain Pass to Summit Lake. At this point, it seemed that essentially everything that hadn't run previously in the season ran during this window. The avalanche activity was a combination of wet slab avalanches initiating on the New Year's and Halloween crust layers, as well as glide avalanches releasing first to the ground and pulling out much wider adjacent pockets failing on either of the two crust layers. It wasn't until April 29, when we began to see temperatures freezing overnight, that the glide/wet slab cycle began to slow down.

On the afternoon of April 24., a group of four snowmobilers were descending the popular Seattle Ridge area at Turnagain Pass at around 1700h when a glide crack released roughly 150 m (500 ft) wide, pulling out a wet slab on the Halloween facet layer roughly another 150 m (500 ft) wide (Figure 7). All four riders in the group were on the slope when the glide crack released. The first and last riders in the group were able to ride off the slab. The third rider in the group was thrown from their machine and came to rest on top of the debris near the right flank of the avalanche. The second rider in the group was caught, carried, and nearly fully buried, with one hand free enough to clear a small air space and punch through to the surface. Roughly two hours after the incident, another section of the slope failed on the Halloween layer, approximately another 150 m (500 ft) wide. To our knowledge, this was only the second recorded glide avalanche in the U.S. involving people. In April 2001, there was a fatal glide avalanche accident in Utah. Following the late April cycle, we observed large avalanches on Turnagain Pass again on May 11 and another cycle that lasted over a week between May 16 and May 27.

Figure 7: Aerial photo of the Apr. 24 Seattle Ridge avalanche. Photo: Michael Lindeman

5. DISCUSSION

5.1 Weather factors contributing to events

For the major avalanche cycles highlighted in sections 4.1-4.4 above, loading was the biggest factor leading to the onset of avalanche activity. While new snow loading also played a role in some of the activity in the spring cycles noted in section 4.5, warming likely played a bigger role for those late-season wet slab cycles. 24- and 72-hour SWE totals prior to each avalanche cycle were unremarkable for the most part– that is, there were many storms of equal or larger magnitude that did not result in any avalanche activity on the layers of concern (Figure 8). Similarly, while most of these cycles occurred during windy periods, there were many other windy days that did not impact these deeper weak layers (Figure 3). The lack of a noticeable trend in storm intensity helps to explain why some of these avalanche cycles were difficult to predict. However, by considering the cumulative SWE load since the previous avalanche cycle, we are able to gain a little more insight (Figure 8). This is one topic that comes up regularly in discussions during periods when we are dealing with a challenging, persistent weak layer. In hindsight, this was the key factor in predicting the February 18 cycle. Forecasters had been anticipating increasing likelihood as relatively small storms continued to load a problematic snowpack, and were waiting for a big enough load to tip the scale and make for a productive artillery mission.

After the initial cycle on the Halloween crust, we find relatively small 24-hour loading events– on the order of 6-13 mm (0.25-0.5 in) SWE– were enough to tip the scales of instability, after the snowpack had seen incremental loading amounting to between roughly 50-76 mm (2-3 in) SWE during the previous weeks. For the New Year's crust/facet layer, this cumulative loading threshold was even smaller, with avalanche activity observed consistently after cumulative loading totals approached 25-38 mm (1-1.5 in) SWE. In the absence of any other useful metric to predict instability, this cumulative loading threshold can provide some insight when dealing with a difficult-to-predict layer. It can provide a basis of support for an extra layer of caution when an otherwise unremarkable storm is approaching that may be problematic if cumulative loading is approaching a threshold that has produced avalanches previously in the season.

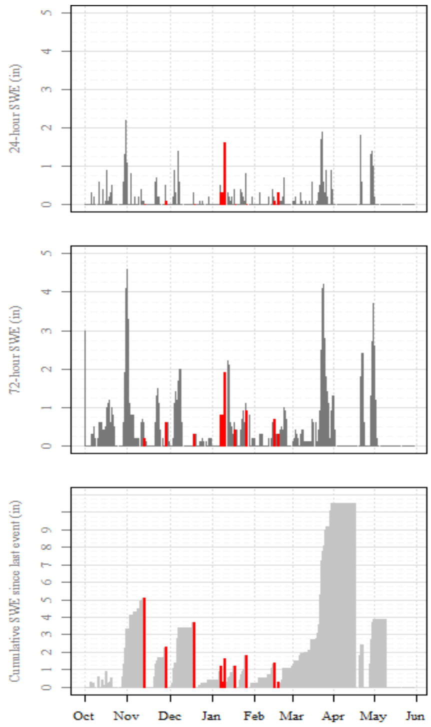

Figure 8: 24-hour SWE totals (top), 72-hour SWE totals (center), and Cumulative SWE since the previous avalanche cycle (bottom). Days with avalanche activity on either crust layer are highlighted in red.

5.2 Complicating snowpack factors

For the Halloween layer, the poor structure was very well-connected across terrain for a fairly tight elevation band (450-900 m or 1500-3000 ft). The layer was thick, with a stout crust and a 20+ cm (8 in) layer of facets on top, roughly double the 10 cm thickness threshold that would designate it as a snowpack 'lemon'. The layer took nearly a month to become reactive, as low-density snow continued to stack up on top of the layer without producing major avalanches. The New Year's layer formed from sea level all the way up to roughly 2100 m (7000 ft) elevation– essentially the upper limit of any terrain that is accessible without flying. This produced another very uniform low-friction layer across start zones, tracks, and runout zones. With facets above and below the crust layer, we would eventually see very large avalanches failing on top of the crust as well as below the crust. At the lower elevations (~ 500 m or 1700 ft), the crust and facets were reactive to small loads and extremely soft slabs. Slightly uphill it took a larger cumulative load and more substantial slab to initiate failure on the persistent weak layers. This change in sensitivity occurred within a very tight elevation band. Even though the weak layers appeared to have a very uniform distribution across the 450-900 m (1500-3000 ft) elevation band, they appear to have developed just differently enough to require different cumulative loads for essentially the same structure.

5.3 Mitigation measures and tracking activity

For the operations with artillery programs, shooting early in the season and shooting often was essential in reducing the potential size of avalanches failing on these persistent weak layers, as well as reducing the geographic distribution of the problematic weak layers. Coupled with the strategy of increased artillery work was thorough tracking of which paths had produced avalanches on the weak layers, and which paths still had a slab of growing depth on top of those layers. At Alyeska, the Snow Safety team thoroughly mapped on Google Earth all avalanches that had released on this layer, making a usable visual tool for terrain management. Areas where the problematic layer was removed through mitigation efforts were open to the public. Slopes that had not released were treated with added caution. Even this method showed its flaws, with the release of the previously mentioned Christmas Chute avalanche (Figure 4) from a small pocket harboring the Halloween layer.

5.4 Public messaging and danger ratings

In the period between Halloween and New Year's Eve, the only day where CNFAC dropped all three elevation bands to Low danger was Dec. 30– after the supportable New Year's crust had formed to ridgetops and with only 5 mm (0.2 in) SWE over the previous week. Following the burial of the layer of facets on top of the New Year's crust, the danger would not drop to Low again until March 1. This was after four days of no precipitation, which was preceded by a storm that brought 28 mm (1.1 in) SWE and did not produce avalanches on either of the persistent weak layers. Following the early March dry spell, the danger would not drop to low again until mid-April, after six days with only 2.5 mm (0.1 in) SWE and minimal avalanche activity confined to new and windblown snow. CNFAC uses a checklist as a prompt to discuss whether it is appropriate to drop to low danger with a persistent weak layer. Key points on the list include the avalanche activity, new snow, and wind events over the previous seven days. We also consider the extent of backcountry traffic over the previous week and will typically not drop to Low danger if we are expecting large crowds following a relatively quiet period. We will only drop to Low if all of the CNFAC forecasters reach a consensus.

In addition to challenges associated with dropping to Low danger, there were multiple periods when CNFAC forecasters struggled to choose between Moderate and Considerable danger ratings. In every instance where we were conflicted, the challenge was centered on justifying the 'Likelihood' and 'Travel Advice' sections of NAPADS. We ended up placing much more weight on the travel advice and much less weight on the likelihood. There was one instance where we favored the likelihood over travel advice, dropping the danger to Moderate two days after a loading event that did not produce natural avalanches. After two days of Moderate danger and no loading, motorized and non-motorized users began to "step out," triggering multiple very large avalanches (see section 4.1 above). We realized we had underestimated the likelihood of triggering an avalanche, and adjusted the danger back up to Considerable the following day. Although it was difficult to make that move without a loading event, it seemed appropriate given the string of avalanche activity, and was well-received by the public.

5.5 *Aerial support*

Like many other areas exposed to avalanche hazard, we often find it difficult or dangerous to access start zones to investigate crowns immediately following avalanche activity. This season was no exception, although we are lucky to have crown profiles from at least three major cycles, which gave us the evidence we needed to determine which layer was responsible. For the Feb. 18 cycle (section 4.3), the data obtained during the ADGGS airborne lidar survey immediately following the event was vital in assessing crown depths and observing multiple layers involved in many of the avalanches. In events following this cycle, we have been able to obtain similar information using Unmanned Aircraft Systems (UAS). The utility of UAS cannot be overstated. The combination of improved information and an almost complete reduction in avalanche exposure to avalanche professionals makes UAS incredibly valuable as an information-gathering tool. In addition to the assistance provided by ADGGS and other local UAS operators, we also work closely with Chugach Powder Guides, a heli-skiing operation whose tenure overlaps with the operations involved in this case study. The company operates daily through mid and late winter and is incredibly helpful in sharing photos and observations regarding the size and extent of avalanche activity in the area that we would not otherwise be aware of.

6. CONCLUSION

Ongoing collaboration between multiple avalanche operations improved our ability to manage a challenging season. This included formal information sharing during regular meetings with avalanche workers from all of the avalanche programs in the area, as well as informal communication through phone calls, emails, and early-morning text messages when things were falling apart.

We were faced with difficult operational decisions that affected each operation slightly differently. While the exact timing of some of these events was difficult to predict, we did walk away with some useful lessons. Increased active mitigation and diligent avalanche mapping enabled us to reduce the geographic extent of weak layers and have a good idea of the terrain that was still harboring a dangerous snowpack. Cumulative loading proved to be the strongest predictor of avalanche activity, but it was not always clear what amount of load would push the snowpack to its breaking point. With more research aimed at tracking cumulative loads, PWL/slab types, and associated avalanche cycles, trends may start to become apparent and usable benchmarks for forecasting. This case study documents an important cycle, with the goal of sharing some of the challenges and lessons learned while dealing with a difficult season.

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