

## DECISION-MAKING AND AVALANCHE MITIGATION DURING A RAPID ONSET WET SLAB AVALANCHE CYCLE

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**ABSTRACT:** Although all avalanche types are difficult to forecast and mitigate, wet slab avalanches are particularly problematic. The dynamics of wet slabs are poorly understood and large wet slab cycles are relatively rare in comparison to dry slab cycles. We provide a case study of a historic wet slab cycle at Crystal Mountain Ski Area in Washington State in March of 2014. This cycle resulted in numerous large natural and explosive-triggered avalanches, including one particularly notable slide that destroyed a 34-year old chairlift and had an alpha angle of only 20°. The avalanches occurred after a brief period of warming followed by rain. Though the amount of precipitation (1.4 inches or 36 mm) on the preceding day was not atypical for this location, we believe the existing snow structure was a key contributing factor to the avalanches. The snowpack contained numerous crusts and layers of facets near the base due to a lack of early-season snowfall, and a deep and relatively homogenous slab formed by a 10-day storm that dropped 12' (3.6 m) of new snow. Water penetration through the slab progressed much more rapidly than expected, perhaps due to the homogeneous nature of the slab. We discuss the snowpack evolution, contributory weather factors, operational challenges, mitigation efforts (including whether or not to use mitigation), and difficult decision-making that allowed the risks of this avalanche cycle to be managed without loss of life. A thin margin for error existed in this event, and we hope other practitioners can learn from our case study.

**KEYWORDS:** avalanche forecasting, avalanche mitigation, decision-making, risk management, wet slab avalanches

### 1. INTRODUCTION

In March of 2014 Crystal Mountain, Washington experienced a historically large avalanche cycle. Low early season snowfall led to a snowpack susceptible to full-depth avalanching. Large storms subsequently built up a sizable slab, and a moderate rain and snow event was enough to tip the balance. The resulting avalanche cycle consisted of numerous full depth wet slab avalanches, some running unexpectedly large and long. This paper outlines the weather and snowpack leading up to the avalanche cycle, the avalanches that occurred, and the operational decision-making and risk reduction that allowed the ski patrol to manage this large event with no fatalities or injuries.

### 2. WEATHER AND SNOWPACK SUMMARY

Crystal Mountain's 2013-2014 season began on October 1st with a limited 1 day opening of skiing off of the Gondola after the upper mountain

received 50 cm (20 in) of snowfall. It was billed as "Rocktoberfest". October continued with sporadic light snowfalls and cold temperatures, resulting in a shallow faceted snowpack. In early November a warming and rain event (34 mm) resulted in free water infiltrating the full depth of the snowpack in many areas. However, the faceted grains at the ground or near thin crusts survived that rain event in many of Crystal Mountain's upper elevation starting zones (Figure 1).

Crystal opened November 11th but low snow limited skiing to Green Valley, an upper elevation area of the mountain. The ski area was not fully opened until December 4th.

Precipitation was well below average through February 8th with only 280 mm (11 in) of SWE on the ground at Crystal's Green Valley Weather plot (1828 m, 6000 ft). Soon after that Crystal experienced sizable snowfall, resulting in a major dry deep slab avalanche cycle beginning on February 17th. Heavy snow on the 18th with 65 mm (2.5 in) of SWE followed by additional 40 mm (1.5 in) of SWE on the 19<sup>th</sup> led to many artificially-triggered avalanches. Several of these slides ran on facets at or near the ground (Figure 2). By Feb

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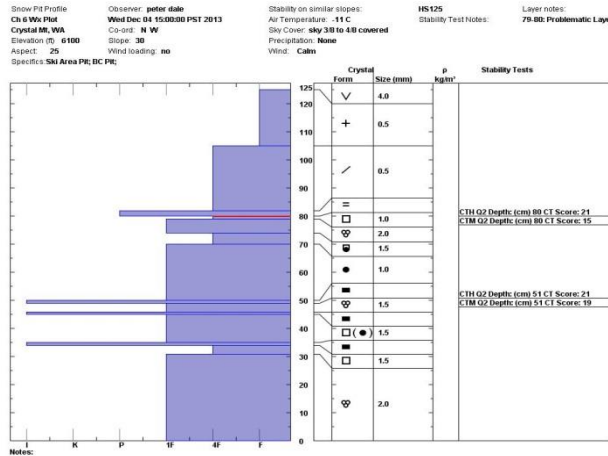


Figure 1: Snow profile (1860 m) from December 4th 2013 showing a relatively thin snowpack with buried thin crusts and facets.

25th the Cascade snowpack was just shy of the 20 year seasonal average for SWE.

The storm that ultimately initiated the wet slab avalanche cycle began with snow on March 3rd. By March 5th the temperature rose, resulting in a mix of snow and rain. By the morning of March 9th an estimated total of 75 mm (3 in) of rain had fallen at the Green Valley weather plot, with half of that total (37 mm) falling that morning. Located at an elevation of 1828 m (6000 ft), the Green Valley plot corresponds closely to Crystal Mountain's mid and upper mountain avalanche starting zones, which range from about 1800 to 2200 m (6000 to 7000 ft). Below our mid-mountain starting zones up to 130 mm (5.1 in) of rain fell during the cycle, which is important because some avalanches ran down these rain-soaked lower elevations. An example of this is the track of the Employee Housing path, which descends all the way to the valley floor at 1250 m (4100 ft).

Even though Crystal Mountain had received warming and rain over week long period prior to March 9th, the weather did not raise any major warning flags given our experience with previous rain on snow events. On the other hand, the snow structure was unique. This unique snowpack combined with relatively common weather conditions was enough to initiate a rapid onset deep wet slab avalanche cycle.

### 3. AVALANCHE SUMMARY

On the morning of March 9th teams conducted avalanche hazard reduction on the Rock Face path to test for wet slabs and to remove wet



Figure 2: Snowfall in February led to numerous dry deep slab avalanches.

surface snow. Explosive tests released a number of wet surface slides. Most notably, these efforts triggered one unexpected deep wet slab avalanche on an adjacent slope. Taking that anomalous result as a cue, Crystal Mountain kept most of its avalanche terrain closed in order to conduct more testing and hazard reduction. Control teams triggered five additional deep wet slabs on the 10th, including an avalanche on the *Employee Housing* path that ran 1 km (0.6 mi), fell 600 m (2000 ft) vertically, and took out a stand of mature timber (Figure 3).



Figure 3: On March 9<sup>th</sup>, the *Employee Housing* avalanche path destroyed mature timber while running just shy of the valley floor.



Figure 4: *The Throne* avalanche. Arrow shows location of lift terminal.

Following these results, Crystal Mountain Snow Safety personnel (including the senior author of this paper) elected to keep much of the ski area closed. Additional explosives triggered three more large deep wet slabs in areas closed to skiing. We limited testing to avalanche areas where teams could operate with a reasonable degree of safety. At the end of the day the ski area was completely closed and we tested additional avalanche-prone areas. At 4:45 pm a starting zone in an area called *The Throne* was shot with an 11 kg (25 lb) charge lowered on to the slope with a plastic sled. This triggered a deep wet slab avalanche (WS-AE-O-R4/5-D4) that heavily damaged the 34 year old High Campbell chairlift.

This large and destructive avalanche ran much farther and with more volume than had previously been observed. In fact, avalanches have only reached the Queen's Run ski trail (in the runout of *The Throne*) five times in the past 51 years. Those events resulted in only shallow deposits (<1 m, <3.3 ft) on the very edge of the trail. In contrast, the March 10th event fell 304 m (1000 ft) vertically and ran a distance of 629 m (2064 ft). This is 180 m (590 ft) farther than any slide previously observed for this path. Further, the slide deposited more than 0.4 hectares (1 acre) of debris up to 10 m (33 ft) deep. Our measured alpha angle of 20° further demonstrates the extent of this historically large slide (Figures 4 and 5). For example, although minimum alpha angles for extreme runouts in Alaska, the Sierra, Colorado, and

Norway are all less than exceed our value, average alphas all exceeded 19.8 degrees (Mears, 1988). Johnston and Jamieson (2010) looked at extreme runouts for 28 avalanche paths near Fernie, British Columbia and found a minimum angle of 19.8 and an average of 23.2 degrees.

#### 4. A "PERFECT STORM" FOR DEEP WET SLAB AVALANCHES

As mentioned previously, the warming and rain that led to this avalanche cycle were not exceptional weather events. However, the snowpack was unique, and we believe the snowpack structure played a key role in this event.



Figure 5: The two-story bottom terminal of the lift hit by the avalanche from *The Throne* on March 10<sup>th</sup>. The avalanche came from the right.

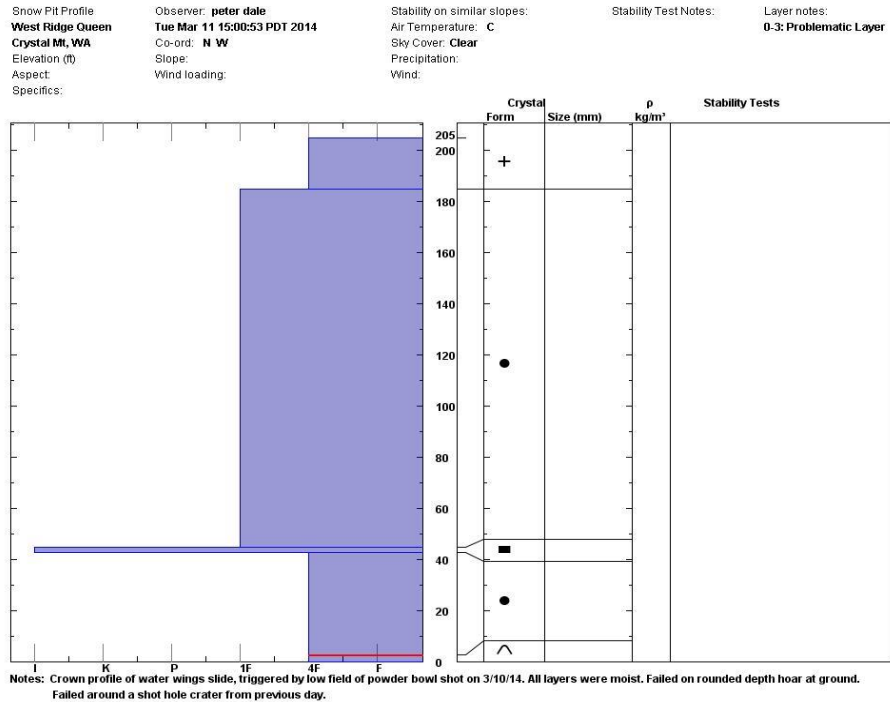


Figure 6: The snowpack at the time of the avalanche cycle consisted of a relatively homogenous slab over the top of a series of crusts and faceted layers.

The faceted layer that formed in October persisted on many high-elevation north-facing slopes. Faceted crystals have also been present during other documented large wet slab avalanche cycles (Reardon and Lundy, 2004). At lower elevations this layer was saturated with free water from the early November rain event, putting a solid crust near the bottom of the pack. When storms began in mid-February, some slopes released deep dry slab avalanches on the facets near with ground. However, other slopes did not release and the facets persisted in those locations. Another factor is that the slab was relatively homogenous and without many discernable layers since it essentially formed during a continuous three week storm cycle (Figure 6). We hypothesize that the lack of significant layering allowed water to quickly infiltrate the slab and travel to the weak layer. Thus, the slab and weak layer combination was a key factor in the rapid onset of instability despite a relatively common (for our area) warming and rain on snow event.

## 5. RISK MANAGEMENT AND DECISION-MAKING CONSIDERATIONS

Wet slab avalanches pose a particularly difficult forecasting challenge. Both our theoretical and

practical knowledge of wet slabs is relatively lacking compared to dry slabs. Though there are some case studies (e.g., Reardon and Lundy, 2004), little solid theoretical foundation exists. From a practical perspective, avalanche workers typically do not have much experience with wet slabs. While they often see multiple dry slab avalanche cycles every winter, they may only observed a sizable wet slab cycle once every five or 10 years. Yet, these cycles are important because they produce large, destructive, and long running slides. Because of the unknowns associated with wet slabs, Crystal Mountain Snow Safety regards them with a degree of increased uncertainty which is partially offset with the use of more frequent explosive testing.

This case study provides an opportunity to examine the decision-making utilized to manage the risks associated with this deep wet slab cycle. Though not this formally, members of the Crystal Mountain Ski Patrol, ski area management, and the lead author of this paper made the following risk analysis and decisions in this order:

### 5.1 Risk identification

On the morning of March 9th we tested for larger wet slabs on the Rock Face path due to the recent warming and rain on snow event. This is a large unsupported slope that has a history of producing large wet slabs during thaw events and is a classic indicator slope for wet slabs. We use four aerial trams for avalanche mitigation in this area, and we often deploy larger charges when testing for wet slab instability.

As expected, that morning several 11 kg (25 lb) charges on the trams produced wet slabs on Rock Face. What was unexpected was one deeper wet slab that ran sympathetically in an unusual release pattern. This unexpected avalanche demonstrated that we had a potential risk of deep wet slab avalanches.

### 5.2 Risk verification

We needed to determine whether this one deep release was an anomaly or if this was indicative of a bigger problem. Using a 25 lb. explosive charge lowered onto an adjacent slope that rarely produces avalanches due to skier compaction, we triggered another large wet slab on wet grains near the ground. This verified that we certainly had a significant deep wet slab avalanche risk.

### 5.3 Immediate risk reduction

Recognizing the risk of further high probability/high consequence events, we closed the majority of our avalanche terrain to limit the public's risk exposure. Crystal's avalanche terrain is compartmentalized with ropelines and gates for this purpose, and closures can be accomplished very quickly. This allowed us to "shrink the ski area" so we could focus on the problem at hand.

### 5.4 Determining the extent of the risk

Our next step was to determine the extent of the deep slab instability. In other words, "How bad is this?" The first slope we tested was an avalanche path called Employee Housing. This avalanche starting zone is immediately to the north of Rock Face and has a similar aspect and elevation. This path has the potential to reach structures in the employee housing area, though fortunately no structures have ever been hit. The first large shot was made while the visibility was very poor with fog and mist. When the release occurred it looked big, but we were unable to determine its true magnitude until we could hear timber breaking in the path below. This deep slab WS-AE-O-R4-D4

fell about 600 m vertically and ran about 1km. Since the next shot could potentially affect several homes in the employee housing complex, we fully evacuated the area. This shot produced another deep wet slab that joined the starting zone of the first release, but did not damage any property. We tested another closed avalanche area known as the Bear Pits, releasing several large deep wet slabs failing on moist rounds on top of a crust right above the ground. By the end of March 9th, we knew the answer to our question: conditions were clearly quite bad, perhaps worse than we had observed in the last several decades at the ski area.

### 5.5 Determining how to further reduce the risk over the long term

This was a critical decision. The two alternatives were:

- Close most or perhaps all of the ski area and make no attempt to reduce the hazard. We reasoned that a closure without hazard reduction would have left a continuing degree of uncertainty regarding the potential for deep wet slabs the rest of the season. A substantial amount of our expert terrain could have been closed indefinitely and there was also the immediate risk of natural deep wet slabs.
- Keeping most of the avalanche terrain closed and attempting to artificially release the deep wet slabs. We eventually chose this option, believing there was an opportunity to reduce the uncertainty and future risk at a time of high instability.

On March 10<sup>th</sup> poor visibility made it impossible to use using a helicopter for mitigation work. The challenge was to do the explosive work in a way that exposed the patrollers to minimum hazard. The *Powder Bowl* path was shot from the ridgeline early that morning and produced a large wet slab WS-AE -R4-D4-O with a 3.5 – 4 m (11 – 13 ft) crown running on an ice layer just above the ground. A rectangular pocket released sympathetically about 100m away failing on a layer of wet facets near the ground. This was a very atypical release (Figure 7).

Several additional paths were tested at the end of the day after the ski patrol had swept the hill. *The Throne* was shot with an 11 kg (25 lb) ANFO charge belayed onto the slope on a plastic sled. This released another very large wet slab (WS-AE-O-R4/5-D4) running just above the ground (Figure 8). This path received heavy ski



Figure 7: The Powder Bowl avalanche released on March 10<sup>th</sup>. The slide on the right was triggered sympathetically. New snow had fallen before this picture was taken.

compaction throughout the season, demonstrating that ski compaction does not eliminate the danger of full depth wet slabs. This is the avalanche that damaged the 34 year old High Campbell chairlift as described in the event summary. We continued extensive testing for the next several days, including extensive aerial blasting from a helicopter.

#### 5.6 *Reassessing the risk*

Most of the avalanche terrain had now either released or had been thoroughly tested. During the next several days a cooling trend helped stabilize at least the surface layers. By the following weekend we had most of the avalanche areas open. We continued to monitor the potential for deep slabs through the end of the season.

### 6. DISCUSSION

This event gives us an opportunity to apply our lessons learned to help forecast and mitigate future deep wet slabs cycles at Crystal Mountain, and possibly in other areas and snow climates:

- ❖ *The snow structure resulting from our atypical season played a significant role in this avalanche cycle*

Most of the deep wet slabs in this event released either on wet facets or polycrystals on crusts near the ground. The slab structure above the failure layers was relatively homogenous, with few of the strong crust layers that we typically expect throughout our maritime snowpack. We hypothesize that the relatively homogenous slab allowed rapid free water infiltration into the weaker layers below. This event reminds us that with wet slab avalanches we need to make sure to pay attention to the characteristics of the slab and not just focus on the weak layer.

- ❖ *Continual testing of the snowpack during warming and rain on snow events is critically important*

Deep wet slab avalanche cycles are difficult to forecast. We believe it is important to reduce uncertainty to a reasonable degree whenever we have the opportunity through explosive testing and artificial release. We test indicator slopes frequently when free water is present, particularly in the spring. Having an indicator path (such as the *Rock Face*) is useful for this purpose.

- ❖ *Wet slabs require using larger explosive charges for testing and hazard reduction*

We generally use either 11 kg (25lb) or 7 kg (16 lb.) charges for deep wet slab instability. We also



Figure 8: A sizable natural deep slab wet slab avalanche in the surrounding backcountry occurred concurrently with the avalanche inside the ski area. This is the Crystal Lakes basin, approximately 2.4 km from *The Throne* avalanche path.

deploy the charges in the air where possible using aerial bomb trams or a helicopter. Our experience is that smaller charges are not as effective in testing for and/ or reducing this deep wet slab instability.

- ❖ *During wet slab cycles, some paths may run much farther than expected.*

As discussed previously, the avalanche produced by *The Throne* path was surprisingly large, with an alpha angle of just 20 degrees. Similarly, Marienthal et al. (2012) report on a wet slab avalanche cycle at Bridger Bowl, Montana that also had a few large avalanches; one alpha angle measured by the second author of this paper was just 17 degrees. The size of the avalanche in *The Throne* has caused the Crystal Mountain Snow Safety team to question how far other paths like the *Employee Housing* path at Crystal Mountain might run.

- ❖ *Wet slab avalanches may run farther than predicted dry snow avalanche runouts*

Over the past 30 years at Crystal Mountain, the avalanches with the longest runouts have been wet slabs. Similarly, some of the largest avalanches observed at Bridger Bowl in the past

30 years have also been wet slabs. These observations run contrary to the conventional wisdom that even in a maritime climate the longest running (or “design”) avalanches are always soft slab/dry powder slides.

- ❖ *There is a risk associated with not attempting to reduce the hazard.*

Our decision to close much of the avalanche prone terrain and actively reduce the risk was based on years of experience and institutional knowledge. We have periodically observed wet slabs that have released naturally without any prolonged or dramatic warming “weather trigger”. In general, we have found that deep wet slabs have been resistant to explosive triggering. We have had cases where we have been unable to release the slabs with large charges only to find the next morning that the path had avalanched overnight. The risk of a natural deep slab avalanche occurring initially or a skier-triggered avalanche when the ski area was reopened was deemed too great. We did not want to live with this type of uncertainty for the rest of the season when we had an opportunity to reduce it at a time of peak natural instability.

Interestingly, a natural deep wet slab cycle did occur in the surrounding backcountry on March 10<sup>th</sup>, but it was not visible until the 11<sup>th</sup> due to poor visibility. Several large wet slabs ran on paths with similar aspects and elevations as the ski area. The closest avalanche released in Crystal Lakes basin, approximately 1.5 miles (2.4 km) to the south of *The Throne* (Figure 8). These natural avalanches graphically illustrate the potential risk of not attempting to reduce the hazard.

## 7. CONCLUSION

This rapid onset deep wet slab cycle was one of the worst seen by the senior author in 35 years of avalanche forecasting and consulting. We have added our understanding of the factors involved in this cycle to the institutional knowledge of the Crystal Mountain Snow Safety Program. The warming and rain was not remarkable for our maritime climate, but the associated snow structure was atypical. Based on weather factors alone, we failed to anticipate the rapid onset of the cycle and its magnitude. Fortunately our policy of continuous testing with explosives revealed the scope of the problem and allowed us to mitigate the risk to both the public and to Crystal Mountain employees. During this cycle, we made difficult risk management decisions without great choices. Given the severity of the situation, we made sure to involve Crystal Mountain's top management in our decisions. Though a chairlift was damaged, we are grateful we managed this extreme avalanche cycle with no injuries or loss of life.

## ACKNOWLEDGEMENTS

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