DEPTH HOAR, AVALANCHES, AND WET SLABS: A CASE STUDY OF THE HISTORIC MARCH, 2012 WET SLAB AVALANCHE CYCLE AT BRIDGER BOWL, MONTANA

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ABSTRACT: During this past winter, southwest Montana had many large avalanches and days of high avalanche danger. In the Bridger Mountains the most prominent and active weak layer was a 30-55cm thick layer of depth hoar. This layer developed in November 2011 and persisted throughout the season. Precipitation was below average between December and early February, but each storm consistently produced artificially triggered avalanches on this layer. Higher snowfall rates and above average SWE in late February and March produced natural avalanche activity in the backcountry on the depth hoar. In late March 2012 a near isothermal snowpack, combined with a period of above freezing temperatures and heavy snowfall, produced an historic skier triggered and explosive controlled full depth wet slab cycle on the depth hoar. This event occurred on in-bounds terrain that was closed at the time, and had previously been heavily skied and controlled with explosives. We will review meteorological and snowpack factors that were associated with avalanche activity on the depth hoar within Bridger Bowl ski area and in the surrounding backcountry. Weather data from stations at Bridger Bowl and snowpack observations taken throughout the ski area will be used to discuss the factors associated with the timing of avalanche activity on the depth hoar layer. Patterns, trends, and outcomes will be highlighted which may be of wider value to the industry in managing these types of instabilities in future years.

1. INTRODUCTION

The wet slab avalanche cycle on March 27th, 2012 at Bridger Bowl, MT was an historic event that underscored a season that had an above average number of fatalities and the most avalanche warnings issued in SW Montana since the Gallatin National Forest Avalanche Center (GNFAC) was founded in 1990 (Chabot et al., 2012).
This event resulted from a layer of depth hoar that formed in November, rapid warming, and possibly the loading, of an isothermal snowpack. Wet slabs can be one of the more difficult challenges for an avalanche forecaster, and the future likelihood of managing wet snow avalanches in an operational setting may increase with changing climate (Lazar et al., 2008; Peitzsch et al., 2012). This paper will review patterns and trends in meteorological data and snowpack observations that led up to the wet slab avalanche cycle on March 27th.

The avalanche cycle at Bridger Bowl on March 27th is fairly unique from events in previous studies in that the avalanches were in previously skier compacted and explosive controlled terrain, and seven separate wet slabs were triggered on the same morning across the entire ski area (Fig. 1). While Previous observations of deep slab events in skier compacted and explosive controlled areas suggest that it is rare to see more than one or two dry deep slab events during a cycle in skier compacted terrain (Savage, 2006; Comey and McCollister, 2008), it is not uncommon for many wet slabs to occur over the course of a 2-3 day cycle (Reardon and Lundy, 2004; Conway, 2005; Peitzsch et al., 2012). In fact, many wet slab events being concentrated across very few days (a single avalanche cycle) in a season is likely the rule rather than the exception.

In contrast to dry slab avalanches, which fail mainly from increased stress, wet slab failure is mostly dependent on a decrease in strength, and in some cases an increase in stress. The addition of free water to the snowpack is a significant part of this process (Kattelmann, 1984; Conway and Raymond, 1993; Reardon and Lundy, 2004; Baggi and Schweizer, 2009; Peitzsch et al., 2012). Meteorological variables suggesting introduction of water to the snowpack based on SWE loss or settlement, and sustained warming have been used to forecast conditions leading to wet slabs (Baggi and Schweizer, 2009; Peitzsch et al.,

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Figure 1: Overview of the location (black outlines), and order (1-6), of large wet slab avalanches that failed on the depth hoar layer on March 27th, 2012 at Bridger Bowl. All avalanches released within 4 hours of the first event at 0730. Snowpack observation sites are denoted with letters A-G (table 2).

2012). Conway and Raymond (1993) observed the majority of wet slabs to occur in the upper 30-50cm of the snowpack directly after the onset of rain (1-2hr) during rain-on-snow events, except when the snowpack was relatively stable before. They noted that avalanches that had a delayed response (up to 13hr) to rain were deeper and harder to predict. Weak layers, crusts, ice lenses, or capillary barriers (a significant difference in grain size between adjacent layers), that may impede water flow and allow water to flow along the layer boundary rather than through the snowpack, can contribute to wet slab formation. The presence of capillary barriers was useful for forecasting wet slabs in Davos, Switzerland, along with increased load on a weakened snowpack and days since the snowpack went isothermal (Baggi and Schweizer, 2009). Reardon and Lundy (2004) also note that wet avalanche activity peaks during the transition from winter to summer snow, which can similarly relate to days since the snowpack went isothermal. Reardon and Lundy (2004) describe wet slab avalanches that have a weak basal layer. While non-basal weak layers have also been observed as failure planes for wet slabs upon the interaction with free water, they are less frequently an issue in ski area settings due to the frequent disturbance of the snowpack (Kattelmann, 1984). However, some ski areas (e.g. Big Sky, Montana) often deal with deep weak layers that are not basal, and may persist through skier compaction and explosive testing into the wet slab season as a result of a seasonal snowpack structure of hard slabs capping weak layers (Savage and Buotte, Pers. Comm., 2012). Although the variables used to forecast wet slabs in these studies are likely limited to their respective study areas, they may be suggestive of the types of variables to watch for elsewhere.

2. STUDY AREA

2.1 Climate, Weather, and Avalanche Terrain

Data for this case study come from Bridger Bowl ski area between November 2011 and April 2012. Bridger Bowl is located 24 km northeast of Bozeman, Montana in the Bridger Mountains (Fig. 2). This area exhibits an intermountain avalanche climate (Mock and Birkeland, 2000). From 1984 to 2012 Bridger Bowl recorded an average annual snowfall of 637cm, snow water equivalent (SWE) of 47cm, and new snow density of 7.4% between November 1st and March 31st at the Alpine weather station (2280m a.s.l.).

The ski area is located on the east side of a north-south oriented ridgeline. Sixty percent of the ski area is avalanche terrain as classified by slope angle, with elevations between 2075m and 2677m, and an average aspect of 98°. Starting zones at Bridger Bowl are primarily between 2400m and 2677m. Much of the higher angle terrain is steep, rocky, and unable to retain snow, so there are very few starting zones steeper than 45°.

Daily meteorological data are manually recorded at 1600h by ski patrollers at the Alpine weather station located at an elevation of 2280m. Minimum and maximum air temperature, snow depth, new snow (24hr), and new snow water equivalent (SWE) for the 2011-2012 winter are presented in this paper. Snowfall increases with elevation, and significant differences in storm totals are often observed between starting zones and the weather station. Also, temperature is typically lower in higher elevation starting zones.

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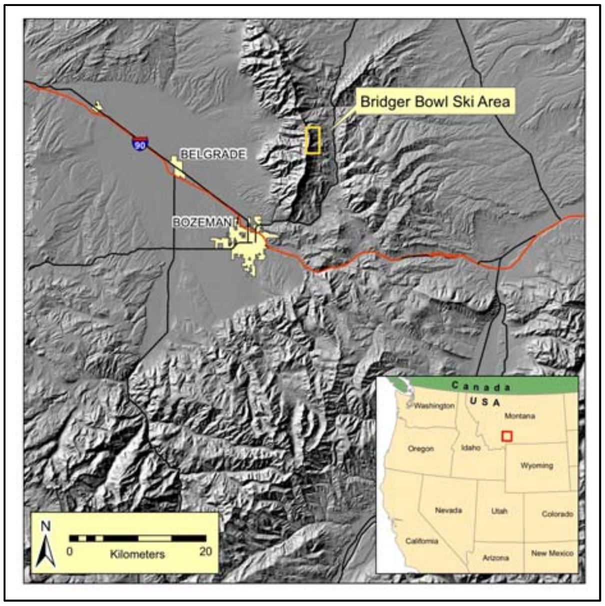


Figure 2: Location of study area in southwest Montana.

2.2 *Avalanche Records*

All avalanches that are triggered by explosives as well as any significant avalanches triggered by skiers or that occur naturally are recorded by Bridger Bowl ski patrol. These records were used as well as observations of natural and human triggered avalanche activity in the backcountry from the GNFAC archives.

Avalanche depth and layers involved are used in this study to determine when avalanches failed on the depth hoar layer. Avalanches that involved all layers, or were recorded as sliding to the ground, are considered to have failed on the depth hoar layer. Furthermore, the depth of each avalanche was subtracted from the total snow depth at the Alpine weather station and avalanches that exceeded a value 15cm less than the total snow depth, and were not recorded as failing in new snow, were used as events that failed on the depth hoar layer.

2.3 *Snowpack Observations*

Snowpack observations are from the records of the authors of this paper, the ski patrol, and the GNFAC. Observations were collected in areas that were considered to have snowpack and terrain characteristics similar to avalanche starting zones within and adjacent to the ski area. These areas were revisited until the depth hoar layer appeared to be disturbed and no longer representative of less disturbed and likely weaker areas. Observers recorded stability test results, snowpack observations for each layer, and site characteristics (Greene et al., 2010). Temperature profiles were taken in the spring as the snow became isothermal. Average hardness of the slab was derived by averaging the hardness, weighted by thickness, of each layer above the weak layer. A stability index was created, which is based on whether the weak layer propagated during any ECT test in that snowpit.

Height of the depth hoar is included because a number of stability tests are noted as failing on a layer of facets above the depth hoar layer. These layers are all considered part of the 2011-2012 depth hoar layer because the exact location of the failure plane varies throughout snowpits. During the winter of 2011-2012 these facets developed into depth hoar in most locations at Bridger Bowl, so it is appropriate to consider their early faceted forms as part of the depth hoar layer.

3. OBSERVATIONS

3.1 *Weather and Snowpack*

Snow depth at the Alpine weather station was 30cm on November 30th after receiving 60mm of SWE (58% of average) for November. From December 1st to 29th Alpine received just 26mm of additional SWE resulting in no significant increase in total snow depth (Table 1). Average temperature for both November and December was -3.3°C which is the historical average for November and 2.8°C above the historical average for December. Despite relatively warm temperatures, the shallow snowpack and cold dry clear nights typical of this area were enough to create a base of facets and depth hoar 20-30cm thick before the first significant snowfall began on December 30th (Table 1 & 2).

Total SWE for December was doubled in a single storm (from 26mm to 65mm) between December 30th and January 1st, yet reached only 68% of the historical average for the month. The snow depth at Alpine was 58cm on January 31st. Average temperature during January was -3.3°C, 2.8°C above average, but remained cold enough to allow for continued development of basal facets and depth hoar in the shallow snowpack (Table 1 & 2). Increasing thickness and grain size of the depth hoar layer, and development of overlying facet layers into depth hoar was observed from early January to early February (Table 2). Variability in and between the various areas of snowpack observations prevents any significant quantification of this development. However, the authors of this paper that observed this layer's development can confirm that it generally increased in thickness and grain size between early January and early February.

Precipitation rates picked up in early February and temperatures were some of the lowest of the season. Continued heavy precipitation over the last nine days of February brought the monthly amount of SWE to 134mm (168% of average). This trend continued between March 1st and 20th (Table 1). Snow depth at Alpine on March 20th marked the highest depth during the operational season. Snowpits at higher elevations show depths up to 210cm around this time with depth hoar still at the base of the snowpack (e.g. B Gully, Table 2). Fractures were hard to initiate in extended column tests due to the great depth of the slab, yet they produced sudden clean collapses on the soft depth hoar.

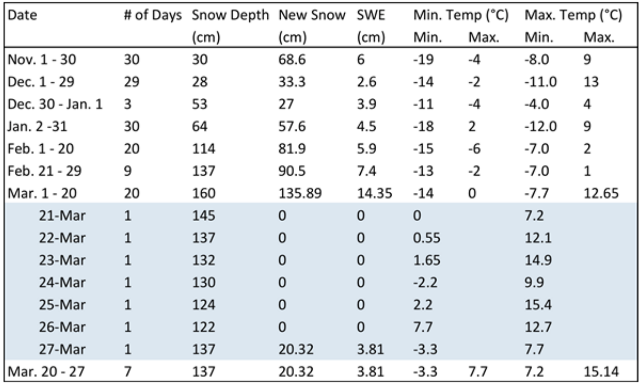
Average temperatures in March were 1.7°C (4.5°C above average). Minimum temperatures of 0°C were recorded on the nights of March 9th, 14th and 17th. The first occurrence of multiple nights with above freezing temperatures at the Alpine weather station began on the night of March 20th. Between March 20th and 25th there was only one night with below freezing temperatures, and on the night of the 26th temperatures dropped below 0°C and 38mm of SWE fell overnight (Table 1).

The exact date when the snowpack became isothermal was not documented. However, a snowpit dug on March 17th had measured temperatures less than -1.0°C in the middle of the snowpack, and a snowpit dug on March 24th, just meters above what became a large wet slab crown three days later, had a temperature of -0.1°C measured at 100cm below the surface, and slightly colder temperatures in the top 20cm of the snowpack (Fig. 3).

3.2 *Avalanche activity*

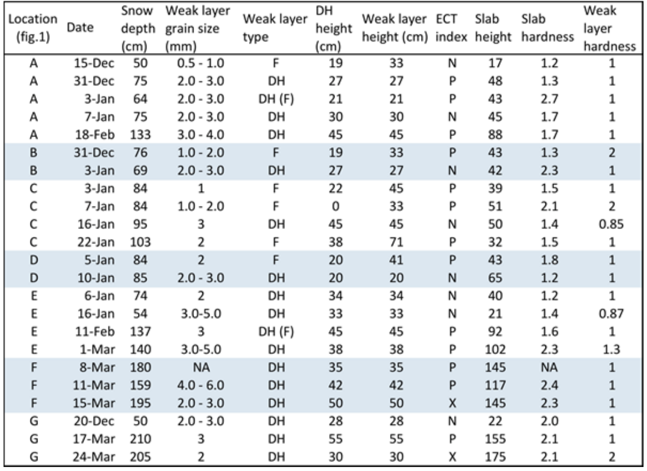
Small storms in mid-December were enough to create small artificially triggered avalanches on the depth hoar layer (Fig. 4). Enough snow fell on December 30th and 31st to create a dense slab that resulted in large artificially triggered slab avalanches on the depth hoar layer through January 6th despite no new snow after January 1st (Fig. 4a).

Table 1: Weather data recorded at the Alpine weather station from November 2011 to March 2012. Summarized by periods determined by storms, weak layer formation, or warming that are described in the text. Days directly preceding the wet slab cycle are shown individually.



Date	# of Days	Snow Depth (cm)	New Snow (cm)	SWE (cm)	Min. Temp (°C)		Max. Temp (°C)	
					Min.	Max.	Min.	Max.
Nov. 1 - 30	30	30	68.6	6	-19	-4	-8.0	9
Dec. 1 - 29	29	28	33.3	2.6	-14	-2	-11.0	13
Dec. 30 - Jan. 1	3	53	27	3.9	-11	-4	-4.0	4
Jan. 2 -31	30	64	57.6	4.5	-18	2	-12.0	9
Feb. 1 - 20	20	114	81.9	5.9	-15	-6	-7.0	2
Feb. 21 - 29	9	137	90.5	7.4	-13	-2	-7.0	1
Mar. 1 - 20	20	160	135.89	14.35	-14	0	-7.7	12.65
21-Mar	1	145	0	0	0		7.2	
22-Mar	1	137	0	0	0.55		12.1	
23-Mar	1	132	0	0	1.65		14.9	
24-Mar	1	130	0	0	-2.2		9.9	
25-Mar	1	124	0	0	2.2		15.4	
26-Mar	1	122	0	0	7.7		12.7	
27-Mar	1	137	20.32	3.81	-3.3		7.7	
Mar. 20 - 27	7	137	20.32	3.81	-3.3	7.7	7.2	15.14

Table 2: Snowpack observations.



Location (fig.1)	Date	Snow depth (cm)	Weak layer grain size (mm)	Weak layer type	DH height (cm)	Weak layer height (cm)	ECT index	Slab height	Slab hardness	Weak layer hardness
A	15-Dec	50	0.5 - 1.0	F	19	33	N	17	1.2	1
A	31-Dec	75	2.0 - 3.0	DH	27	27	P	48	1.3	1
A	3-Jan	64	2.0 - 3.0	DH (F)	21	21	P	43	2.7	1
A	7-Jan	75	2.0 - 3.0	DH	30	30	N	45	1.7	1
A	18-Feb	133	3.0 - 4.0	DH	45	45	P	88	1.7	1
B	31-Dec	76	1.0 - 2.0	F	19	33	P	43	1.3	2
B	3-Jan	69	2.0 - 3.0	DH	27	27	N	42	2.3	1
C	3-Jan	84	1	F	22	45	P	39	1.5	1
C	7-Jan	84	1.0 - 2.0	F	0	33	P	51	2.1	2
C	16-Jan	95	3	DH	45	45	N	50	1.4	0.85
C	22-Jan	103	2	F	38	71	P	32	1.5	1
D	5-Jan	84	2	F	20	41	P	43	1.8	1
D	10-Jan	85	2.0 - 3.0	DH	20	20	N	65	1.2	1
E	6-Jan	74	2	DH	34	34	N	40	1.2	1
E	16-Jan	54	3.0-5.0	DH	33	33	N	21	1.4	0.87
E	11-Feb	137	3	DH (F)	45	45	P	92	1.6	1
E	1-Mar	140	3.0-5.0	DH	38	38	P	102	2.3	1.3
F	8-Mar	180	NA	DH	35	35	P	145	NA	1
F	11-Mar	159	4.0 - 6.0	DH	42	42	P	117	2.4	1
F	15-Mar	195	2.0 - 3.0	DH	50	50	X	145	2.3	1
G	20-Dec	50	2.0 - 3.0	DH	28	28	N	22	2.0	1
G	17-Mar	210	3	DH	55	55	P	155	2.1	1
G	24-Mar	205	2	DH	30	30	X	175	2.1	2

From then until February 24th, very few, if any, avalanches were observed on the depth hoar until a skier triggered an avalanche on Saddle Peak to the south of the ski area. Two days later, a natural avalanche ran on the depth hoar layer near this same area (Fig. 4b). Avalanches continued to occur naturally on the depth hoar in the backcountry, and a large deep slab cycle on the morning of March 20th marked the last dry slab activity observed in the backcountry on this layer (Fig. 4c).

Wet slabs were observed in the backcountry as early as March 23rd when a snowmobiler triggered a slide 6.5 km north of the ski area near Ross Peak (Fig. 4d). Multiple wet slabs were recorded on March 26th including one spanning multiple paths directly north of the ski area boundary, and two on slopes near the slide recently triggered by a snowmobiler (Fig. 4e). Numerous wet slabs were triggered in the new snow on March 27th, and six historic wet slabs were triggered on the depth hoar layer (Fig. 1 & 4f).

4. DISCUSSION

Wet slab avalanche activity can occur when liquid water moves through the snowpack, and decreases the snowpack’s strength. However, wet slabs do not always occur when liquid water is introduced to the snowpack.

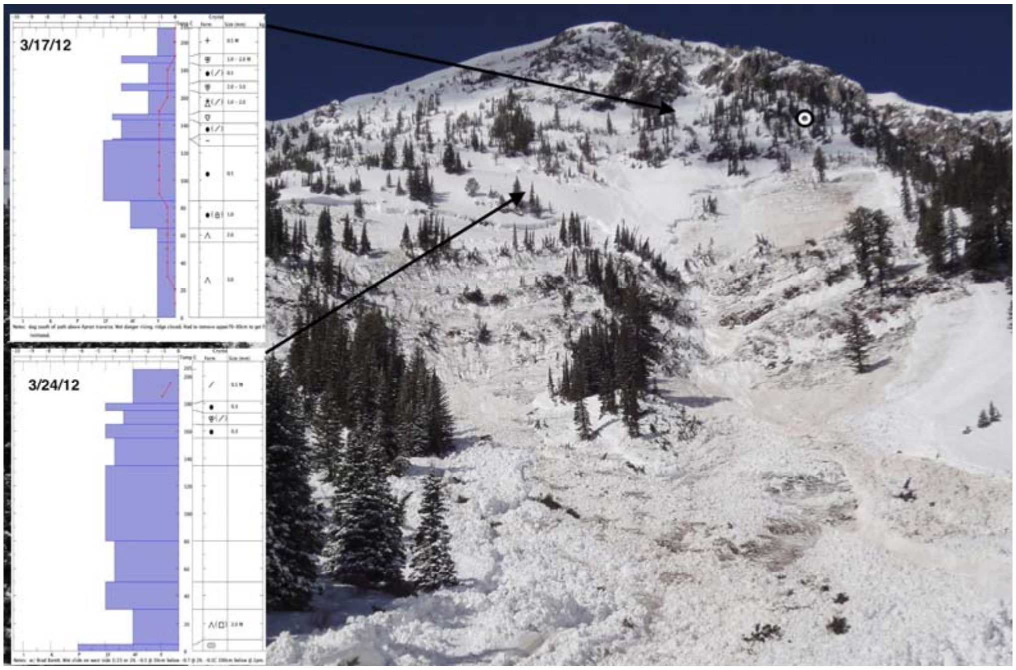


Figure 3: Crown of Bridger gully wet slab from 3/27, snowpit profiles (3/17, 3/24) and locations. White circle in upper right is the shot placement of 2 gallons of ANFO and two boosters (1.8kg) that triggered this slide. The crown is up to 2m deep.

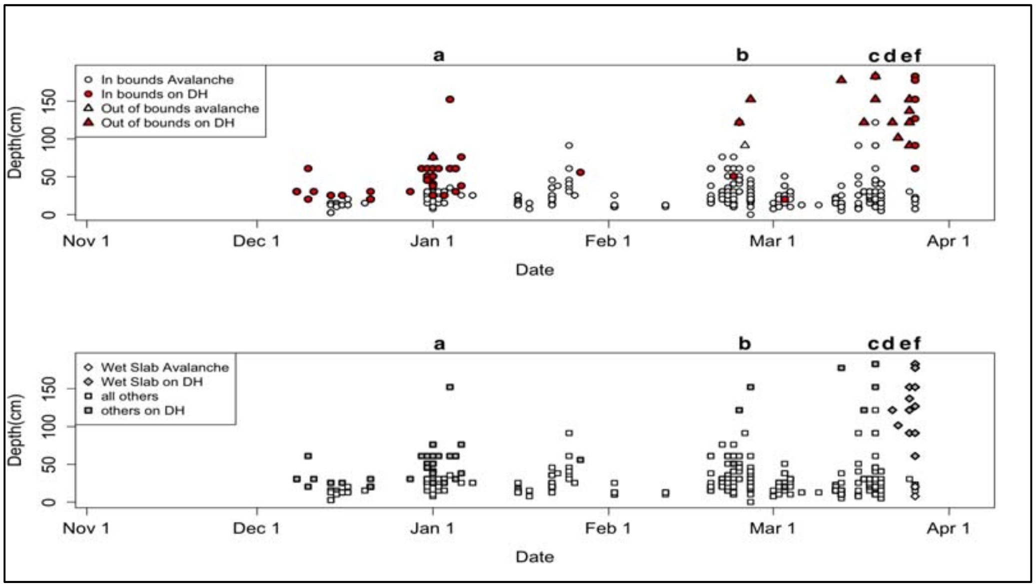


Figure 4: Avalanche depth, avalanches that slid on the depth hoar in bounds and out of bounds (top), and avalanches that were either wet slabs or not (bottom) during the 2011-2012 winter at Bridger Bowl. Main events described in the text are labeled a-f.

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The controlling factor is thought to relate to the development of vertical flow channels that allows water to flow through the slab, maintaining the slabs cohesive character, and pool at capillary barriers or crusts. If the right amount of water is introduced to the right snowpack structure at a rate that prevents it from flowing through a boundary layer, water will pool and run along this layer and a wet slab avalanche may be triggered (Kattelmann, 1984; Conway and Raymond, 1993; Reardon and Lundy, 2004; Peitzsch et al., 2012).

On March 27th, 2012 a 2m deep snowpack supported by an old layer of depth hoar provided an ideal structure for wet slab activity (Reardon and Lundy, 2004; Peitzsch et al., 2012). Depth hoar was observed below a warm snowpack on March 24th, 2012 at Bridger Bowl, with smaller grain size than previously observed, and was recorded as moist indicating wet snow metamorphic processes. The upper 40cm of the snowpack (wet grains and small rounded grains (0.5mm)) and the base of this snowpack (faceted grains undergoing wet snow metamorphism) showed similar characteristics to structures described in previous studies (Fig. 3) (Reardon and Lundy, 2004; Peitzsch et al., 2012). The similarities can be further supported by observations taken by authors of this paper on the morning of the wet slab cycle at the crown near the previous snowpit (Fig. 3). These observations indicated that water had flowed through the snowpack to the base, which still showed weak and wet characteristics similar to weak layers described previously. Furthermore, below freezing temperatures the night before the previous snowpit was dug (Table 1) can explain the cooler dry layers at the top, and the two above freezing nights between digging this pit and the wet slab cycle is likely cause for the upper snowpack to begin wet snow metamorphic processes and release water into the snowpack.

The layer of depth hoar that provided a failure plane was formed from November through January. Depth hoar layers remain a problem until they either melt or are destroyed. One storm at the end of December provided the first opportunity to test this layer's strength, and seven days of avalanche control resulted in widespread slab avalanches on this layer in an attempt to reduce larger activity in the future. We expected skier compaction and avalanche control to destroy depth hoar layers. However, while there was extensive explosive control work, many places did not receive heavy early season skier traffic due to extremely thin snow cover. Quickly increasing rates of precipitation in February allowed for preservation of depth hoar in areas that historically receive heavy skier traffic earlier in the season.

While the exact date of when the snowpack went isothermal is not known there is evidence to suggest that it happened on, or shortly after, March 24th. Snowpack observations from March 24th show a snowpack that is very near isothermal, if not yet. Wet slab avalanche activity peaking on the 26th further supports assumptions that the snowpack recently reached isothermal (Reardon and Lundy, 2004; Baggi and Schweizer, 2009).

The onset of wet slab avalanche activity began on March 23rd after the first two consecutive nights of the month with above 0°C temperature at the Alpine weather station (Table 1). Natural wet slab activity peaked on March 26th after the warmest night of the season (minimum 7.7°C) and 5 consecutive nights with only one below freezing (-2.2°C) (Table 1). The night of the 26th brought cold temperatures (-3.3°C), and 20cm of snow (38mm SWE) capped the warm snowpack, adding load and likely insulating old snow layers from cooling or freezing.

The wet slab avalanche cycle on March 27th had the right ingredients for an historic and rare event. A shallow snowpack through January and below average skier compaction in the early parts of the season allowed for weak layer development. A thick slab was built over this layer in February and March, and continued snowfall provided new snow at the top of the snowpack. Rapid warming melted the surface snow and introduced liquid water to the snowpack. This water likely formed flow channels through the slab, allowing the slab to maintain its cohesive, slab-like characteristics. When the water reached the basal weak layer of depth hoar, the capillary barrier formed by the interface of the depth hoar with the smaller grained crystals above allowed water to flow along that interface and weaken the associated grains. A significant load added to this snowpack overnight combined with this decrease in strength tipped the scale and resulted in this historic avalanche cycle

5. CONCLUSION

Meteorological patterns preceding the wet slab cycle are consistent with those used previously to forecast for wet slabs, which suggests that some of these variables are useful to forecast for wet slabs in different climates and terrain. Warming, settlement, increasing load on a weakened snowpack, presence of capillary barriers, a source for liquid water, and days since the snowpack went isothermal have previously been used to forecast wet slab avalanches (Conway and Raymond, 1993; Reardon and Lundy, 2004; Conway, 2005; Baggi and Schweizer, 2009; Peitzsch et al., 2012). While the results of this case study are preliminary and qualitative, they support previous findings that wet slab avalanche activity is closely related to meteorological and snowpack variables implying rapid warming trends, snowpack settlement, increased load, an existing weak layer (or capillary barrier), newly isothermal, and a source of liquid water.

To conclude, there are many times when a majority, or maybe even all of these factors exist, yet there is no wet slab activity. And there are likely times when only a few of these exist and there is wet slab activity. Understanding when and where wet slab activity will ensue requires further investigation. The wet slab cycle of March 27th at Bridger Bowl had many instabilities align to create a unique and infrequent event of historic proportions.

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