DEEP SLAB AVALANCHE HAZARD FORECASTING AND MITIGATION: THE SOUTH FACE AT BIG SKY SKI AREA

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ABSTRACT: In December 1995, the Big Sky Ski Area installed a tram to the summit of Lone Mountain, accessing over 130 hectares (320 acres) of avalanche terrain in an area historically known as the South Face. During the 2006-7 season, an additional 40 hectares (100 acres) of avalanche terrain on the South Face will be opened to the public. The South Face's windy alpine setting, relatively large path size, and generally southeast aspect combine to present both interesting and significant avalanche hazard forecasting and mitigation issues. This paper focuses on observed deep slab avalanche activity on the South Face of Lone Mountain since 1995 and the implications that this activity has had on the ski area's avalanche hazard forecasting and mitigation practices. The examination of a data set of 74 recorded deep slab avalanches (crown size >1.2m, hard slabs, failing on persistent weak layers or interfaces) highlights trends and themes in the weather and snowpack factors that contributed to the observed events. As would be expected, multi-day precipitation events and strong prevailing winds are important factors. Interestingly, every avalanche in the data set had either a crust or a hard ice layer as the bed surface. The past eleven years of experience on the South Face has helped dictate what tools and techniques Big Sky avalanche practitioners currently employ to evaluate and deal with potential deep slab instabilities. The dramatic spatial variability encountered on the South Face decreases the usefulness of study plots and data pits and forces us to rely more on hasty pits and probing. During hazard reduction work, 1-2 kg hand charges have generally been effective triggers for these relatively large hard slab avalanches. This paper does not offer any hard scientific theories or conclusions, but instead presents what avalanche practitioners at Big Sky have observed and learned about dealing with a challenging piece of avalanche terrain.

KEYWORDS: deep slab instability, crusts, ice, facets, explosives, avalanche forecasting

1 HISTORY

In 1995, Big Sky Resort installed a jig back gondola (the Lone Peak Tram) to take skiers to the top of Lone Peak, accessing over 130 hectares (320 acres) of avalanche terrain in an area known as the South Face (Figure 1). This area of the mountain had been visited by Big Sky Snow Safety personnel and ski patrollers for at least 20 years prior to 1995, and, during times of good snow stability, the South Face had been available to skiers on a "sign out and hike" basis since the 1980's. Jon Ueland, Big Sky Snow

Figure 1: Aerial view of the South Face of Lone Mountain. Photo by K. Birkeland.

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Safety Director from 1986-2000, was the architect of the initial South Face snow safety plan (Ueland, 1994). The avalanche hazard reduction plan called for several teams to conduct hand routes with explosives with an avalauncher in place as another option. A deflection berm was built to protect the Shedhorn lift from large slides. Field experience has resulted in some minor changes to the snow safety plan, but the bulk of it remains intact. The berm was reoriented and enlarged after an avalanche in December 1996 overran the berm and severely damaged the top terminal of the lift.

2 TERRAIN AND CLIMATE

Big Sky Resort is located in the Madison Range of the Rocky Mountains about 80 km (50 miles) north of West Yellowstone, MT and 80 km (50 miles) southwest of Bozeman, MT. The ski area operates entirely on privately owned land spanning 2 peaks, Andesite Mountain and Lone Mountain. Lone Mountain is a conical glacial horn with several ridgelines extending from the summit (elevation 3403 m or 11,166 feet). Only a few peaks approach Lone Mountain's elevation for at least 100 km (60 miles) in any direction. The upper 670 m (2000 feet) of the mountain exists above treeline; the area is predominantly devoid of vegetation and consists of scree and talus.

The South Face region faces generally southeast, although starting zone aspects range from due south to nearly due east. Most of the major starting zones on the South Face are situated between 3050-3350 m (10-11,000 feet). Slope angles in the starting zones range from 34-50 degrees with the more active deep slab performers falling in the 38-46 degree range. Maximum vertical fall for the major paths is approximately 670 m (2000 feet). The major paths are over 100 m (330 feet) wide and some can slide together, reaching widths of approximately 330 m (1000 feet). Maximum runout distances approach 1.5 km (just under 1 mile). A few of the South Face avalanche paths are classic concave alpine bowls, but many paths contain multiple starting zones and exhibit concave, convex, and planar features. Some starting zones are located immediately below obvious ridge crests and form cornices, but many starting zones lie on the lee side of subtle ridges or a significant distance below ridgelines.

Lone Mountain is geographically located in the intermountain snow avalanche climate, but it tends to display a more continental climate than most locales in the intermountain zone (Mock and Birkeland, 2000). Like many mountain locations on the east slope of the Rocky Mountains, Lone Mountain is characterized by relatively cold, dry, and windy conditions. The Lobo mid-mountain weather study plot is located at 2719 m (8920 feet) elevation, just below treeline on the east face of Lone Mountain. This manual weather station receives approximately 760 cm (300 inches) of snow annually. Direct observations from Big Sky Snow Safety workers over the past 20 years have lead to an approximate alpine annual snowfall of 1100 cm (433 inches). Average snow density is around 7%. Temperatures in the South Face starting zones average around -12ºC (10ºF) during the December-February period. However, temperature inversions can result in extended periods with highs approaching +10ºC (50ºF) nearly any month of the year. Prevailing winds are southwest to northwest, resulting in frequent loading and cross loading of the South Face starting zones. Wind speeds often blow in the 32-80 km/hr (20-50 mph) range, and wind events in the 80-130 km/hr (50-80 mph) range are observed on several occasions each season. Typical storm systems produce several days of light precipitation, yielding 24 hour accumulations in the 3-15cm (1-6 inch) range. Large 24 hour storm totals in the 40-100 cm (15-40 inch) range occur but are fairly infrequent (approximately 1-3 events per winter) and tend to be isolated to the terrain on the South Face.

3 SNOWPACK

Big Sky Snow Safety workers observe dramatic spatial variability in Lone Mountain's snowpack. Snowfall usually starts to accumulate in the starting zones in October and by April, snow depths range anywhere from 0 to 4 m (0-13 feet). Frequent new snow avalanches prevent many of the South Face starting zones from accumulating extremely deep snowpacks;

some of the South Face paths release well over 50 times a year. Wind and sun are the dominant factors in shaping and creating the snowpack on the South Face. The combination of dry snow and breezy conditions often creates hard wind slabs composed of .2-.5 mm snow particles. The snowpack tends to be significantly harder and denser than northerly leeward aspects at the same elevation. Typical profiles in the South Face starting zones show mostly pencil hard layers of dense, wind deposited snow with little delineating different layers.

The lower layers of the snowpack typically contain some crusts and facets. The crusts are formed by solar input, heat, and occasionally rain. The facets may be formed by classic temperature gradient metamorphism processes, diurnal recrystalization, melt layer recrystalization, or possibly the difference in grain size between the crusts/ice and the smaller adjacent crystals (Armstrong, 1985; Birkeland, 1998; Colbeck and Jamieson, 2001). Less dense surface layers (freshly fallen snow, near surface facets, surface hoar) comprised of more intricate crystal types tend to be destroyed by either solar input, wind events, or skier traffic before they can be buried intact. Warm, sunny spells, especially in October and November, can create significant ice layers in the lower part of the snowpack. One fairly common deep slab avalanche producing stratigraphy is formed when early season October or November snows are followed by a significant southwest to west wind event, creating hard slabs and a smooth surface in the starting zones. A clear and warm weather pattern following the burial of local terrain variation can lead to the formation of a hard ice layer in the starting zones approximately 15-40 cm above the ground. This scenario has been responsible for several deep slab avalanche cycles on the South Face in the past 11 years.

In a ski area setting, ski compaction's affect on the snowpack should be considered. Many of the potential weak layers and bed surfaces that have produced deep slab activity form and are buried well before skiers and snow safety personnel enter the South Face area. Once these layers are buried beneath a very hard slab, they are not directly affected by skier traffic. Boot packing may be effective in some years, but often times the slabs capping the weak layers are hard enough that they are effectively impenetrable to ski boots. Our preseason bootpacking efforts have been directed to other parts of the ski area where boot packing is more efficient. Once the South Face is open to the public for the season, ski traffic is fairly effective in preventing potential weak layers from being buried intact. However, the uphill capacity of the Lone Peak Tram is only 700 people per day; considering all of the terrain available from the summit of Lone Mountain, these 600-700 "skier laps" are responsible for tracking and compacting approximately 1000 acres of avalanche terrain (starting zones and avalanche tracks). During daytime snow and/or wind events, skier traffic does not provide adequate stabilization or compaction in many of the South Face starting zones. Additionally, skier traffic has not been 100% effective in compacting newer low density snow on to ice layers. On several occasions, we have observed wind events scour up to a meter of "compacted" snow off of ice layers that then may become covered with hard wind slabs, protecting the ice layer interface from skier traffic. The dubious nature of ski compaction in this terrain is supported by the fact that some of the deep slab avalanches used in this paper's data set failed in layers that formed after the slope was opened to the skiing public for the season.

4 AVALANCHE OBSERVATIONS

Avalanche data collected since the South Face was opened to the skiing public in 1995 was examined, looking for hard slab avalanches over 1.2 m (4 feet) deep that failed in old snow layers. The >1.2 m (4 feet) depth criteria was chosen to eliminate any new snow avalanches that were improperly recorded. This data screen produced a set of 74 avalanches. These occurrences would be classified as class 3-4 in the avalanche size-destructive force rating system (Canadian Avalanche Association, 2000; Greene, et al., 2004). For each event, crown depth, vertical fall, trigger, explosive size, weak layer, bed surface, daily high and low temperature, presence and direction of any recent significant temperature trend, 12 hour new snowfall, 1.5 to 4.5 day storm snowfall at 1 day intervals, snow base depth, and year-to-date snowfall were noted. All temperature and snowfall measurements were collected at the Lobo mid-mountain weather study plot, approximately 1.6 km (1 mile) from the South Face avalanche paths. Figure 2 summarizes the data.

The glaring omission is wind data; unfortunately, our wind instrumentation has been in a near constant state of flux over the past decade (i.e. moving stations, abandoning stations, malfunctioning equipment). Despite the lack of formal wind data, we feel confident stating that all of the avalanches in the data set were preceded by a 40-130 km/hour (25-80 mph) SW to NW wind event sometime in the 5 days prior to the recorded event and usually within 36 hours prior to the event (Big Sky Snow Safety and Ski Patrol observations).

5 DISCUSSION

Similar to results from Jameison's deep slab instability case study (Jameison, 2000), cumulative storm snowfall over a longer period (3-5 days) appears to correlate better with deep slab instability than 12-36 hour new snow totals. Interestingly, 38% of the avalanches occurred on days without any new snow and 82% occurred on days with less than 10 cm (4 inches) of new snow. Snow readily available for transport coupled with 32-80 km/hour (30-50 mph) prevailing winds produces significant loads in the South Face starting zones, independent of precipitation. The generally dry, low density snow and large windward fetch zones provide abundant transportable snow. Pencil hard slabs of 30-60 cm (1-2 feet) depth are often observed following wind events with no recorded precipitation. Additionally, experience has led us to believe that deep slab instabilities often remain sensitive for a period of days following a significant loading event, whether the load is precipitation or wind caused.

The daily high and low temperatures appeared to be fairly random. Air temperature trends were not a significant variable when looking at the avalanches as a group; however, the author feels that a dramatic warming trend was probably a factor in one of the skier triggered deep slabs.

The weak layers involved were strikingly consistent. Nearly all of the occurrences failed on faceted crystals, and the few events not characterized as faceted weak layers were characterized as weak interfaces with no discernable weak layer. Although weak layer thickness is not included in the data, it is worth noting that the vast majority of the occurrences had weak layers less than 5 cm thick. Many of the weak layers would be more accurately characterized as interfaces between bed surfaces and slabs. The lack of deep slab activity associated with thicker, more advanced faceted layers (depth hoar) is notable but explainable; when thicker depth hoar layers form on the South Face, avalanches typically release before the slabs grow to 1 m (3 feet) depths. If the weak layer is “too weak”, the rapid loads applied to the starting zones in this terrain tend to produce 30-90 cm (1-3 foot) deep avalanches, events that were too small to be in the data set. We have observed a few natural cycles that fit this description in the past 11 years.

The recorded bed surfaces were another interesting feature in the data set. All of the events had either crusts (40%) or hard ice layers (60%) as bed surfaces. On at least 3 occasions, including the December 1996 avalanche that damaged the Shedhorn lift, two deep slab avalanches ran on the same hard ice layer/bed surface with a 3-4 week period between events. In these instances, the weak layer was extremely thin.

The avalanches in the data set were predominantly triggered with hand deployed explosives, although 4 large natural releases were observed and ski patrollers ski triggered 3 large deep slabs. Patrollers were caught, taken for rides, and uninjured in the 3 ski triggered events. Five slides were released with 1 kg (2.2 pound) avalauncher rounds. Since the Tram has proven to be operable in more adverse weather conditions than initially expected, we are able to perform hand routes and have not used the avalauncher on many occasions, averaging only 2-5 shooting missions per year since 1995. In comparison, hand routes are performed approximately 75-100 times a season

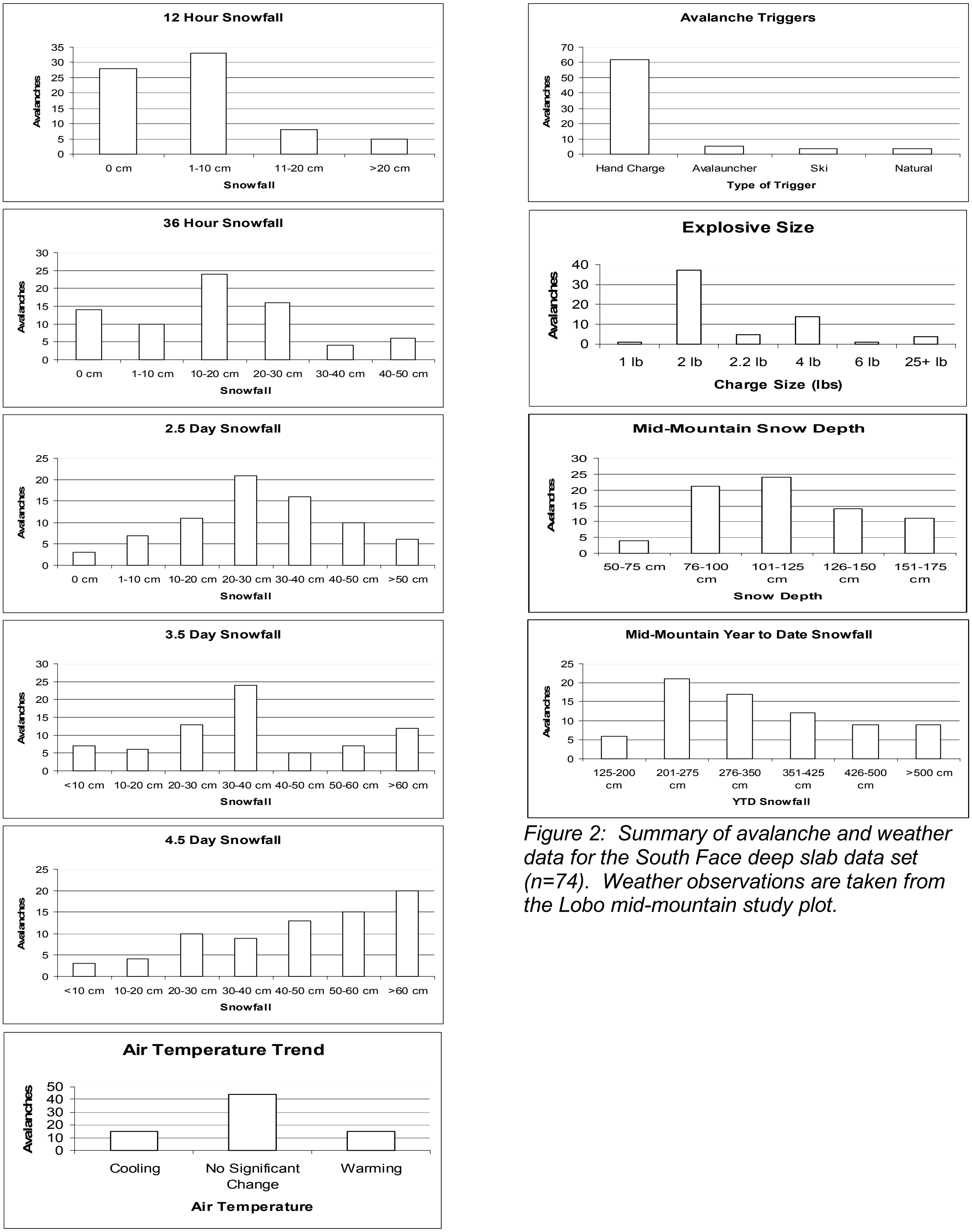

Figure 2: Summary of avalanche and weather data for the South Face deep slab data set (n=74). Weather observations are taken from the Lobo mid-mountain study plot.

on the most active terrain on the South Face. To protect the Shedhorn lift during times of extreme avalanche hazard and blizzard conditions, conducting abbreviated hand routes is preferable to blind firing avalauncher rounds into the starting zones.

The size of the explosive is an interesting feature in the data set. One avalanche was released with a .5 kg (1 pound) gelatin dynamite hand charge. Sixty seven percent of the hand charge released events were triggered with ~1 kg (2 pound) Pentolite boosters, our standard hand charge, and 23% were triggered with 2 kg Pentolite boosters. One slide released with a ~3 kg (6 pound) Pentolite charge, and 9% were triggered with Pentolite primed ANFO charges, either 11 kg (25 pound) or 22 kg (50 pound) bags. The noteworthy observation is that deep slab instabilities can be successfully managed with relatively small explosive charges. Over the past decade, we have shifted away from using larger ANFO charges to mitigate hazard on the South Face for a number of reasons. On 2 occasions, a 1 kg “cover shot” triggered a deep slab avalanche before the planned ANFO shot was deployed. In the South Face’s challenging terrain, smaller shots are often easier to deploy into their intended target zone. Also, the complex nature of many of the starting zones and the dramatic spatial variability in the snowpack seem to promote a “don’t put all of your eggs in one basket” approach; in these relatively large paths, a few well placed 1-2 kg shots may be more effective than 1 larger shot.

Many of the 1 kg charges detonated in a deep snowpack where the weak layer was at least 1.2 m (4 feet) below the explosive, and a few 1 kg charges triggered avalanches when the explosive detonated at least 2 m (7 feet) above the weak layer. In these particular cases and in many of the other events, the snow surface was very hard, impenetrable to ski or boot. These hard conditions result in less attenuation of the explosive’s shockwave and probably allow a larger force to affect deeper weak layers than the force that would be applied to the deep weak layer with soft surface conditions. Big Sky’s current South Face avalanche hazard reduction plan relies on hand routes with 1-2 kg Pentolite boosters due to their relative success triggering deep slab avalanches in the South Face terrain.

6 OPERATIONAL IMPLICATIONS

Every snow safety program has its preferred set of tools and techniques that effectively solve the problems presented by their given terrain, weather, snowpack, and operational parameters. We evaluate deep slab stability/instability on the South Face paths by identifying snow stratigraphy issues (weak layers and bed surfaces, bad interfaces), determining the spatial extent of the layers in question, performing stability tests in the starting zones, and testing slopes frequently during and after loading events.

We do not dig many full data pits nor maintain a study plot for the purpose of tracking snow stratigraphy. Lone Mountain’s climate and complex terrain creates a tremendous amount of spatial variability in the snowpack on starting zone, slope, and larger scales. Individual forecasters may return to dig pits in a given area to roughly track temporal changes in stratigraphy, especially in bad depth hoar years on more easterly and northerly aspects and during spring warming of the snowpack. However, we have found that we spend our time more effectively by digging several quick hasty pits, noting the presence or absence of the weak layer/bed surface in question and performing a few stability tests before moving on to the next site. After digging enough hasty pits to confidently answer the “is there a potentially bad layering profile on this slope” question, we may probe the slope. This provides a general impression of the spatial distribution of ice layers and crusts and a better mental picture of slab thickness and distribution. When the opportunity arises, we take pictures of snow surfaces that may pose problems later in the year (i.e. hard ice layers or rain crusts on the surface in the early season). When questionable layers are buried early in the season or during prolonged storm events, photographing different areas is not an option and we rely more on meteorological observations, probing, and digging hasty pits.

Stability tests yield interesting and often puzzling results when evaluating deep slab instabilities, especially when very stiff slabs are involved. We predominantly use the compression test (McClung and Schaerer, 1993) and the Stuffblock test (Johnson and Birkeland, 1994) because they are both fairly quick to perform and both tests evaluate the effects of compressive forces on shear. We do not put a lot of stock in the qualitative scores for either test; our experience is that high quantitative scores observed with either test, and with stability tests in general, do not necessarily indicate good deep slab stability. However, our observations indicate that shear quality (Birkeland and Johnson, 1999), or fracture character (van Herwijnen and Jamieson, 2004), may be a better indicator of potential current or future deep slab instability, especially when hard ice layers are present at the shear interface. We have noted that quality 1 or sudden planar shears are associated with deep slab instability more frequently than low quantitative scores (easy compression test or low Stuffblock drop heights). This observation may be attributed to scaling affects of the various test scores or by the fact that isolating columns eliminates or alters the tensile forces and different creep rates that exist in the slab while it is intact on the slope.

In the ski area setting, we use explosives as the ultimate deep slab stability test. Explosives eliminate much of the uncertainty attributable to pits and stability tests. Explosives testing often yields additional information by observing fracture line size, shape, and propagation characteristics (Ueland, 1996). When faced with a snow stratigraphy that is capable of producing deep slab avalanches, the nature of the new snow load dictates how aggressively slopes are tested with explosives. Special attention is given to slopes that accumulate new hard slabs over the entire slope rather than just isolated pockets in the starting zones. If, during a multi-day loading event, hazard reduction work is not performed on one day (i.e. weather related lift closures) or a suspect starting zone does not release, the slope(s) in question remains suspect and is(are) treated with extra caution the next day. Several of the 2-3 m (6-10 foot) deep avalanche events occurred after failing to release new snow avalanches the previous day when forecasters or hazard reduction workers felt they should have. In these cases, the suspect slope retained a significant hard slab when all observations (i.e. avalanche activity on adjacent paths, cracking, and amount of additional snow load) indicated that it should have released.

7 CONCLUDING REMARKS

The South Face expansion at Big Sky has proved to be quite the educational experience over the past 11 years. The extent of the role that hard ice layers appear to play in deep slab instability is something that was not entirely expected, especially considering a couple of large repeat events that failed on weak interfaces between the ice and the slab above with no discernable weak layer in between. In the South Face environment, the nature of the new load has proven to be extremely important. If an avalanche is to release 2-3 m deep, the weak layers in question are relatively strong as they are supporting an enormous load already; it is an extremely challenging endeavor to accurately predict how much of an additional load the slope will need to fracture. The data set of 74 deep slab releases contains a number of outliers, events that are not easily explainable even after the fact. While 11 years of daily observations has allowed us to characterize some trends, we may have experienced an abnormally active or inactive period; this challenging piece of avalanche terrain will certainly continue to surprise and impress us and others in the future.

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