FORECASTING FOR NATURAL AVALANCHES DURING SPRING OPENING OF THE GOING-TO-THE-SUN ROAD, GLACIER NATIONAL PARK, USA

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ABSTRACT: The annual spring opening of the Going-to-the-Sun Road in Glacier National Park presents a unique avalanche forecasting challenge. The highway traverses dozens of avalanche paths mid-track in a 23-kilometer section that crosses the Continental Divide. Workers removing seasonal snow and avalanche debris are exposed to paths that can produce avalanches of destructive class 4. The starting zones for most slide paths are within proposed Wilderness, and explosive testing or control are not currently used. Spring weather along the Divide is highly variable; rain-on-snow events are common, storms can bring several feet of new snow as late as June, and temperature swings can be dramatic. Natural avalanches - dry and wet slab, dry and wet loose, and glide avalanches - present a wide range of hazards and forecasting issues. This paper summarizes the forecasting program instituted in 2002 for the annual snow removal operations. It focuses on tools and techniques for forecasting natural wet snow avalanches by incorporating two case studies, including a widespread climax wet slab cycle in 2003. We examine weather and snowpack conditions conducive to wet snow avalanches, indicators for instability, and suggest a conceptual model for wet snow stability in a northern intermountain snow climate.

KEYWORDS: Avalanche forecasting, natural avalanches, wet snow avalanches, Glacier National Park

1. INTRODUCTION

The Going-to-the-Sun Road (GTTSR) is one of the premier attractions in Glacier National Park (GNP), Montana. It opened in 1933 after 12 years of construction and is one of GNP's most heavily used facilities. The two-lane, 80-kilometer road traverses the park from west to east, crossing the Continental Divide at Logan Pass at 2026m elevation. The Park closes a 56km section of the road each winter due to inclement weather, heavy snowfall, and avalanche hazards. Snow removal (Figure 1) to re-open the GTTSR starts in April, with the mean road opening on June 9.

The spring opening attracts considerable attention; local media regularly report on the progress of the snow removal, and GNP maintains a website with frequent updates and photos of snow removal operations. This attention is in large part due to the road's social and economic influence in the region. The opening of the road typically starts the tourist season in the Park and surrounding region. Visitors to GNP, the vast majority of whom drive the GTTSR, contribute $204 million annually to the regional economy (BBC, 2003). This contribution is overwhelmingly concentrated in the four to five months that the GTTSR is open, creating tremendous local pressure to open the road as early as possible.


Figure 1: Dozers and rotary snow blower removing deep snow from Rimrock.

The opening date depends on weather conditions during April, May and June because spring weather strongly influences the extent and severity of natural hazards to snow removal crews (Klasner and Fagre, 2000). Snow avalanches are the primary hazard. Several avalanche accidents have occurred in the 71 seasons of spring opening. In May 1953, a slide caught four GNP employees clearing snow after a storm. Two of the four were partially buried; one died of trauma. The two others were fully buried; one died, while the second survived a seven-hour burial (Walter,

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1983). In 1964, a bulldozer and operator triggered a wet slab that carried both off the road (Figure 2). The driver was injured but survived. There have been numerous other incidents and close calls, often resulting in buried machinery or costly damage to infrastructure. Slides in April 1991 caused $150,000 damage to the GTTSR (U.S.D.A. Westwide Avalanche Network, 1991).

Figure 2: View of the 1964 accident at the Big Drift. Crown visible in upper left. *NPS photo*.

For most of the 71 years of spring opening, crew foremen with little formal avalanche training have made the decisions for whether to work and when to stop work in avalanche zones. Crews typically start work early and end work in avalanche zones by mid-afternoon, or postpone work immediately after spring storms. The foremen and crews have amassed considerable local experience and avalanche knowledge that has allowed them to avoid most accidents.

In 2002, GNP instituted its first formal avalanche hazard forecasting program for snow removal operations. For the 2003 season, GNP established a daily forecasting program with two full-time avalanche specialists. This paper describes the avalanche hazards threatening snow removal operations on the GTTSR and the tools and strategies the program has developed to address the unique forecasting challenges of spring opening.

2. CLIMATE AND WEATHER

The Continental Divide strongly influences snowfall and weather on the GTTSR. Both Maritime and Continental weather systems affect the road and surrounding area. A westerly flow and mild, moist Pacific systems dominate winter weather, though influxes of cold Arctic air occur irregularly. In general, areas west of the Divide tends to have milder, cloudier, and wetter weather than those east of the divide, where more variable conditions prevail (Finklin, 1986). The collision of Maritime and Continental weather systems on the Divide can create harsh conditions. During the winter of 2003-4, the weather station at Logan Pass Visitor Center recorded temperature changes of 20-25 degrees C in one hour, and wind gusts to 190 kmh.

The snowpack during the April-June snow removal season is highly variable. The snowpack typically peaks during this period, as does interannual variability (Klasner and Fagre, 2000). At the Flattop SNOTEL station (1920 m), 16 air km northwest of Logan Pass, the average peak snow water equivalent (SWE) occurs on April 27 (1970-2004). However, the date of peak SWE ranges from March 27 to May 27, and peak SWE totals range from 780 to 1830mm. The Pacific Decadal Oscillation (PDO) strongly influences the variability on a 20-30 year cycle (Selkowitz et al. 2002).

Only 20% of the average annual precipitation total of 2083mm falls during the April-June period. The drier spring conditions often result from sustained periods of synoptic high pressure. These periods typically last two to ten days, during which the weather is characterized by sunny, warm days and mild nights. Daytime temperatures in the vicinity of the GTTSR range from 10 to 20 degrees C, and nighttime lows hover around freezing. This fair weather typically results in rapid melt of the accumulated winter snowpack.

However, when winter weather patterns continue into spring, extended periods of wet weather occur. Precipitation can occur as rain or snow. The 2002 season was remarkable for its late-season snowfall. Three major storms occurred, two in May and one in June. A total of 480mm of SWE accumulated at Flattop SNOTEL from April through June. This translated to at least 2.8m of snowfall. A storm on June 8-10 dumped 1.5m of snow containing 137mm of SWE, the highest total during plowing season in 35 years.

3. AVALANCHE HAZARDS

3.1 Avalanche paths

The avalanche paths threatening the GTTSR are predominantly sunny, windward slopes (Figure 3). The paths east of the Divide face east through south; those west of the Divide face southwest through west. Exceptions occur in the bowl-shaped start zones of the large west-side paths -- Haystack Creek, Big Bend, and Triple Arches. Parts of these bowls face west-northwest through northwest. Some west side paths are also shaded each morning by the narrow spine of the Continental Divide known as The Garden Wall, which rises 75-275m above the start zones.

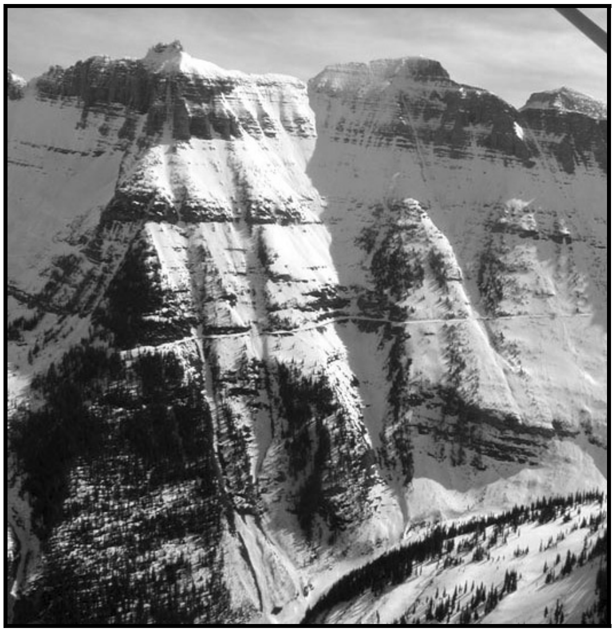

Figure 3: Aerial view of Triple Arches area showing generally sunny aspect of start zones, confined paths and road crossing mid-track. Photo taken mid-morning.

This orientation to the sun is a significant factor in springtime avalanche conditions. The start zones are subject to direct solar radiation much of the day and temperature swings can be dramatic. The site’s mid-hemisphere latitude (48^{o} 40’ N) and the time of year magnify insolation. Although the latitude means short days and weak insolation in the winter, it makes for longer periods of ever-more intense insolation – and shorter periods of freeze – as the season progresses. The length of daylight nearly doubles from late December to late June (8.2 to 16.2 hours); average monthly radiation increases 7.5 times in a similar period (1.05×10^{8} j/m^{2} in December to 7.95×10^{8} j/m^{2} in July) (Finklin, 1986). Data from the Garden Wall weather station show 13 hours of radiation in the start zones in early April and 17 hours by early June.

The windward aspect of most start zones makes them subject to wind erosion and scouring during much of the winter, before the snow becomes unavailable for transport. Because of the relatively deep snowpacks in the area, this scouring typically thins the snow cover rather than clearing it off altogether. Snow depths in the start zones are often less than on adjacent slopes with shallower slope angles. Avalanches during the winter may also contribute to thinner snow cover. The thinner snow pack in the start zones sometimes leads to a weaker springtime snowpack that can be more quickly affected by temperature swings.

Avalanche hazards on the 56km section of the GTTSR re-opened each spring vary with elevation and location of the road. To a lesser extent, they also vary with time of year. Each end of the road is situated in a valley bottom, where it crosses a few generally well-defined avalanche runout zones (Figure 4). These slide paths can produce large-magnitude, destructive dry slab avalanches (to destructive class 4) as a result of mid-winter storms. They do not pose a hazard to spring snow removal operations, except in limited locations. The large debris piles that result from mid-winter slides in the valley-bottom paths can create a significant obstacle to snow removal operations in these runout zones.

Springtime forecasting efforts focus on a 23km stretch of the GTTSR that climbs over Logan Pass from the valley on each side of the Divide. This stretch starts at Packers Roost on the west side and extends to Siyeh Bend on the east side. It is sometimes referred to as the alpine section of the GTTSR.

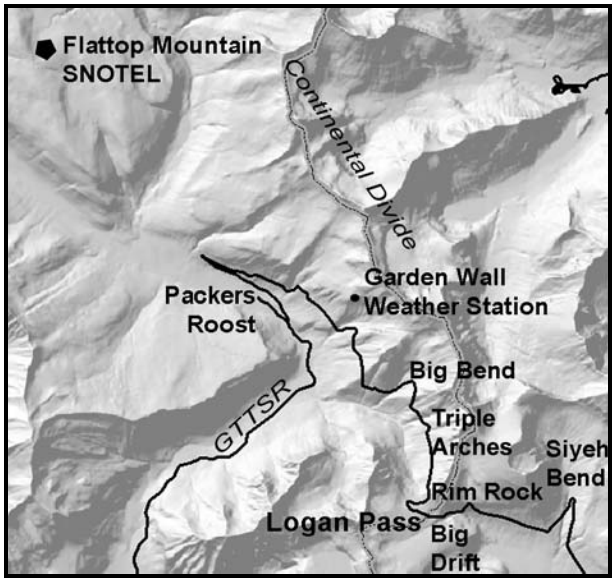

Figure 4: Map showing the alpine section of the GTTSR and locations named in text.

The alpine section of the GTTSR is generally situated in the tracks of the avalanche paths it traverses. The avalanche paths below Triple Arches typically have confined tracks with well-defined safe zones to either side; the road crosses these paths lower to mid-track. Small slides and sluffs reach the road in this section infrequently, and exposure time for vehicles traveling through the paths is generally short. Forecasting in this section focuses on the times that crews are removing snow and avalanche debris in the paths.

As the GTTSR gains elevation near Logan Pass, the exposure to avalanches increases. Many avalanche paths in the sections between Triple Arches and Rimrock (west side) and Siyeh Bend and Logan Pass (east side) have unconfined tracks. The road crosses these avalanche paths in mid to upper track (Figures 3 and 5). There are few safe zones in this section, and those that do exist offer limited, if any, protection from most avalanches. Small slides, including sluffs, can reach the road, and the shorter distance between the road and starting zones reduces the time in which spotters can warn equipment operators working on the road. Forecasting in these sections addresses hazards to both snow removal and travel to and from work sites.

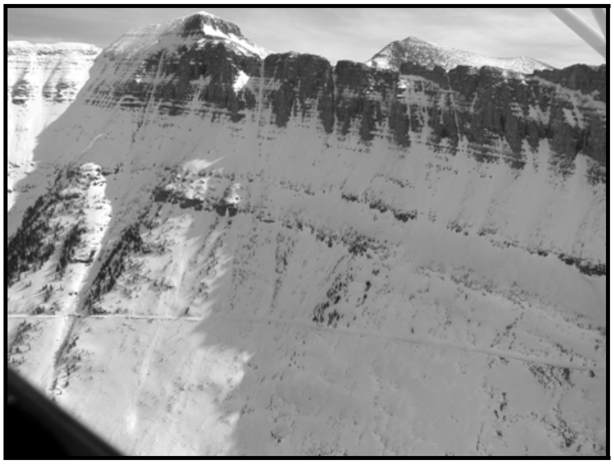

Figure 5: Aerial view of GTTSR showing unconfined paths in The Slopes in early season. Photo taken mid-morning.

3.2 Avalanche types

Avalanche hazards on the GTTSR include most avalanche types: dry slab and dry loose snow avalanches, wet slab and wet loose snow avalanches, cornice fall avalanches, and glide avalanches. The only avalanche type that does not affect the GTTSR is serac avalanches.

During spring snow removal, dry slab avalanches are the least common avalanche type. Both dry slab avalanches and dry slab forecasting practices are well-described in avalanche literature and we will not reiterate those discussions in this paper. Forecasting for this avalanche type relies on standard practices during the brief, infrequent times when dry slab avalanche hazard exists.

Loose snow avalanches are the most common type of avalanche on the slopes affecting operations on the alpine section of the GTTSR. Dry loose avalanches are less frequent due to the rapid effects of sun and warm temperatures on new snow. They typically occur during or immediately after storms on steep slopes below rocks, cliffs, or trees. They are mostly Class 1 in size, though some reach Class 2.

Wet loose snow avalanches are the avalanche type that most frequently affects snow removal operations on the GTTSR (Figure 6). In new snow, they occur with warming, sun or rain. In old snow, they occur during periods of dramatic warming and sustained solar radiation. The release of wet loose snow avalanches follows warming or solar radiation that increases melt in surface and near-surface snow layers. The heat and radiation break down bonds between grains, increasing water content and decreasing the cohesion of the snow. The rate at which this occurs depends on the age of the snow, the initial strength of the snow and bonds between grains, the albedo of the snow, and for new snow, the initial cohesion and grain type. Like dry loose slides, they are often triggered by snow falling off of trees, rocks and cliffs. Wet loose slides can entrain considerable amounts of snow as they travel down slope, including subsurface snow during hot, sunny conditions. The largest wet loose avalanche observed to date on the slopes surrounding the GTTSR was class 3 in size and traveled 900 vertical meters.

Figure 6: Debris from a typical wet loose snow avalanche covering road, May 11, 2003.

Wet loose snow avalanches pose a significant threat to snow removal operations on the GTTSR. Large avalanches of this type can bury people and machinery working in slide paths. The nature of the terrain also makes the consequences of small loose avalanches serious. In places where the road traverses above cliffs, even small slides can push workers and small vehicles off the road. In many sections of the road, the road cut is itself a terrain trap where small avalanches could bury a person. Loose slides tend to be more of a hazard higher on the road, where the road is closer to starting zones and escape time is reduced.

Wet slab avalanches are infrequent but can produce extremely destructive and unsurvivable avalanches. Wet slab avalanches affecting the GTTSR can range from small, class 2 slides involving recent snowfall to climax, class 4 avalanches of the season's accumulated snowpack (Figure 7). The smaller slabs typically occur when warm, sunny days immediately follow spring storms. Larger wet slab avalanches range from class 3 to class 4 in size, with crowns of 1-2 meters, and vertical falls of 1000 to 1500m.


Figure 7: Crown fracture of a destructive class 4 climax wet slab running the evening of April 22, 2003. Fracture depth is 1.2 to 1.5m.

Glide avalanches are the circus oddity of the avalanche world; they are poorly understood and given little attention. They are rare to non-existent in many avalanche climates and are not thought to pose much threat to people or property. They seem to require a relatively unique combination of snow climate, bed surface, and temperature to occur. In glide avalanches, the snow at the base of the snowpack fails and the entire snowpack glides downhill, creating a tensile crack at the crown known as a glide crack (Figure 8). The flanks and stauchwall remain intact, however, and failure may not occur. If it does, it can happen hours or weeks later. The slab downslope of the crack often wrinkles and buckles as the slab glides down slope. The mechanism for failure at the bed surface is lubrication by free water, often produced by melting in the upper layers of the snowpack.


Figure 8: Aerial view of glide crack on bedrock showing downslope wrinkling. April 4, 2004.

On the GTTSR, glide activity often occurs in the same places each year (Figure 9). In some seasons the activity is limited to glide cracks with slabs that melt in place; in other seasons glide avalanches occur. These "repeat offenders" often have bedrock or bear grass as a gliding surface. We have observed glide avalanches on all aspects in the vicinity of the GTTSR. They are most common on east through northeast slope, perhaps because of the orientation of the underlying strata, which dips to the northeast on many peaks in the upper McDonald Valley.

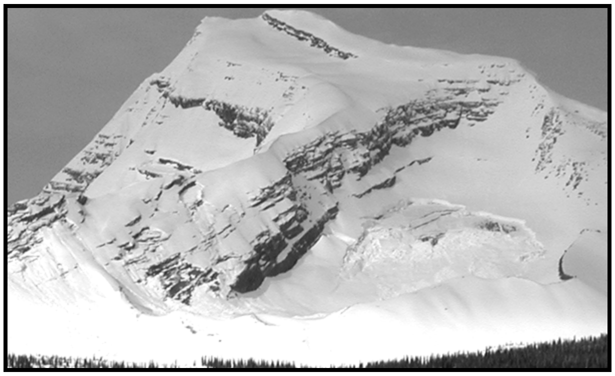
Figure 9: Annual glide avalanches on the northeast face of Heavens Peak. May 24, 2004.

Glide avalanches pose an infrequent but serious hazard to snow removal on the GTTSR.

Although glide avalanches are common on slopes in the vicinity of the GTTSR, they occur only in isolated places on the slopes above the road. In some places, such as the lower slopes of Mt. Gould, they occur annually, but debris does not reach the road when they fail. One particular glide crack in the Show Me path in Haystack Creek, presents a difficult forecasting challenge. The Show Me crack forms most years but with different outcomes. In 2003, it formed but did not result in a glide avalanche. In 2004, it produced a glide avalanche, but the debris did not reach the road or trigger the slope below. In 2002, the crack resulted in a glide avalanche that triggered the slope below, resulting in a large magnitude slide that swept over the road.

4. OPERATIONAL FORECASTING PROGRAM

4.1 Program description

Prior to 2002, Glacier National Park had occasionally consulted with local avalanche professionals but had no formal avalanche hazard mitigation program. During the 2002 plowing season, GNP instituted an avalanche program through a partnership with the USGS Northern Rocky Mountain Science Center (NRMSC). That season, a USGS avalanche specialist provided weekly avalanche hazard forecasts on Monday afternoons prior to the crews' four day work week. In 2002 the GTTSR had its second latest opening on record, primarily due to near-record snowfalls during May and June. The resulting effect on the local economy caught the attention of the Montana congressional delegation; in 2003, Congress appropriated funds for implementing new technology and science to improve the efficiency of the snow clearing operations. Beginning in the 2003 season, GNP utilized a portion of this appropriation to formalize the avalanche program by funding two avalanche specialists – the authors - to provide daily avalanche forecasting during the spring opening of the GTTSR. The new program continues the partnership with the USGS; one of us is a NRMSC employee and the other is an employee of GNP.

In addition to forecasting, the program provides real-time snow safety. During the workday, the equipment operators are in avalanche tracks where stability assessment is difficult at best, and it is of utmost importance that they remain focused on the mentally-demanding task of keeping their equipment on the narrow roadbed. Our mobility affords us access to avalanche starting zones above the work area, where we can effectively monitor changing snow conditions during the day. This monitoring provides an additional margin of safety to the crew during periods of rapidly decreasing stability, or it allows them to work longer when the hazard is not increasing as expected.

The new program has increased avalanche awareness among equipment operators through regular avalanche safety training. Although the plowing crew does not need to understand the intricacies of snow stability evaluation, a working knowledge of avalanche terminology and mechanics provides them with tools to make independent decisions when necessary and establishes a common language for sharing information. Further, in the event of an avalanche incident the equipment operators will likely be the first responders, so hands-on rescue training with avalanche beacons, shovels, and probes is imperative and is provided annually.

One aspect of the avalanche program has become unexpectedly important: information dissemination to park personnel and the public. Because the GTTSR is GNP's primary attraction, there is no shortage of intra-park and public curiosity regarding the progress of the spring opening. Yet very few people get the opportunity to witness the plowing firsthand due to the intrinsic hazards of being up on the road during the spring and possible interference with snow removal operations. Our flexibility and mobility provide us with a unique opportunity to document the often dramatic and spectacular events of the spring opening of the GTTSR. We post photos, narratives, and hazard forecasts on the GNP intranet daily, and the photos are publicly accessible on GNP's on-line visitor center (http://www.nps.gov/glac/whatsnew/montana.htm). The latter provides invaluable education and information; it has been extremely well received by the public and reduces the flood of questions posed to park employees.

4.2 Development of tools and infrastructure

Critical to any avalanche forecasting program is access to real-time weather data from locations representative of avalanche starting zones. Fortunately, upon the institution of the forecasting program in 2002, two representative remote automated weather stations were already in place. The first was the Flattop SNOTEL station, located at 1920m 12-15km northwest of the major west-side avalanche paths. The station's long period of record (1970-2004) spans roughly half the history of the GTTSR. Despite its mid-elevation location, our experience has shown the Flattop site to be extremely valuable for precipitation and SWE measurements, though the temperature data (1982-2004) has been less useful. Additionally, a USGS weather station established in 1995 at Logan Pass (elev. 2033m) provides temperature, relative humidity, wind, and solar data.

Neither station was established to provide data for the avalanche program, and during our first season we soon learned that they did not supply the slope-specific data needed for accurate forecasting. Flattop provides precipitation data but is too low for accurate starting zone temperatures. While the Logan Pass site is situated at a higher elevation, it is still lower than most starting zones. Its location upon the Continental Divide subjects it to a complicated, if not violent, mixture of warm Pacific weather systems, cold Arctic air, and spring upslope/wrap-around storms. It often provides data accurate for one side or the other, but during some weather events it is not representative of either side. Experience quickly taught us that when forecasting primarily for natural wet snow avalanches, where melt and freeze play crucial roles in determining snow stability, obtaining representative temperature and radiation data are vital.

To collect this data, we selected a site situated at 2240m on a protected sub-ridge extending west from the continental divide (Figure 10), immediately adjacent to the largest avalanche path threatening the GTTSR. This location provides safe, year-round access, excellent proximity to avalanche starting zones, and the highest feasible elevation. We installed the Garden Wall weather station in December 2003, with additional work in early April 2004. To supplement the usual array of temperature, relative humidity, and wind sensors, we chose a Kipp and Zonen CNR1 net radiometer. The CNR1 instrument measures incoming and outgoing solar and long wave radiation; from these we can calculate net radiation, albedo, and snow surface temperature and net radiation. In one season it proved to be a valuable tool in evaluating the energy balance, and resultant melt or freeze, of the snowpack. Further experience will undoubtedly increase the utility of this device.

We developed a database (Figure 11) to facilitate storage and analysis of the substantial amounts of data collected from remote weather stations and manual observations of snow conditions and avalanche occurrence. In addition to providing tabular and graphical views of remote weather station data, the database allows cataloging of avalanche, weather, and snowpack observations made during field days. Since we create the daily avalanche forecast within the database, it is stored in a table that we can later cross-reference with other records or observations.

Figure 10: Garden Wall weather station (2240m) installed December 2003 adjacent to the Haystack Creek avalanche paths.

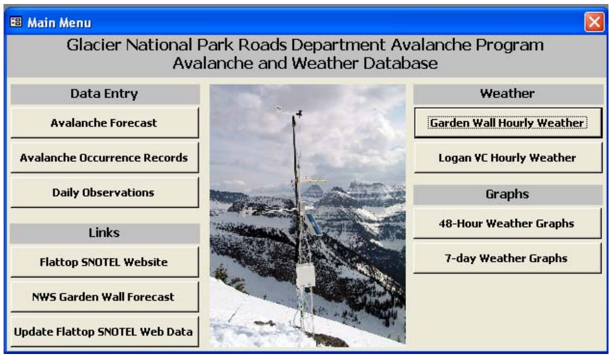

Figure 11: Proprietary database allows access to weather station data, entry of snow and avalanche observations, and generation of a daily avalanche forecast.

5. WET SNOW AVALANCHE FORECASTING CASE STUDIES

Our forecasting focuses on wet loose and wet slab avalanches. Both pose a significant hazard to snow removal on the GTTSR; the first are a frequent, sometimes daily occurrence, and the second, though very infrequent, are typically large, destructive and dangerous when they do occur. In reviewing the literature on wet slab avalanches, we found few detailed descriptions of the mechanism for wet slab avalanche release. Free water is generally recognized as a significant component in the failure of wet slabs (McClung and Schaerer, 1993), and failure of wet slabs is described as occurring after a loss of strength rather than an increase in stress (Tremper, 2001).

The conditions under which wet slab avalanches occur are better described (Tremper, 2001). These conditions typically include days with intense and sustained solar radiation, multiple nights without a re-freeze of the surface snow, and heavy rain on old snow. Paradoxically, the conditions under which wet snow avalanches occur are also typical of early summer weather, both in GNP and throughout western North America. Yet summer snow rarely avalanches, despite prolonged periods of such conditions. Even wet loose avalanches are rare to non-existent in summer snow. The GTTSR has opened with widely varying amounts of snow in the paths above it for seventy years, yet there has never been a significant avalanche-related accident on the road after opening. Thus, conditions alone do not create wet snow avalanches; there is a transition between winter and summer snow, and at some point during this transition, wet snow avalanche activity peaks. Since snow removal on the GTTSR occurs during this transition, our task has been to detail its stages and processes in order to forecast wet snow avalanches more precisely and accurately.

After a limited period of observations – just three seasons – we have developed a conceptual model that guides our forecasting. Since we do not view the model as conclusive or definitive, we end with a summary of questions and caveats with which we continue to grapple. Finally, we examine two separate avalanche events and their implications for spring snow forecasting. We hope that the unique forecasting challenges during the spring opening of the GTTSR provide some general insights into the prediction of avalanches in a spring snowpack.

5.1 Conceptual model for wet snow stability

The presence of liquid water is the most significant component in wet snow avalanches. Melting in the surface and near-surface layers of the snowpack produces liquid water that can destabilize surface layers or drain down to lower layers of the snowpack. At first this drainage is inefficient; free water flows easily through some layers and accumulates in others. In time, water forms channels through which it flows preferentially through to the ground. At this point the snowpack can drain even large amounts of water. Wet snow avalanches seem to occur when liquid water production overwhelms the drainage capacity of the snowpack. That can occur in two ways: (1) when there are no preferential flow paths, as when melt first introduces liquid water into a cold, dry snowpack, or (2) when flow channels exist but are not sufficient to drain an increase in water volume, such as that produced by increased melting or rain.

The introduction of liquid water alone does not cause wet slab avalanches. Each year the snowpack melts, producing liquid water, yet wet slab avalanches do not occur every season. A second critical component in wet slab avalanches is snow structure (McClung and Schaerer, 1993). Our observations suggest that a significant weak layer must be present for wet slab avalanches to occur. It may also be possible that a significant textural change that impedes water drainage may be enough. In the field, we look for thin weak layers composed of large, persistent grains that are noticeably softer than adjacent layers. Climax wet slab avalanches seem to require that such layers are widespread at or near the base of the snowpack, having formed early season. We are looking primarily for textural differences between adjacent layers, particularly in characteristics such as hardness, grain size and grain type. McCammon and Schweizer (2002) describe a similar process for dry snow.

Coming into spring, persistent weak layers have sufficient strength to support overlying layers of snow before the introduction of liquid water. This water drains into the weak layer from the layers above and then, due to the textural discontinuity, accumulates in the weak layer before draining. The water starts melting the already weak bonds between the grains, the layer loses strength, and when it can no longer support the layers above, fractures. The weak layer must be relatively weak to start so that the weakening and subsequent fracture occur before efficient drainage channels are established and water flows through the layer without accumulating.

From our experience, a snow structure conducive to wet slab avalanches has three components: a “water factory,” a slab, and “the funny business” (Figure 12). The water factory is the surface and near-surface layers where radiation and warm temperatures are actively melting snow and creating liquid water. This component is roughly 50cm or less thick and composed of wet grains that have undergone wet snow metamorphism. Grain sizes are 1-3mm, and grain types are rounded polycrystals or clustered rounded grains. Melt-freeze or rain crusts are commonly interspersed in the water factory; these can either be deteriorating or quite strong, depending on the time of day. With the exception of crusts, the layers in this component are soft - fist to four fingers hardness – unless frozen, in which case they can be one finger to knife hard.

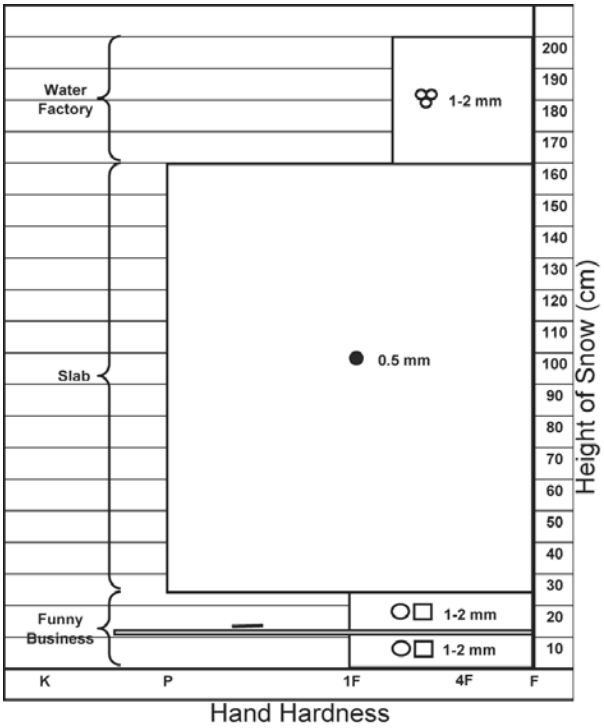

Figure 12: Schematic profile of snow structure during a wet slab avalanche cycle in April 2003.

The slab is the midpack layers; it is 75-125cm thick and composed of fine-grained snow that has not undergone significant wet snow metamorphism. It is composed of small (.5mm or smaller) rounded grains with little to no water visible between grains. Some ice layers or decomposing crusts may be present. The transition between these upper two layers can be abrupt. The layers in this component are pencil to knife hard.

Beneath these two components is “the funny business.” This region is thinner, generally 30-50cm, with a significant weak layer present. It is composed of mixed grain types, generally coarser than the layer above. Grains at the ground may be large and have undergone some wet snow metamorphism due to above freezing temperatures. The grains of the weak layer are 1-2mm, and show some angularities and corners, though they might no longer be classified as faceted grains. In hand-hardness tests, however, they feel like faceted grains.

It is important to note that our model is based on a very limited set of observations. We use it to guide our forecasting rather than as a definitive description of the mechanism for spring avalanches. We continue to wrestle with a number of yet-unanswered questions, such as how warming temperatures, settlement, and the introduction of liquid water affect slab properties such as creep rates and viscosity, and how those contribute to wet slab avalanches. Also unclear is whether wet slab avalanches can initiate in any pronounced textural change in the snowpack, or require a defined weak layer.

Anecdotally, wet slabs are said to occur shortly after the slope in question begins to cool, such as when it comes out of the sun and into shadows (McClung and Schaerer, 1993). We have not yet observed enough wet slab avalanches to guess whether the occurrence of such slides is due to shadowing and cooling, or simply the lag time needed for liquid water to percolate deep enough to accumulate in a weak layer. Our observations in the 2003 cycle are that wet slab avalanches did not occur on the more shaded parts of slopes. They did, however, occur late in the day. Anecdotal evidence also suggests that wet slab avalanche cycles occur only once during a given season (Williams, 2004). Again, we have not observed enough cycles to confirm this observation, though it would seem likely if our conceptual model is accurate.

<u>*5.2 Wet loose snow avalanche case study*</u>

A wet loose avalanche cycle from May 2004 illustrates the influences of solar radiation and temperature on the stability of storm snow over a week. On Monday, May 10, a hasty snow profile in the upper Slopes showed HS 104cm, with nearby sites up to 130cm. Hardness was one finger plus to knife throughout, and nearly all layers were composed of moist, rounded polycrystals. The snow surface was well-frozen old snow with a trace of new snow.

On May 11 and the early morning of May 12, Flattop SNOTEL recorded 20cm of snow (Figure 13). In field observations on May 12, we measured 30-40cm of new snow on the road at roughly the same elevation (1920m) as Flattop. A snowpit above the road at 2060m showed 55cm of accumulated snow, with several density and hardness changes throughout this snow. Hardness ranged from fist to one finger minus, with the softest snow at the surface. Strong winds had blown some slopes bare of new snow while others had drifts a meter or more deep. Visibility was limited, but it appeared avalanche activity during the storm was minimal.

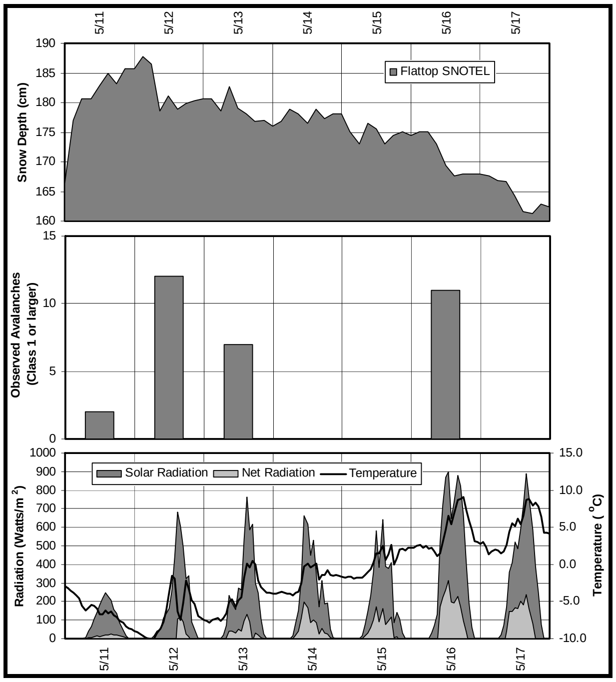

Figure 13: Weather data and observed avalanches above the GTTSR for a loose snow avalanche cycle occurring May 11-17, 2004.

Later that morning, several sluffs hit the road, and four class 1-2 loose slides occurred in Haystack Creek by 1500 hours. All of these were dry loose slides, and most occurred following rapid settlement caused by rising temperatures. Temperatures at Garden Wall climbed 8.5°C in six hours, from -10.1°C at 0700 to -1.6°C at 1300 (Figure 12). From 0400 to 1000, Flattop SNOTEL showed a 5°C temperature rise, and the storm snow settled 8cm or 40%. Average hourly radiation values also spiked. Though skies were obscured most of the day, we noted occasional breaks of diffuse sun. These breaks were sufficient to raise hourly radiation averages from 200-250 W/m^2 on May 11 to 440-680 W/m^2 for four hours on May 12.

The rising temperatures and solar radiation had a rapid effect on the storm snow. By late afternoon on May 12, eight wet loose class 1-2.5 slides hit the road above Triple Arches. These slides left debris up to 6 meters deep on the road (Figure 14).

Figure 14: Class 2 wet loose snow avalanche that occurred in the Slopes on May 12, 2004.

Overnight temperatures dropped well below freezing, and on May 13, temperatures at the Garden Wall weather station again warmed rapidly, climbing from -7°C to 0°C by mid-afternoon. Despite snow showers (2.5cm accumulation) and clouds, average hourly radiation values rose higher than the previous day, peaking at 765 W/m^2 and staying above 500 W/m^2 for four hours. Seven additional wet loose slides occurred on the slopes above the road late that afternoon.

We observed no additional avalanches on May 14 or 15. Temperatures May 14 remained below freezing. By midday May 15 they climbed to 2.5°C and remained there overnight. Hourly average solar radiation peaked at 662 W/m^2 on May 14 and 641 W/m^2 on May 15. Both peaks were lower than those of the previous two days, and neither day had average values over 500 W/m^2 for more than three hours.

On May 16, however, skies cleared and solar radiation and temperatures spiked. Average hourly solar radiation peaked at 901 W/m^2, and there were nine total hours in which averages were higher than 500 W/m^2. Temperatures shot up to 9°C by late afternoon, an increase of 7.5 degrees. The snow depth at Flattop dropped 7cm between 0600 and 1500, leaving snow depth at the site identical to the start of the storm. The station showed a 25mm loss of SWE that day. The crew reported regular avalanche activity by early afternoon, and 11 class 1 or larger slides ran in slopes affecting the road (Figure 15). Eight of these were class 2, and a total of nine hit the road, leaving debris piles up to five meters deep. No slides occurred in this layer the next day, despite similar temperatures, radiation values and settlement.

Figure 15: Class 2 wet loose snow avalanche in Triple Arches on May 16, 2004.

The May 12 and 16 wet loose avalanche cycles share several common characteristics. Both occurred during or immediately following several hours of warming, dramatic spikes in solar radiation, and rapid settlement. There were also interesting differences between the two days of activity. Solar radiation values were much lower on May 12; there were only two hours with averages greater than 600 W/m^2 compared to eight on May 16, and the maximum hourly average was 682 W/m^2 on May 12 versus 901 W/m^2 on May 16.

Wet loose avalanches occurred on days when solar radiation values increased from the previous day or climbed higher than the most recent day of avalanche activity. Overnight freeze, or the lack of overnight freeze, did not seem a primary factor in these slides. Wet loose slides occurred on May 12 and 13 despite strong overnight freezes, and also occurred on May 16 after overnight temperatures rise from 0 to 2.7^{o}C. Wet loose slides did not occur on May 14 or 15 after overnight minimums of -4.2^{o}C and -1.9^{o}C, respectively.

We conclude that wet loose avalanche activity occurred when spikes in water production caused by increased radiation and warming temperatures overwhelmed existing drainage capacity created by a previous spike. In part this process occurs because repeated melt-freeze cycles create larger grain sizes, which drain better due to reduced capillary action, so the older the snow, the more energy needed to create excess water. To generalize, rapid changes led to the wet loose avalanches; the avalanches did not occur when the snowpack or weather conditions remained in a steady-state condition. LaChapelle's axiom holds true: "Any rapid change in the mechanical or thermal energy state of the snowpack is a precursor to avalanching. And I emphasize rapid." (Tremper, 2001)

5.3 Wet slab avalanche case study

In late-April 2003, weather and snowpack conditions aligned to produce a large, widespread wet slab cycle in the mountains surrounding the GTTSR. This impressive event included 10 wet slab avalanches, ranging from destructive class 2 through 4. This cycle provided an unparalleled educational opportunity, and observations we made during this period provided the essential foundation for the development of the conceptual model described in Section 5.1.

March through early-April 2003 was generally cool with several substantial accumulations of new snowfall (Figure 16). Although two short periods of above-freezing average temperatures resulted in three days with measurable SWE loss at 1920m, these decreases were small (10-15mm) and likely did not occur at higher elevations. While we lack conclusive snowpack data prior to the avalanche cycle, it is probable that the basal faceted layer was still dry in mid-April.

On April 18, a high-pressure system began dominating GNP weather, bringing sunny skies and gradually increasing temperatures. Solar radiation values began rising immediately, and by April 20 the average daily temperature measured at Logan VC (elev. 2033m) climbed above freezing. Also beginning April 20, overnight pooling of cold air in the McDonald Valley caused a strong temperature inversion. Despite clear night skies, the warm air advection kept temperatures in the upper elevations well above freezing. On April 20, we observed a destructive class 2.5 glide avalanche on a peak north of the GTTSR. The warming conditions began producing melt at Flattop SNOTEL, which recorded 20mm SWE loss on April 21, with 30mm lost April 22. This melt was obvious during our field observations on April 22, when we noted significantly increased runoff in streams, waterfalls, and down the road surface. By April 22, the temperatures at Logan VC had been

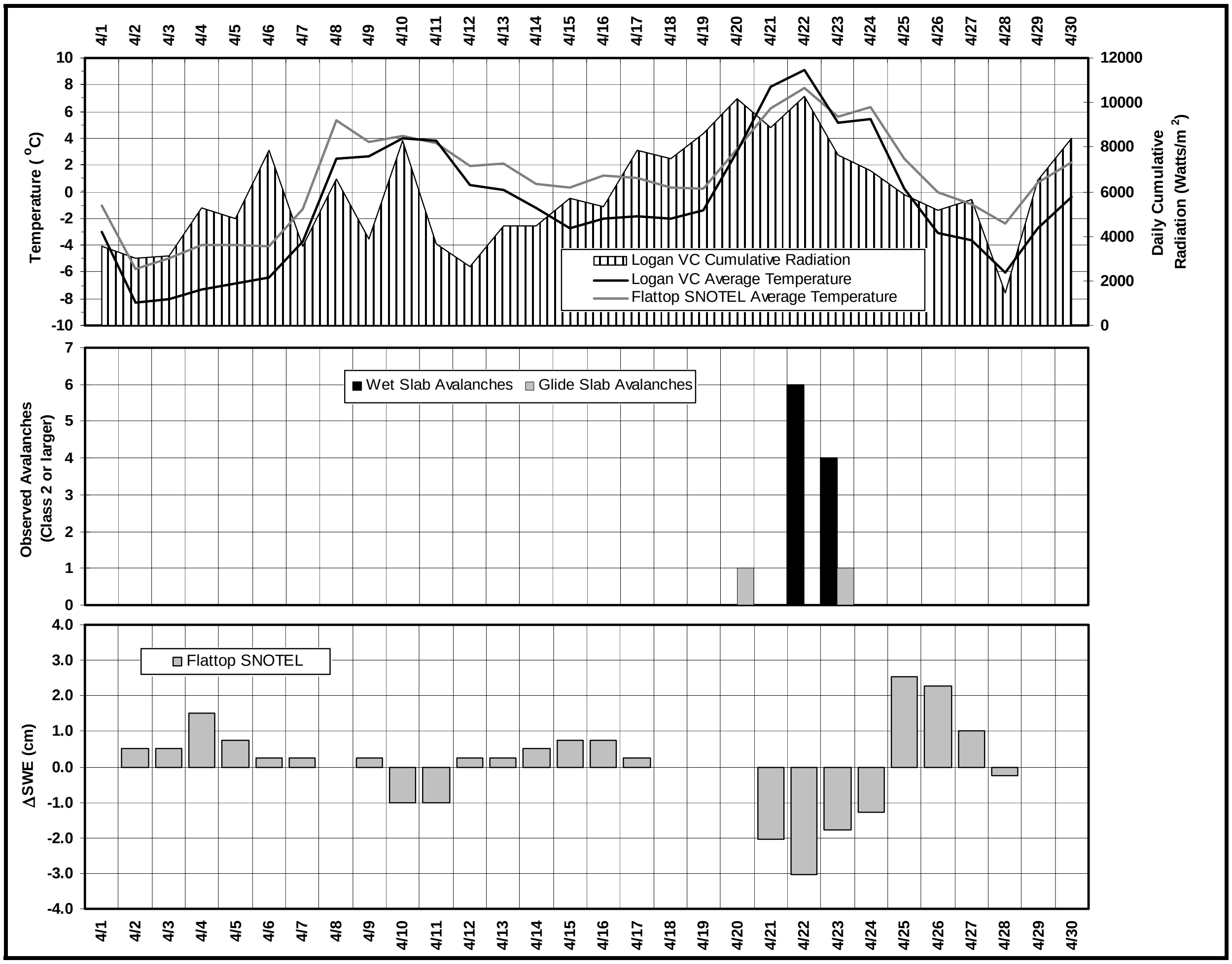

Figure 16: Weather data and observed avalanche occurrence for the April 22-23, 2003, wet slab cycle. Avalanches include those observed on the GTTSR and others noted during an overflight in the vicinity of the road. Weather data is from the Flattop SNOTEL (elev. 1920m) and Logan VC (elev. 2033m) sites.

above-freezing for three nights and meltwater was clearly beginning to move through the snowpack.

On April 22, both the average daily temperature and SWE melt peaked. At 1745, a local bicyclist on the GTTSR stopped before crossing the Haystack Creek avalanche path. While deciding whether to cross, she heard what she described as a gunshot sound. Moments later, literally tons of wet snow were pouring over the roadway (Figure 17).

We classified this wet slab avalanche as a destructive class 4; we estimated it was 250m wide, 1.2-1.5m deep, and ran 1370m vertically (Figure 18). During our investigation of the crown on April 23, we also noticed the crowns of two other climax wet slabs, one a destructive class 4 in the nearby Triple Arches path (Figure 19) and the other a smaller class 2 avalanche.

Figure 17: Debris from the Haystack Creek class 4 climax wet slab avalanche crossing the GTTSR at 1745, April 22, 2003. Corwyn Wyman photo.

On the morning of April 24, we discovered that a hangfire release in Haystack Creek had hit the road the previous evening, and that another class 4 wet slab had also occurred in the Big Bend path, between Haystack Creek and Triple Arches (Figure 20). All four wet slab avalanches observed April 23-24 had occurred on southwest aspects. Later that afternoon, on a helicopter overflight of the Continental Divide, we noted six other climax wet slabs had released; only two were on aspects other than southwest. All avalanches in the wet cycle initiated at elevations between 2300 and 2600m. As we grew concerned that the wet slab avalanches could sequence onto more northerly slopes, the arrival of winter-like weather on April 25th effectively ended the cycle.

Figure 18: The April 22, 2003, Haystack Creek class 4 avalanche viewed from McDonald Creek.

On April 23, we investigated the crown of the Haystack Creek avalanche. A snow profile at the crown revealed a unique structure, possessing properties representative of both dry and wet snowpacks (Figure 12). The remnant facets atop the ice crust were readily apparent as the failure layer and became known as the “Funny Business” for the remainder of the season. We referred to the top 40cm - the zone of solar-induced surface melt – as “the Water Factory.” Between these layers was a relatively homogenous region of small rounded grains less than 0.5mm in size. The “Slab” was characterized by an appearance more similar to that of dry snow – the grains appeared to be dominated by equilibrium rather than wet snow metamorphism.

Figure 19: Triple Arches class 4 climax wet slab, April 22, 2003.

Figure 20: Big Bend class 4 climax wet slab, April 23, 2003.

Prior to the high pressure arriving April 18, the snowpack in the upper-elevation starting zones was likely dry and had changed very little since late-winter. As the Water Factory – the temperature and sun-warmed surface layer – went into around-the-clock production, meltwater began percolating through the snowpack. For the water to bypass the high capillary retention of the small-grained Slab layer, preferential drainage paths likely formed; these eventually delivered the free water to the basal weak layer. Percolating water likely accumulated in the remnant facet layer, the most significant textural discontinuity. The underlying ice crust may have provided an additional impediment to water flow through the weak layer. We hypothesize that as meltwater began to accumulate in the cold, dry faceted snow, it subsequently weakened until it could no longer support the overlying slab, resulting in the widespread wet slab avalanche cycle described.

We remained concerned about the possibility of additional wet slab avalanching throughout the 2003 spring opening. Our conceptual model did not (and still does not) address the possibility of lingering wet slab instability. While most of the southwest-facing paths had run during the late-April cycle, a few had not, despite snow profiles that revealed a similar structure. Why didn't these slide? If another warming event occurred, would the facets weaken further or was the instability gone after the initial introduction of meltwater? Of greater concern was the possibility of wet slab avalanches sequencing from sunny, southwest-facing slopes aspects to cooler northwest-facing slopes. Our snowpits revealed very similar snowpack structures on both aspects. Given a longer warming trend, would the northwest aspects have avalanched as well? Would the instability rise on northwest-facing paths with another period of melt? Since the 2003 season did not bring another heat wave on par with April 18-24 until a month later, we were not able to satisfactorily answer these questions.

Until the end of May, temperatures remained cool and our profiles showed the snowpack structure had changed very little since the wet slab cycle. With snow removal nearly completed, GNP management was beginning to discuss opening the road. Although we hypothesized that additional wet slabs were unlikely after the initial cycle, without prior experience to rely on, we hoped for a sustained warming event to test this theory. By mid-May, this had yet to happen.

Fortunately, May 21 brought the onset of warmer and sunnier weather. Over the next week, Flattop SNOTEL recorded 20-30mm of SWE loss per day, with a total of 150mm lost before the road opened May 30. This melting period pumped significant amounts of meltwater through the snowpack, and with no wet slab avalanche activity, we felt the transition to a stable summer snowpack was completed.

With the benefit of hindsight from the 2003 and 2004 forecasting seasons, it seems one of the more significant lessons of this avalanche cycle is that the presence of a persistent weak layer is necessary in order to have significant wet slab instability. While the weak layer in 2003 was basal facets formed in early-winter, we can envision many other structural weaknesses that could result in wet slab avalanches under the right conditions; surface hoar and near-surface facets are obvious possibilities. In theory, any textural discontinuity could provide a focal point for water accumulation and resultant weakening. However, a persistent weak layer exists in a weakened state, and likely requires less water accumulation to initiate fracture.

In 2004, the snowpack structure and weather conditions stood in sharp contrast to those of 2003. A deep early-season snowpack and warm spring temperatures resulted in a strong, relatively homogenous snowpack during the 2004 plowing season. Further, significant periods of melt in March may have established efficient drainage paths very early in the spring. Profiles performed in early-April dramatically contrasted with those from the 2003 season; no persistent weak layer was found and the entire snowpack showed evidence of wet snow metamorphism. None of the elements that our wet snow model suggested as necessary for wet slab avalanches were present, and we observed no delayed-action, climax wet slabs in 2004.

6. FUTURE REFINEMENT OF TOOLS AND TECHNIQUES FOR WET SNOW FORECASTING

6.1 Data relevance for wet snow avalanche forecasting

During the past two seasons, we have observed that forecasting for wet snow avalanches relies on different kinds of information than forecasting for dry snow avalanches. Whereas increasing instability in a dry snowpack is often apparent, increasing instability in wet snow is subtle and must be inferred. One of the tenets of predicting dry snow avalanche hazard is the need to collect Class 1, low entropy, or "Bull's-eye" data. Observations of instability clues such as recent natural avalanche activity, avalanches resulting from explosive testing, cracking and collapsing of the snowpack, and the results of stability tests in representative locations readily indicate instability in a dry snowpack (McClung and Schaerer, 1993; LaChapelle, 1980; Fredston and Fesler, 1994).

These Class 1 factors do not have corollaries when forecasting for wet snow avalanches; traditional stability tests are not representative, explosive testing is of questionable value, and wet snow avalanche hazard, especially wet slab instability, is often so acute that the classic instability clues such as recent avalanche activity may only be present when it is too late. So we have found ourselves relying on Class 2 and 3 factors from which we infer wet snow instability. The primary factors we use are snowpack structure, minimum and maximum temperatures, SWE fluctuations, and net radiation. We have found a number of other clues that consistently indicate wet snow stability. These include a frozen snowpack, shallow ski pole and ski penetration during the heat of the day, and the presence of red algae on the snow surface. It appears that stable conditions in a wet, spring snowpack are more apparent than in a dry snow cover, so our forecasting infers wet snow instability from Class 2 and 3 factors and the presence or absence of consistent signs of stability.

6.2 Development of new tools

The necessity for more indirect data encourages us to investigate non-traditional measurements and tools. In addition to standard weather parameters, we use SWE loss, net radiation balance, and snow surface temperature. Because SWE loss seems to be an important indicator of the presence of liquid water, the installation of a lysimeter in a representative location would seem beneficial. A lysimeter might provide more accurate measurements of meltwater percolation through the snowpack. When performing snow profiles, we often struggle to accurately quantify the water content of the various snow layers. Use of time domain reflectometry (TDR) to measure water content (Waldner et al, 2001) might allow more accurate temporal monitoring of water saturation. Perhaps such a device installed *in situ* could monitor the real-time wetting of a known weak layer. Eventually we hope our weather and avalanche database will provide the necessary data to run a nearest-neighbors model, providing us with yet another tool in the quest for relevant information.

6.3 Explosive testing or control

A reader might wonder whether we use explosives for stability testing or hazard mitigation. GNP has sporadically experimented with avalanche mitigation tools over the years. These have included attempts to trigger avalanches using the sonic booms of supersonic military jets, use of a 75-mm recoilless rifle, and helicopter bombing of a cornice. Explosive use is currently a controversial topic in GNP. A request in the winter of 2004 to use explosives on Park lands to mitigate avalanche hazard on the Burlington Northern Santa Fe Railroad on the southern Park boundary (Reardon et al, this volume) highlighted this controversy.

The use of explosives for stability testing or avalanche control would raise a number of environmental concerns. GNP manages 95% of the Park as designated Wilderness. The GTTSR bisects this Wilderness, and the use of explosives in the start zones to protect a structure outside the Wilderness boundary might violate National Park Service policy. In addition, a proposal for explosive testing or control would raise questions about wildlife disturbance, such as the possible effects on newly awakened grizzly bears, which are known to frequent the GTTSR vicinity in the spring.

If GNP were to deem explosives an appropriate tool, using them would encounter several practical issues. For one, the delivery of explosives to the starting zones would be problematic. Nearly all the starting zones are inaccessible on foot or on skis. Artillery or helicopter placement would be the only practical options, and each has its own set of complications, not the least of which are daunting expense and regulations, and the lack of consistent flying weather.

Finally, the use of explosives is generally considered to be less effective in wet snow than in dry snow. Wet snow tends to attenuate the explosive shock, which can be countered to a certain extent through the use of large explosive charges, But since wet snow can quickly go from stable to extremely unstable and back again in a short period, the timing and placement of explosives would need to be impeccable to achieve any degree of confidence in the results. If we were able to accurately predict this critical period, the use of explosives probably would be unnecessary.

A related possibility is to control wet slab, and particularly glide, avalanches using aerially-deployed water drops, like those used for wildland firefighting. While at first glance the concept seems far-fetched, it might be a far more environmentally sound procedure. Foreseeable disadvantages are the possible need for prohibitive amounts of water and the associated expense.

7. CONCLUSION

In 2002, Glacier National Park established a formal program to provide avalanche hazard forecasts for the spring-time snow removal operations on the Going-to-the-Sun Road. During the season, which typically runs from April through June, equipment operators removing snow from the upper 23km segment of the GTTSR are exposed to a variety of avalanche hazards, including loose snow avalanches, wet and dry slab avalanches, and glide avalanches. In this road section, the GTTSR lies mid-track in numerous large avalanche paths capable of destructive class 4 slides.

The GTTSR lies in a northern intermountain snow climate, notable for large seasonal fluctuations in snowpack structure and highly unpredictable spring weather.

The mechanics of wet snow avalanche instability are not as well defined as for dry snow. Based on a somewhat limited dataset collected during the three years of program operation, we have developed a conceptual model for wet snow instability. While future seasons will undoubtedly help us to refine this model, it has provided a starting point for operational forecasting of natural wet snow avalanches. The conceptual model includes snowpack and weather processes that may lead to either stability or instability.

As an illustration of the model, we examined two case studies involving wet loose snow and wet slab avalanches, respectively. In the spring, loose snow avalanches occur commonly and are most frequent when the upper region of the snowpack cannot effectively drain meltwater, resulting in water accumulation in, and subsequent weakening of, the surface layers. These conditions are likely in the early spring and following new snowfall. The heat-absorbing capacity of rocks can also overwhelm the drainage capacity of adjacent snow.

In contrast, climax wet slab avalanches are less frequent due to the need for a specific combination of snowpack and weather factors. If a weak layer or other significant textural discontinuity is preserved through the late winter and into the spring, a sudden and sustained warming event may cause a dramatic rise in the wet slab instability. Solar radiation and warm ambient temperatures produce meltwater at the surface which can quickly reach a deep weak layer, largely bypassing the mid-pack via preferential flowpaths. Our experience and that of others indicates that several nights without a freeze are necessary to provide a sufficient pulse of water to cause weakening and potential fracture of a deeply-buried weak layer. For both climax wet slab avalanches and wet loose avalanches, it appears that it is the rate of change rather than absolute values of temperature, radiation and other weather parameters that lead to instability and avalanching.

Presently, our conceptual model does not address the likelihood of additional wet slab avalanches releasing after an initial cycle, either on similar aspects or more shaded ones. Anecdotal evidence suggests that additional wet slab avalanches on similar aspects are unlikely, but this does not address the possibility of wet slabs sequencing onto shadier slopes.

A lack of Class I stability factors pertaining to wet snow has encouraged some creativity in the search for high-quality data. For the 2004 season, we added a weather station with a net radiation sensor and a proprietary database to our arsenal, but other tools such as TDR water content measurements, lysimeters, or nearest-neighbor models may prove useful in the future.

8. ACKNOWLEDGMENTS

We would like to thank the many avalanche professionals who readily shared with us their observations and experiences with spring avalanches and forecasting. Their insights have led us to our conceptual model. In particular, we would like to thank Paul Baugher, Karl Birkeland, Tom Kimbrough (Kimbrough-san), Chris Landry, Mark Moore, Marty Schmoker, Craig Wilbour, and Knox Williams. We would also like to thank Mark Dundas for his assistance with just about everything. Blase Reardon would also like to thank Dan Fagre and Karen Holzer for generously supporting extended time away from his regular duties. Lastly, we would like to express our appreciation for the Glacier National Park road crews and foreman, who do dangerous work with spirit and professionalism, and who watch out for us while we watch out for them.

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