NATURAL AVALANCHES AND TRANSPORTATION: A CASE STUDY FROM GLACIER NATIONAL PARK, MONTANA, USA

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In January 2004, two natural avalanches (destructive class 3) derailed a freight train in John F. Stevens Canyon, on the southern boundary of Glacier National Park. The railroad tracks were closed for 29 hours due to cleanup and lingering avalanche hazard, backing up 112km of trains and shutting down Amtrak's passenger service. The incident marked the fourth time in three winters that natural avalanches have disrupted transportation in the canyon, which is also the route of U.S. Highway 2. It was the latest in a 94-year history of accidents that includes three fatalities and the destruction of a major highway bridge. Despite that history and the presence of over 40 avalanche paths in the 16km canyon, mitigation is limited to nine railroad snow sheds and occasional highway closures. This case study examines natural avalanche cycles of the past 28 winters using data from field observations, a Natural Resources Conservation Service (NRCS) SNOTEL station, and data collected since 2001 at a high-elevation weather station. The avalanches occurred when storms with sustained snowfall buried a persistent near-surface faceted layer and/or were followed by rain-on-snow or dramatic warming (as much as 21^{o}C in 30 minutes). Natural avalanche activity peaked when temperatures clustered near freezing (mean of -1.5^{o}C at 1800m elev.). Avalanches initiated through rapid loading, rain falling on new snow, and/ or temperature-related changes in the mechanical properties of slabs. Lastly, the case study describes how recent incidents have prompted a unique partnership of land management agencies, private corporations and non-profit organizations to develop an avalanche mitigation program for the transportation corridor.

Keywords: Avalanche History, Avalanche Forecasting, Natural Hazards, Northern Rocky Mountains

1. INTRODUCTION

1.1 History and Setting

John F. Stevens Canyon lies on the southern and western boundaries of Glacier National Park (GNP) (Figure 1). It is drained by the Middle Fork of the Flathead River, a National Wild and Scenic River, and Bear Creek, a tributary of the Middle Fork. The Great Bear Wilderness (GBW) lies to the south and west of these two waterways. The canyon serves as a major regional transportation corridor; the Burlington Northern Santa Fe (BNSF) Railroad and U. S. Highway 2 pass through the canyon (Figure 2).

The railroad was completed in 1891; a second set of tracks allowing simultaneous east and westbound traffic was opened in 1910. Railroad operations are centered in Essex (elev. 1150m). From 32 to 44 trains travel through the canyon per day; the trains carry a total of 61 million tonnes of freight per year. Both the number and length of trains have increased over the past decade. Some trains haul hazardous materials, and Amtrak passenger trains run through the canyon twice-daily (*Daily Inter Lake*, March 8, 2004). Much of the freight in the canyon is either grain or shipped in containers. The tracks lie within 30m of the GNP boundary.

Figure 1: Aerial photo showing south-facing avalanche paths on Running Rabbit Mountain (elev. 2339m) in Glacier NP. Natural avalanches derailed a train here January 28, 2004. BNSF Railroad and highway visible lower left. Photo by D. Stoneman.

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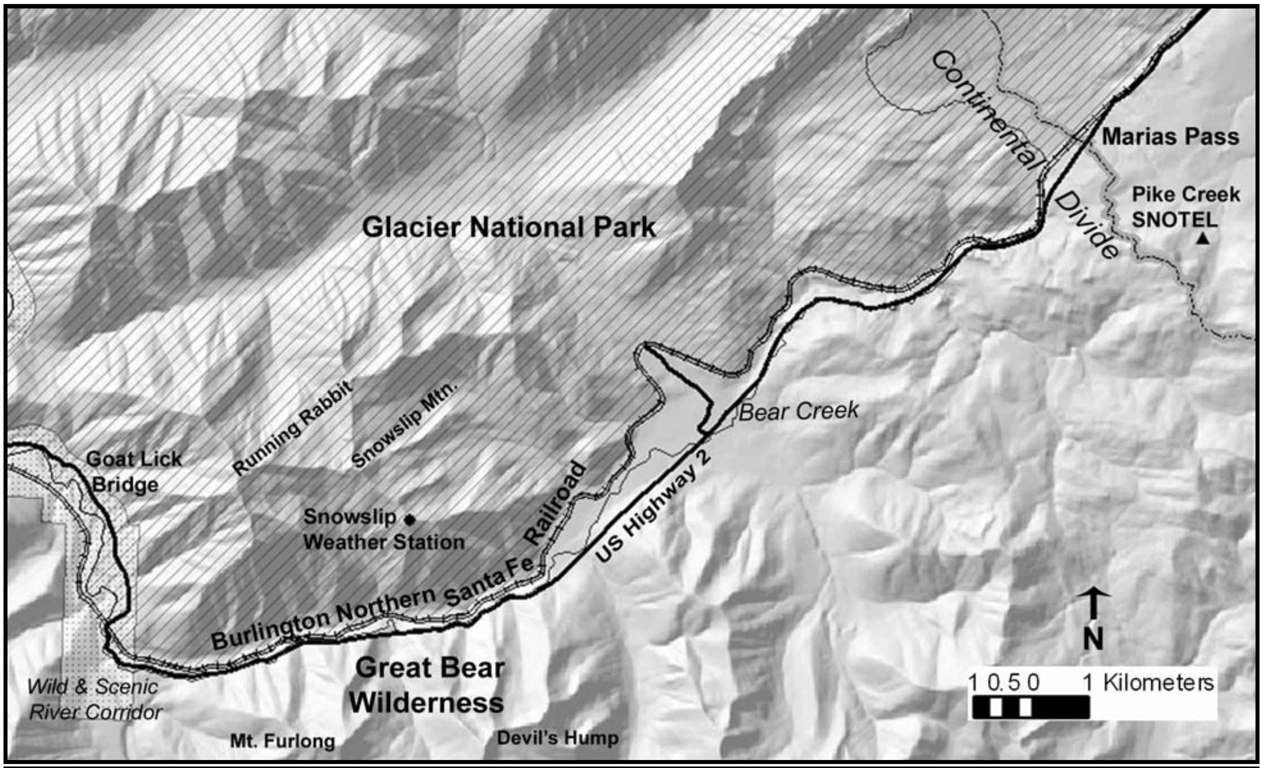

Figure 2: Map showing section of John F. Stevens Canyon where avalanches disrupt traffic on railroad and highway. Sites discussed in text are marked on map.

U. S. Highway 2 opened to traffic in 1930. It was not kept open during the winter until the early 1940's. At present it is the only year-round route across the Continental Divide for several hundred kilometers north and south. The Montana Department of Transportation (MDOT) estimates more than 1000 vehicles travel the highway daily during the winter (*Great Falls Tribune*, Jan. 30, 2004).

Over 40 avalanche paths threaten the transportation infrastructure in a 16km section of Stevens Canyon (Figure 3). These are concentrated in the 8.5km stretch of Bear Creek between its junction with the Flathead River (elev. 1175m) and the small community of Snowslip (elev. 1359). Natural avalanches have disrupted traffic in the canyon since 1910, possibly earlier. No avalanche control has been conducted, so accounts of the disruptions comprise a long-term record of natural avalanches.

1.2 Climate and Snowpack

The John F. Stevens Canyon is in a snow-dominated region that receives over 70% of its annual precipitation at higher elevations as snow. The Continental Divide strongly influences snowfall and weather in Stevens Canyon, often acting as a physical barrier between predominantly Maritime weather patterns on the western side and predominantly Continental weather patterns on the eastern side. Annual precipitation can vary from 40cm on the eastern side adjacent to the plains to 350cm on high-elevation slopes on the western side. A westerly flow and mild, moist Pacific systems dominate winter weather for Stevens Canyon, which is west of the Divide. Periodic influxes of cold Arctic air occur, often coming from east of the Divide and rushing down the Canyon. In general, more variable conditions prevail in areas east of the divide (Finklin, 1986).

Winter months are the cloudiest; the November-January period receives only 20-35% of the maximum possible sunshine for that time of year. December and January are the wettest months of the year and over 55% of the annual precipitation is received during the 5-month period of November-March. The low-elevation Essex site in the Stevens Canyon receives 1000mm of annual precipitation and 400cm of snow. Marias Pass, at the head of the Stevens Canyon, receives 680cm of winter snow.

Serreze et al. (1999) summarized the basic patterns of snow accumulation and ablation in eight regions they define in the western U.S.

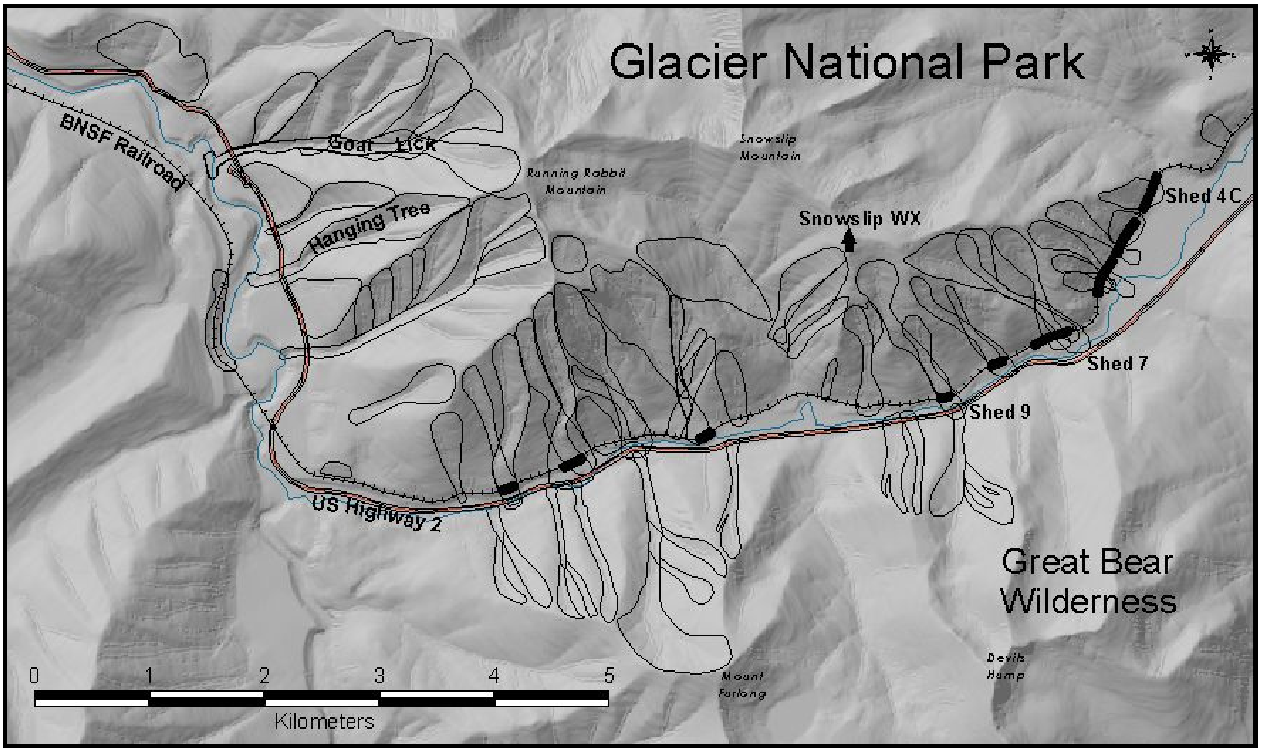

Figure 3: Avalanche Paths in John F. Stevens Canyon.

The accumulation-ablation pattern for the Stevens Canyon is most similar to the pattern for the Idaho/Western Montana region and both mean maximum snow water equivalent (SWE) and snowpack persistence are greater than in all regions defined by Serreze et al. (1999), with the exception of the Sierra Nevada and Pacific Northwest. Interannual variation in April 1 SWE averaged 26.8% for nearby SNOTEL sites and the Pacific Decadal Oscillation (PDO) strongly influences long term SWE trends on a 20-30 year cycle (Selkowitz et al., 2002).

Although large seasonal fluctuations in snowpack depth and structure occur, Stevens Canyon would most commonly be classified as lying in a northern intermountain snow climate (Mock and Birkeland, 2000). December and January average temperatures at Pike Creek SNOTEL (-7^{o}C and -6.7^{o}C respectively) are characteristic of intermountain snow climates. The average seasonal SWE of 74cm is less than the 100cm threshold for coastal snow climates. Rainfall is not rare, however, and the canyon can receive more than 8cm of rain per winter. These rain-on-snow events subject the typically intermountain snowpack to coastal conditions, a combination which can result in dramatic avalanche events.

2. AVALANCHE HAZARDS AND MITIGATION

2.1 Avalanche paths and types

Over 40 avalanche paths threaten transportation infrastructure in Stevens Canyon. Most of these paths are situated in GNP on the southern flanks of Running Rabbit (elev. 2339m) and Snowslip (elev. 2222m) mountains (Figures 1, 3-7). These avalanche paths have vertical falls of 100m to 1000m, with most paths falling 500m to 700m over 1-1.5km. Most of these paths have southerly aspects, with a few having east or west aspects. Our field observations show that they are generally cross-loaded by prevailing westerly winds. The larger paths in this group have multiple starting zones feeding into confined and sometimes deeply channelized tracks (Figures 5 and 7). Starting zone slope angles are generally shallow (33-36^{o}). Track angles are 11-25^{o} (Martinelli, 1984), though our field studies have measured angles from the highway to the starting zones as high as 27^{o}. The significant exception to these patterns is a short (170m), east-facing, unconfined and steep slope with a very short track at the east end of the canyon (Figure 6). On the south side of the canyon, there are also north-facing paths on Mt. Furlong (elev. 2253m) and Devils Hump (elev. 2337m) in the GBW. These paths are mostly steep gullies with steep starting zones and vertical falls of 300-500m.

The avalanche paths in Stevens Canyon can produce medium to large sized, wet and dry slab avalanches. In most instances, avalanches large enough to reach the highway or railroad and disrupt traffic would be classified as destructive class 2.5-4, though there are a few places where sluffs can reach the railroad or highway. The largest avalanches are dry snow avalanches (Martinelli, 1984). Many avalanches that disrupt transportation in the canyon are wet slab avalanches. These can leave very large debris piles when they release piecemeal and run down the path in multiple surges (Martinelli, 1984). Reports of avalanches often note that the slides originated mid-slope, at elevations of 1700m and higher (Beals, 1910; Martinelli, 1984).

Figure 5: Aerial photo showing (L-R) Shed 8 and Shed 7 avalanche paths on Snowslip Mountain, with cornices formed by prevailing west winds. Visible in lower center is east end of Shed 7, where slides have blocked entrance to the shed numerous times. Photo by D. Stoneman.

Where snow sheds do not protect the tracks, the railroad also employs signal fence to warn dispatchers and engineers of avalanche debris blocking tracks. The fence is an avalanche detection system (McClung and Schaerer, 1993) that consists of wires strung between posts on the uphill side of the tracks. When an avalanche breaks the wires, it triggers a blocking signal for trains on either side. The blocking signal requires trains to proceed at a reduced speed, in order to prevent them from running into debris and becoming stuck or derailing. Most signal fence is located in smaller avalanche paths that run more frequently but with less volume than the larger paths. The signal fence requires extensive maintenance and must be replaced after avalanches trigger it. This maintenance often places signal maintainers and smaller railroad vehicles in avalanche paths during periods of avalanche hazard. Even small slides can pose significant risk in these situations.

Figure 6: Aerial photo of burned-out snow shed (4-C) showing steep, unconfined avalanche path. Photo by D. Stoneman.

The highway has fewer defenses. Martinelli (1984) recommended doubling the clearance under the Goat Lick Bridge from 16m to 32m to allow slides to pass beneath it. When it was rebuilt in 1979, the channel was excavated only slightly, increasing the clearance under the bridge to 19m (Figure 7). Since then, debris has filled Snowslide Gulch to within 3m of the bridge, but has struck the bridge only once, in February 1982.

At the I-Beam path, the highway has been raised above the track by filling the channel and placing a culvert through the fill. The embankment acts as a dam, reducing the number of avalanches that reach the road surface there. Historic accounts of avalanche incidents indicate that slides disrupted traffic on the highway in this path multiple times after 1939. Slides in recent years, however, have filled the drainage nearly to the level of the road surface but have not reached it.

Figure 7: Aerial photo of west-facing Goat Lick Avalanche path showing multiple start zones and deeply channelized track under rebuilt highway bridge. Photo by D. Stoneman.

Natural reforestation of the slopes above the railroad and highway has also served to reduce the number of slides affecting transportation in Stevens Canyon. Wildfires in the early part of the century, notably 1910 and 1923, left many slopes bare of trees. Natural reforestation since then has reduced or eliminated slides on short, steep slopes that previously threatened either the railroad or highway. One example is the slope between Sheds 7 and 8, which is now densely forested; however, Jenks (1933) listed multiple avalanche incidents there early in the 20^{th} century. A second is Hanging Tree North, where the Montana Highway Department proposed terracing of the start zone in 1957 that the National Park Service did not allow (Emmert, 1957). Photos from the time show far less vegetation on the slope than exists presently, and few slides have reached the highway there in recent years. Conversely, a wildfire in the mid-1990s at the Unnamed slide path burned a stand of mature trees and created or reopened a slide path where an avalanche derailed a train in 2004. In Stevens Canyon, fire suppression and resulting reforestation can be viewed as a form of avalanche mitigation.

During periods of avalanche hazard, the primary protection for traffic on the railroad and highway has been closures. These closures typically occur after slides have blocked the railroad or highway. Because there is no forecasting program in place, closures are not undertaken in response to rising hazard. In most cases, the railroad has stopped traffic only long enough to clear avalanche debris. During significant avalanche cycles in December 1996 and January 2004 the railroad restricted traffic to the outside track and/or delayed passenger trains. In 2004, the railroad also stopped all trains for 29 hours. The protocol for such closures is informal. The highway sometimes closes due to reduced visibility and drifting snow, effectively eliminating the risk to traffic during rising avalanche hazard. The highway also generally reopens shortly after avalanche debris is removed from the road. In the past 10 years both the railroad and highway have consulted with Glacier Country Avalanche Center (GCAC) when deciding the timing of cleanup operations and reopening. The closure of the railroad and highway can have significant economic impacts, and the potential of such impacts influences decisions regarding closures.

2.3 Avalanche Mitigation Planning

The January 2004 incident in which avalanches derailed a BNSF train and struck a commercial truck on U. S. Highway 2 generated considerable interest and controversy. The resulting closures forced highway traffic to detour 450km, shut off east and west bound passenger service on Amtrak, and led to the backup of over 112km of freight trains. There were immediate discussions between a wide range of business and government officials, including railroad representatives, governors of two states, local and national offices of the National Park Service, and others. Local media reported the incident immediately, with follow-up articles the next six weeks (*Hungry Horse News,* March 11, 2004). Much of this interest and controversy was prompted by the railroad's proposal to use explosives to test snow stability on slopes above the tracks.

One important outcome of this controversy was a revived interest in planning for mitigation of future avalanche hazard. The Great Northern

Environmental Stewardship Area (GNESA) has led this planning effort. GNESA is an affiliation of parties with a financial, economic, scientific, political, management or regulatory interest in Stevens Canyon. It includes representatives of state and federal agencies such as GNP, the Flathead National Forest (FNF), and MDOT; BNSF Railroad, utility companies, canyon businesses; and non-profit advocacy groups such as GCAC. GNESA formed before the recent avalanche incidents. It was a response to grain spills along the BNSF tracks that led to the deaths of grizzly bears, a threatened species. The bears fed on spilled grain along the tracks and were hit by trains.

GNESA provides a forum for competing interests in the canyon and a mechanism for pooling resources among them. Several committees are examining issues that influence avalanche safety in the corridor. BNSF, GCAC, and the USGS have partnered to install radio telemetry equipment to the Snowslip Weather Station (Figure 8). Communication protocols and infrastructure for avalanche incidents have been improved, forecasting alternatives are being considered, and work has begun on an avalanche atlas and detailed risk assessment. Clearly, a better understanding of natural avalanche frequencies and their climatic drivers will substantially strengthen GNESA's efforts.

3. WEATHER AND SNOWPACK PATTERNS IN SIGNIFICANT AVALANCHE CYCLES

3.1 Data

We compiled a detailed and representative history of avalanche activity in Stevens Canyon for the period 1910-2004 from a variety of relevant sources. C.O. Jenks, a Great Northern Railroad official, maintained a map delineating the sites and dates of slides that affected the railroad in the canyon from 1910-1933 (Jenks, 1933b). Ranger D. Panebaker compiled a partial history of avalanches in the Walton area (circa 1983). Martinelli (1984) detailed the avalanche cycles of February 1979 and 1982. Butler and Malanson (1986) based a partial history of large-magnitude avalanches in the Canyon on historic photographs, newspaper accounts, and tree-ring data from the Shed 7 and Goat Lick paths.

We consolidated the information in these histories and attempted to fill the gaps with data from a variety of primary historical sources. These included personal field observations, accounts in the Walton Ranger Station logs, interviews with railroad and highway employees, and reports on the Glacier Country Avalanche Center website (www.glacieravalanche.org). We also reviewed correspondence, reports and other material archived in Glacier National Park and at the Minnesota History Center, which houses many records from the Great Northern Railroad.

Figure 8: Snowslip Weather Station, elev. 2134m.

Among these sources, accounts of smaller avalanche events tend to be the least complete. Larger avalanche events, especially those that disrupted traffic on the highway or railroad, are better documented. Records of these incidents are typically specific regarding the particulars of the most notable avalanche such as time and location, extent of debris, period of closure, and damage. However, these records tend to omit the details of slides that occurred during the same event but with less dramatic results. Martinelli (1984), for example, briefly describes 19 avalanches in addition to the one that destroyed the Goat Lick Bridge, then notes "Many other avalanches ran, but caused no problems to structures or people." Despite the lack of standardization, many incidents are described in multiple sources, allowing information to be cross-referenced and verified, and some omissions to be rectified. When combined, information from these sources comprises a representative though incomplete record of avalanche occurrence in the canyon for the period 1910-2004.

For our analysis of weather influences, we relied on data from the USDA National Resources Conservation Service (NRCS) Pike Creek SNOTEL station. SWE data are available from this station for the 1977-2004 water years. Precipitation data are available for the 1981-2004 winters, and temperature for 1989-2004 winters. The Pike Creek SNOTEL is located 0.75km east of the Continental Divide and 3km southeast of Marias Pass, at an elevation of at 1807m. That location is 11-18km east of the avalanche paths in the study area and at roughly the same elevation as the lower start zones.

We used SWE measurements from Pike Creek SNOTEL as a proxy for snowfall in Stevens Canyon. The NRCS uses SWE measurements from the station to estimate snowpacks on both sides of the Divide, and our field observations have shown that data from the station roughly represent snowfall patterns in Stevens Canyon. We used SWE rather than precipitation because a comparison of SWE and precipitation values during the avalanche events we analyzed showed very minor differences in the amounts recorded during the events. The Pike Creek SNOTEL data includes snow depth measurements for the winters 2001-2004; this data allows some calculation of snowfall and snow density for avalanche cycles in these years.

We supplemented the Pike Creek data with data from a USGS weather station installed on Snowslip Mountain in December 2001 (Figure 8). This station records data from a standard suite of sensors. The station is located at 2134m immediately above the avalanche paths on Snowslip Mountain that affect the railroad and highway. It provides site-specific measurements of temperature, relative humidity, wind and solar parameters in the starting zones of these paths. The site is unsuitable for collecting precipitation data due to wind effects. The station was not telemetered at the time of this study and thus not available for forecasting during the avalanche cycles we describe.

Secondary sources of weather and snowfall data for the area include a snow course and weather records from stations near Marias Pass (elev. 1591m) and stations at or near Walton (elev. 1150m). Where relevant, we used data from these stations to supplement the Pike Creek and Snowslip data.

3.2 Avalanche History 1910-2004

Our avalanche record contains 81 avalanche events that disrupted traffic on the BNSF Railroad, U. S. Highway 2, or both. We defined traffic disruptions as any closure or delay due to avalanche hazard or clearing debris from the road surface or tracks. This definition allowed us to focus our analysis on events of sufficient size and scale to have local or regional economic impacts. It also enabled us to rely on the data that is the most consistent among different events recorded by different observers.

Most avalanche events involved multiple natural avalanches, often spread over several days. These 81 avalanche events occurred in 46 winters of the 94-winter period (Figure 9), for a frequency of once every 2.04 winters. The most events recorded in a single winter were five.

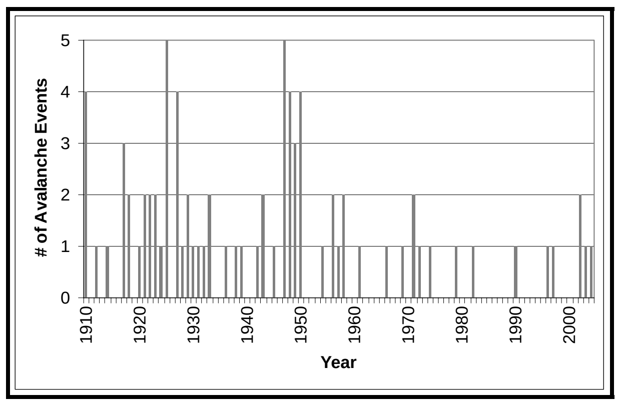

Figure 9: Avalanche Events (n=81) by Year, 1910-2004.

The avalanche events occurred from mid-December through the last week in April (Figure 10). They were concentrated, however, in January and February, with a peak the last week in January and the first week in February. We suspect that the small group of avalanche events that occurred in the last two weeks of April resulted from different conditions and processes than the events distributed through the winter. The late-season avalanches are likely wet snow avalanches due to warming.

The avalanche history contains a number of serious accidents in addition to the 2004 incident. An avalanche derailed six cars of a mail train on March 4, 1929, rolling them several times. The accident killed three men (*Kalispell Weekly News,* 1979). Another derailment in 1947 derailed and punctured a tanker car full of syrup, which bears fed on for weeks (Glacier National Park, 1947). In 1950, a slide buried two workers and

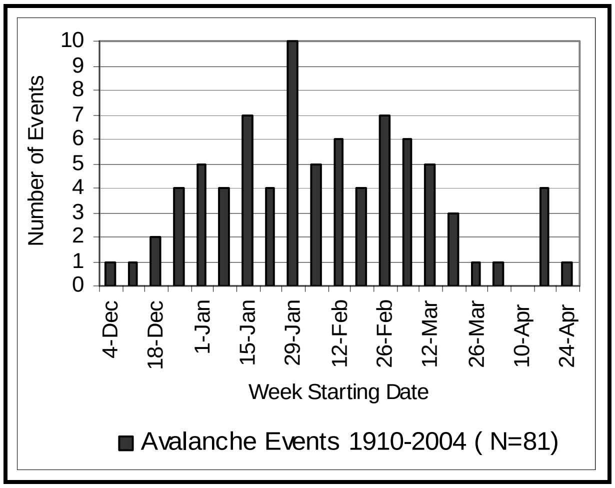

Figure 10: Avalanche events by week, 1910-2004. Avalanche events grouped by first date traffic disrupted.

partially buried a bus driver while they were working to clear debris from an earlier slide. The two workers were reportedly buried under 4m of snow. Other workers dug out one man quickly; they recovered the second after an 80-minute burial, unconscious but alive (*Hungry Horse News*, January 27, 1950). The highway remained closed for most of the next month. A series of large wet slides washed away the Goat Lick Bridge on Highway 2 in February, 1979. The bridge was nearly intact when it came to a rest next to the Flathead River, 75m downhill but 115m upstream of its starting location (Martinelli, 1984). In 1997, an avalanche hit a pickup driven by a railroad employee, carrying him and the truck off the highway (personal comm. Jacobson, 1997; Yudysky, 2004).

3.3 Significant Avalanche Cycles 1977-2004

We examined avalanches and weather patterns from the winters of 1977-2004 because this 28-winter period offered the most complete and representative avalanche and weather data. The period spans 25% of the 112 winters since the railroad was completed through the canyon and 30% of the 94-year period of recorded avalanches in the canyon. Our avalanche record for the 1977-2004 winters in Stevens Canyon contains 18 distinct natural avalanche events that occurred in 10 different winters.

Though most of these avalanche events produced slides that ran to within 100m of the highway or railroad, we limited our analysis to the 10 events in the record that disrupted highway and/ or railroad traffic (Figure 11, Table 1). We termed this group of avalanche events the significant avalanche cycles. Of these 10 significant avalanche cycles, five disrupted traffic on both the highway and railroad. One of the remaining cycles disrupted only railroad traffic and four appeared to have disrupted only highway traffic. Records were unclear as to whether several of these last cycles, in which some slides crossed snow sheds, also disrupted traffic on the railroad.

Figure 11: Photo looking west down John F. Stevens Canyon at debris over Shed 7 and Shed 8. Highway on left. Photo Feb. 15, 1979 by M. Martinelli.

The significant avalanche cycles occurred with a frequency of once every 2.8 years in the 1977-2004 period. That frequency is similar to but slightly lower than the frequency for the entire 1910-2004 period. It is higher than that estimated by Butler and Malanson (1985), and higher than the 5-10 year frequency cited by McClung and Schearer (1993) as typically acceptable for highway traffic.

To facilitate comparisons between significant avalanche cycles, we assigned each major cycle to 10-day analysis periods that included the week prior to the peak of avalanche activity, the peak day of avalanche activity, and the two days immediately following that. The peak of avalanche activity for each significant avalanche cycle falls on day 8 of the 10-day analysis period, regardless of its actual calendar date. For example, data for the January 28, 2004 cycle starts on January 21 (day 1) and ends January 30 (day 10), with the day of peak avalanche activity on January 28 (day 8).

Date of Avalanche Peak	Traffic Disruption	8-day SWE total	# of days w/ recorded slides	# of recorded slides	Notes/Damage/Close Calls
February 12, 1979	Highway and railroad	58mm	2	20	18 avalanches across railroad; closed for 2.5 days. Goat Lick Bridge on U.S. Highway 2 destroyed causing 30-day, 450-km detour. 1 nearby crown 1700m wide.
January 23, 1982	Highway and railroad	102mm	2	6	Microwave relay building moved 30m by slide; vehicle w/ 3 occupants hit by slide; no injuries. Train stuck in debris 4.3m deep.
February 20, 1982	Highway	132mm	2	2	Debris on Goat Lick Bridge & road 7m deep & 300m wide; debris dammed river
January 31, 1990	Highway	137mm	1	1	Debris on road 1.8m deep & 75-100m wide.
February 8, 1996	Highway and railroad	81mm	2	6	Debris 4-5m deep & 20m wide blocked road; debris 70m wide on tracks caused 7 hours cleanup & delay
December 30, 1996	Highway	102mm	3	16	Freight train hit by slides & stuck in debris 4m deep. Railroad blocked 4 other sites & closed ~18 hrs; restricted 72+ hours; 300m signal fence destroyed. 5+ slides on road. Vehicle hit; 2 occupants unhurt
January 25, 2002	Highway	109mm	1	12	Debris partially dammed river at Goat Lick; debris 6m deep & 60m wide blocked road; debris over sheds on railroad.
March 11, 2002	Railroad	94mm	1	1	Debris 1m deep & 15m wide blocked both tracks & damaged signal fence; short delay.
March 11, 2003	Highway and railroad	142mm	4	23	Debris dammed Bear Ck, destroyed utility lines, blocked road 2 places & railroad. Locomotive hit by debris; Amtrak delayed 48 hrs
January 28, 2004	Highway and railroad	89mm	2	9	Freight train hit by 2 slides & derailed in 2 places; 3rd slide misses crew. Truck hit by small slide. Railroad closed 29 hrs.
Mean		105mm	2	10.75	

Table 1: Avalanche events that disrupted traffic on railroad or highway, 1977-2004.

We defined peak avalanche activity as the first day of avalanche-related disruptions. The most consistent and reliable data available for significant avalanche cycles was the date traffic was first disrupted. In all but one case (2003), the greatest number of avalanches was recorded on the first day of avalanche-related disruptions. For 2003, we used the day with the greatest number of avalanches (destructive class 2.5 or greater), which preceded the traffic disruptions by one day.

We felt that this convention – 10-day analysis periods with peak avalanche activity on day 8 - was the best gauge of avalanche hazard when no formal hazard assessments were available. It allowed us to reconstruct and compare the conditions prior to significant avalanche cycles. It also provided a marker for the thresholds at which large-magnitude and/ or widespread natural avalanches occurred.

The major cycles lasted from 1-4 days, with a mean of 2 days. The number of recorded avalanches in each cycle ranged from 1 to 23, and the number of recorded avalanches in a day ranged from 1 to 12, with a mean of 5.3 on the day of peak activity (Figure 11). The total number of days with recorded avalanches was 19. We believe that because of incomplete data our record underreports the number of slides per day and per cycle and may underestimate the number of days in each significant avalanche cycle. We did not attempt to analyze avalanches by size classifications or crown length and depth due to insufficient data.

Our field observations suggest that early avalanches in some significant cycles are dry slab avalanches (Figure 13), while later avalanches are wet slab avalanches. Air-blasts accompanied many of the first avalanches in the 2003 cycle,

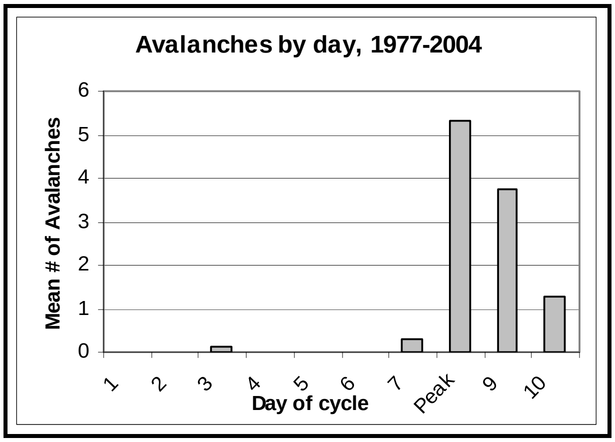

Figure 12: Graph of mean number of avalanches per day during significant avalanche cycles.

notably the Shed 7 and Shed 8 paths. Debris from avalanches in these paths stopped on the north side of Bear Creek, but the air blasts crossed the creek and highway, knocking down trees on the south side of the highway in one location. Later slides in this same cycle were not accompanied by air blasts and had debris more characteristic of wet slab avalanches. In 2004, two dry slab avalanches hit a 119-car freight train, derailing it in two places, a third nearly hit crews cleaning up the derailment, and a fourth dry slab avalanche hit a commercial truck on the highway. Later avalanches in this cycle again had debris typical of wet slab avalanches. Some dry slab avalanches may entrain wet snow at lower elevations, making the debris resemble wet slab avalanche debris.

Figure 13: Debris from Jan. 25, 2002 dry slab avalanche that blocked U. S. Highway 2.

3.3 Precipitation

The total SWE at the start date of each analysis period ranged from 236mm (Jan. 2002) to 612mm (Feb. 1982), with a mean of 437mm (Figure 14). When compared with average SWE for the actual calendar date for the start of each analysis period, it appears significant avalanche cycles occur when snowpacks are both above and below average. Half the cycles occurred with below average total SWE at the start of the analysis period, and half occurred with greater than average SWE. The range was 59% (2003) to 175% (December, 1996) of average SWE, with a mean of 101%. There does not appear to be a relationship between seasonal snowpack and significant avalanche cycles in Stevens Canyon; the principal influences appear to operate on a smaller scale. Interestingly, four of the five avalanche cycles that began with below average total SWE occurred in the past three years.

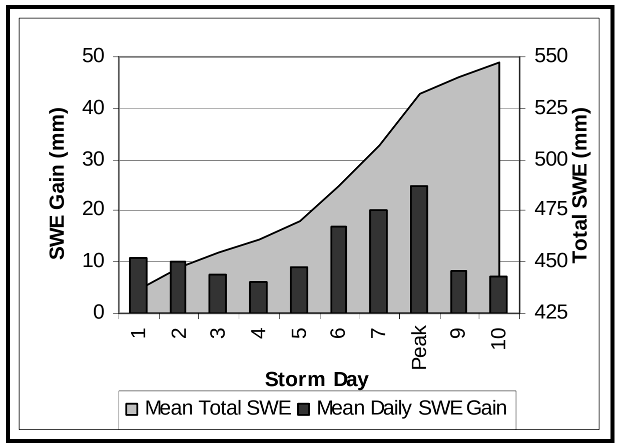

Figure 14: Graph of total SWE and mean daily SWE gain at Pike Creek SNOTEL during 10-day avalanche cycles, 1977-2004. Avalanches peak day 8.

For each significant avalanche cycle, we calculated the gain in SWE at Pike Creek SNOTEL for each day of the 10-day analysis periods. The significant avalanche cycles exhibited a pattern of sustained and progressive loading (Figure 14). On average, precipitation occurred 8.3 days of each period. Moderate SWE gain occurred at the start of the 10-day periods followed by increasing SWE gain on days 6-8. SWE gain typically peaked on day 7 or 8, and then dropped markedly the 2 days after this peak. Daily SWE gain showed the most variability on day 1 and during the peak loading on days 6-8. The total SWE gain for the first 8 days of each significant avalanche cycle (avalanche peak and seven previous days) ranged from 58 to 142mm, with a mean of 105mm. This pattern, in which sustained SWE gain preceded peak avalanche activity, was common to all the significant avalanche cycles in the 1977-2004 period. The number and size of avalanches recorded during each peak did not appear related to the 8-day total SWE gain.

Sustained snowfall of such magnitude is infrequent but not rare in Stevens Canyon. We defined sustained snowfall as an 8-day period with 102 mm of SWE gain, the median for the significant avalanche cycles. Such events appear 23 times in the 28-winter record of SWE data from the Pike Creek SNOTEL. Most (80%, n=10) of significant avalanche cycles were associated with sustained SWE gain of 102mm or more, though peak avalanche activity sometimes occurred before snowfall reached this threshold. However, only 35% (n=23) of storms with sustained snowfall were associated with significant avalanche cycles, while one coincided with another avalanche event. Thus, sustained snowfall is a critical component of significant avalanche cycles in Stevens Canyon, but sustained snowfall does not in and of itself create significant avalanche cycles.

In part the difference between the number of significant avalanche cycles and storms with sustained snowfall results from the different timing of these events. The sustained snowfall events typically occurred earlier in the season than the significant avalanche cycles (Figure 15). Nearly all the storms with sustained snowfall occurred from November through February, with a peak the first week of January – four to six weeks earlier than the peak for significant avalanche cycles in both the 1977-2004 and 1910-2004 periods. Only one sustained snowfall event (March 2003) occurred after March 1. This pattern is congruent with local climatology; snowfall typically peaks during December and January, and then tapers (Finklin, 1986). The early-season storm events may not have resulted in significant avalanche cycles in part because persistent weak layers had not yet formed and in part because of shallow snow in the tracks. Foehn et al. (2002) identify deep snow in the tracks as a necessary condition for catastrophic avalanches.

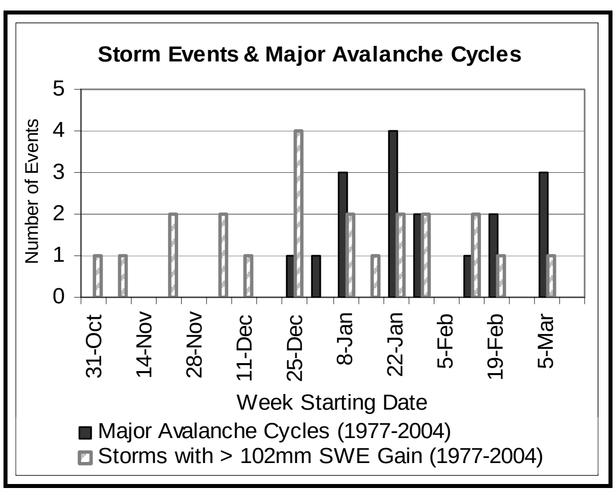

Figure 15: Graph comparing timing of storms with sustained snowfall and significant avalanche cycles.

3.3 Temperature

A second characteristic of significant avalanche cycles in Stevens Canyon is a sharp rise in temperatures. The importance of temperature – and its interaction with precipitation - in significant avalanche cycles in Stevens Canyon was obvious early in this century. In a letter dated January 23, 1933, C. O. Jenks noted "Generally speaking, it is warm weather or rain which causes slides – depending, of course, on the amount of snow in the high hills" (Jenks, 1933a).

Our analysis showed three striking and consistent temperature patterns among the significant avalanche cycles:

- Outbreaks of arctic air followed by marked warming prior to the start of each significant avalanche cycle.
- Near freezing temperatures on the day of peak avalanche activity.
- Differences in the timing, rate, and magnitude of temperature changes that occurred at Pike Creek and Snowslip

For all but one of the significant avalanche cycles, the week prior to the peak of avalanche activity included 3-6 days in which average temperatures at Pike Creek SNOTEL remained below -15°C, and 2-3 days – usually consecutive - with average temperatures of -21°C or lower. The coldest was -32°C, in both 1990 and 2004. These cold episodes typically occurred in the middle of the seven days prior to the peak avalanche activity; the mean temperatures at Pike Creek were lowest on days 3-5, at -14 to -15°C (Figures 16 and 17). The cold temperatures typically resulted from arctic air pooling east of the Continental Divide and spilling through Marias Pass. The one exception to this pattern was the January 2002 cycle, in which average temperatures at Pike Creek never dipped below -10°C in the week prior to the start of the avalanche cycle.

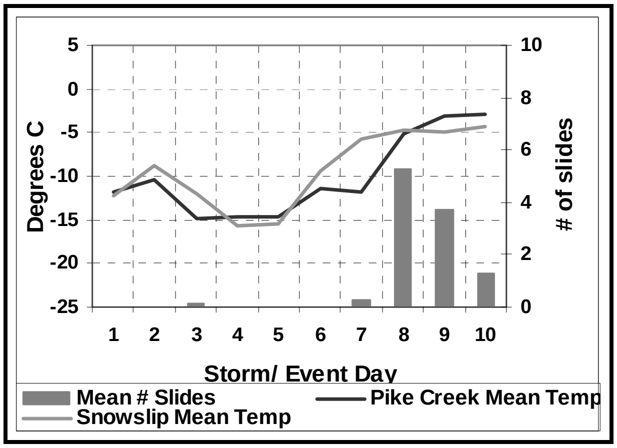

Figure 16: Mean of daily average temperatures at Pike Creek (elev. 1807) and Snowslip (elev. 2134m) during avalanche cycles 1989-2004.

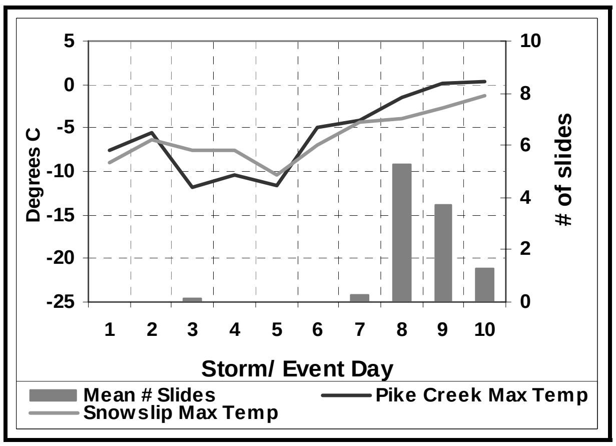

Figure 17: Mean maximum daily temperatures at Pike Creek (elev. 1807) and Snowslip (elev. 2134m) during avalanche cycles 1989-2004.

The cold episodes that prefaced significant avalanche cycles were followed by dramatic warming. The most dramatic warming typically started in day 5 and continued for the next 1-2 days. During this warming, daily mean temperatures at Pike Creek rose 19-32°C, while daily maximum temperatures rose 15-22°C. The exception was again the January 2002 cycle, which saw rises of 5 and 7°C.

As a result of the warming, average and maximum temperatures at Pike Creek on day 8 (the peak day of avalanche activity) consistently hovered within several degrees of freezing (Figure 18). The mean of average and maximum temperatures for day 8 were -5.2°C and -1.5°C respectively. These values would be higher were it not for the 1990 cycle, in which warming of 20°C (from -32°C) occurred very late on day 8 and continued into day 9. Apart from that cycle, mean average and maximum temperatures for day 8 were -0.75°C and 0.75°C respectively, with ranges of 4°C for both. That range is the narrowest range of the 10-day period.

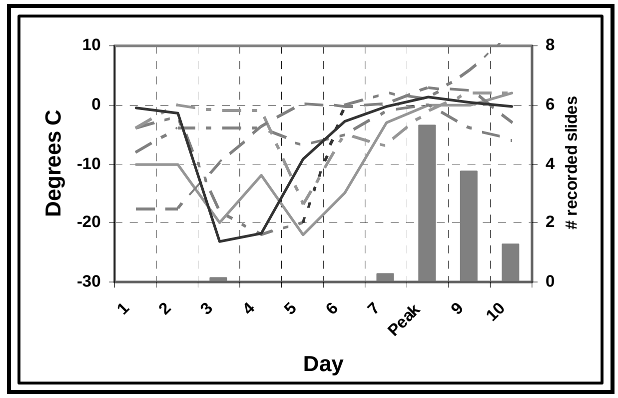

Figure 18: Graph depicting daily maximum temperatures (Pike Creek SNOTEL) clustering near 0°C on day of peak avalanche activity for 6 significant avalanche cycles 1996-2004

Temperature data from Snowslip exhibited similar though less dramatic patterns. The cold episodes were less pronounced at Snowslip weather station, despite it being 350m higher in elevation than Pike Creek. They were shorter in duration (18-27 hours) and involved less dramatic temperature plunges (Figures 16-17). Daily mean air temperatures there still dropped in the middle of the 7 days prior to the start of significant avalanche cycles, but only dipped below -21°C for one day during the March 2003 cycle. The fact that temperatures at Snowslip were less affected by outbreaks of arctic air seemed to be largely a function of the station's location west of the Continental Divide and its higher elevation. The arctic air spilling over Marias Pass during the cold episodes sinks down through Stevens Canyon but is too shallow to affect upper elevation start zones except briefly.

Warming at Snowslip was also less dramatic. Average daily temperatures rose 7-23°C over 2-4 days following the cold episode, and maximum daily temperatures rose 6-10°C. As with Pike Creek, temperatures on day 8, the onset of significant avalanche activity, approached freezing and showed a very narrow range – less than 2°C for both average and maximum daily temperatures. For the 2003 and 2004 cycles, temperatures continued rising the last 2 days of the cycle, with the maximum temperature reaching 8 on day 10 of the 2003 cycle.

The true rate of the warming may not be reflected in the calendar-day values used in this analysis, especially when the warming occurs overnight as happened in at least two of the significant avalanche cycles (1990 and December 1996). Temperature changes in Stevens Canyon can be abrupt; in 2004, the air temperature at Marias Pass shot up 21°C in 30 minutes (-28°C to -7°C) several hours before the onset of avalanching on January 28. Sensors along the railroad measured similar jumps, and the climb was so rapid that a railroad dispatcher in Ft. Worth called a repair team because he thought his equipment had malfunctioned. At the same time, air temperatures at Snowslip made no dramatic rise; they had been -9°C to -6°C for 34 hours. The greatest hourly rise recorded at Snowslip during the significant avalanche cycles was just 8°C.

Near-freezing temperatures are a regular occurrence in Stevens Canyon throughout the winter due to the dominance of mild Maritime weather patterns. Temperatures typically rise to near or above freezing multiple times each winter at the elevation of the starting zones. This warming is generally not abrupt or dramatic; it often involves gradual increases on the order of 5°C to 7°C. However, when Maritime weather patterns clash with Continental weather patterns, and abrupt warming on the order of 15°C coincides with sustained snowfall, the conditions exist for significant avalanche cycles.

3.4 Wind

Prevailing winds at Snowslip are from the west. During the cold episodes in the middle of significant avalanche cycles the winds were generally easterly and light at ridge tops. In the canyon, winds during the cold episodes are often very strong, creating blizzard-like conditions at the elevation of the highway and railroad. These winds result from cold arctic air sinking down the canyon from the Continental Divide.

The light easterly winds would seem to have less influence on slab formation than supposed previously (Martinelli, 1984; Butler and Malanson, 1985). Wind effects became more significant after the cold episodes. During the two days prior to peak avalanche activity, winds shifted abruptly back to the west and increased as warm, Pacific air approached from the west or southwest. Wind speeds during these two days averaged 22km/hr, with gusts up to 70km/hr in 2002, 2003 and 2004. Average wind speeds and maximum gusts are almost the same for the day of peak avalanche activity. In 2002, there was no shift to easterly winds during the 10-day period. The wind speeds during the two days prior to peak avalanche activity are sufficient to redistribute light density snow (McClung and Schearer, 1993) that falls at the start of loading. Wind may transport less snow – and play a less important role in avalanche formation - as temperature, relative humidity, and snow density rise prior to the peak of avalanche activity.

3.5 Snow Structure

We conducted crown profiles for two slides in the significant avalanche cycles of January 2002 and March 2003. Both profiles were done three days after the avalanches ran. These profiles reveal several similarities between the avalanches of the different cycles. The 2002 profile was from an avalanche in the Hanging Tree Main path that blocked traffic on U. S. Highway 2. The slab was 70cm thick at the profile, with depths elsewhere along the crown of 60-90cm. Slab hardness was 4 fingers to 1 finger, with a density of 18%. The avalanche ran on a 6cm, 1-finger hard sun crust that formed 10 days prior to the slide. A thin layer of mixed grains (1-1.5mm, rounds and facets) formed the weak layer between the crust and slab. In some cases the slide stepped down to a pencil hard, 7cm thick rain crust that formed 17 days prior to the slide. Since the slide, 30cm of light density snow had fallen, and height of snow (HS) was 148cm.

The 2003 profile showed a very similar snow structure. The 2003 profile was from a destructive class 4 avalanche in the Shed 9 path; it was conducted three days after the slide ran over Shed 9, dammed Bear Creek, climbed up onto the highway and stopped against a hill on the far side of the road. The slab was 60cm thick at the profile; however, the slide had stepped down to the ground in places and crown depths averaged 1m. Slab hardness was 1 finger; the avalanche initiated on a thin layer of facets atop a 4cm thick crust, but then stepped down to a 17cm crust and to the ground in a shallow, rocky area on one flank. The height of snow was 138cm.

The two profiles show a significant weak layer buried by a thick slab of strong, hard snow, with crusts acting as bed surfaces. We first observed the 2003 crust and facets combination a full month before the avalanche cycle; it failed with moderate results and medium quality shears in stability tests at that time and was not sensitive to human triggering. Over the next four weeks it strengthened sufficiently to hold the tremendous loading (142mm SWE) in the week prior to the avalanche cycle before failing. In contrast, the 2002 weak layer was more developed and more widespread; less loading and warming was required to initiate avalanches on this layer. This combination of not especially sensitive weak layers and thick slabs is an important factor in the significant avalanche cycles in Stevens Canyon, particularly when they occur on relatively shallow slope angles. Large volumes of snow accumulate in the start zones before avalanches release; these accumulations are uncommon so the avalanches that result can be large but infrequent.

3.6 Release of Natural Avalanches

Explanations for release of natural dry-slab avalanches focus on increased stress at weak layers or interfaces due to the rate and amount of loading (McClung and Schaerer, 1993). Foehn et al., (2002) identify load rate as one major factor in the initiation of natural avalanches with large fracture heights and lengths and long runout distances. The precipitation and wind patterns described for the significant avalanche cycles in Stevens Canyon seem to involve just such loading.

However, all significant avalanche cycles in Stevens Canyon from 1977-2004 are also associated with rapid and dramatic temperature increases. Moreover, avalanche activity peaked when temperatures rose to within several degrees of freezing. Few natural avalanches occurred prior to the near-freezing temperatures, even on days with rapid loading from intense snowfall and wind. This correlation of natural avalanche activity and rising temperatures indicates that loading rates and amounts are not the only mechanism for initiating natural avalanches in these cycles. Other evidence for this conclusion is the absence of a strong correlation - described earlier - between sustained snowfall events and significant avalanche cycles.

One explanation for the influence of rising temperatures would be that natural avalanches are triggered by rain falling on new snow. As temperatures warm, precipitation changes from snow to rain, triggering natural avalanches due to increased loading (McClung and Schaerer, 1993) or possibly a wetting of the weak layer (Tremper, 2001). However, rain-on-snow did not occur in all significant avalanche cycles, and in several cycles, notably January 1982 and 2004, most of the avalanches ran before the onset of rain (Martinelli, 1984). This evidence suggests that at least some natural avalanches might be triggered by other processes.

We hypothesize that some of the natural avalanches in the significant avalanche cycles result from the effects of rising temperatures on the mechanical properties of the slabs. Rising temperatures can rapidly decrease stability due to rapid changes in slab properties, particularly a decrease in stiffness or viscosity (the resistance to deformation) (McClung and Schweizer, 1999). The insulating properties of snow prevent temperature changes from rapidly affecting the properties of grains and weak layers deeply buried in the snowpack. Temperature-related changes in mechanical properties are similarly concentrated near the snow surface. Changes in near-surface mechanical properties can, however, have immediate and significant effects on the stresses at deeply buried weak layers or density changes (McCammon, 2004). The initiation of natural avalanches by temperature-related changes of the mechanical properties of slabs has been identified for thin (<0.5m) slabs (McClung and Schaerer, 1993). Foehn et al. (2002) identified temperature-related changes in stiffness as a primary cause of catastrophic natural avalanches in the Alps in 1999. Another possible explanation which we cannot evaluate due to lack of snowfall measurements would be that rapid settlement of storm snow caused by warming contributes to natural avalanches.

3.7 Sequence of Significant avalanche cycles

Significant avalanche cycles in Stevens Canyon from 1977-2004 developed in a similar sequence. Specifically, they started when an episode of arctic temperatures (-20^{o}C to -36^{o}C) interrupted seasonal conditions. Fair weather or light snowfall occurred during this episode, with light easterly winds at ridge tops but often strong easterly winds at road-level in the canyon. There was evidence of temperature inversions during this episode, with cold episodes shorter in duration and not as intense at upper elevations.

Dramatic warming followed this cold episode and typically coincided with more intense snowfall (mean of 21mm SWE per day) and increased westerly winds. The warming appeared to start sooner at the elevation of the starting zones. As temperatures warmed, snow densities increased, and in some cycles the snow changed to rain at mid-slope.

Natural avalanches occurred; the early avalanches in each cycle were often dry slab avalanches and later avalanches were wet slab avalanches. Natural avalanche activity peaked when daily maximum temperatures approached freezing (mean of -1.5°C at 1800m elevation; -4°C at 2134m). These avalanches initiated through rapid loading, rain falling on new snow, and/ or temperature-related changes in the mechanical properties of slabs. In some cases, a buried persistent weak layer reduced the amount of warming or snowfall needed to initiate avalanches and increased the extent of avalanching. The cycles ended when colder temperatures returned.

The sequence described for the significant avalanche cycles of 1977-2004 seem representative of conditions for many, if not most, of the avalanches of the past 94 years. A report of an avalanche cycle on February 23, 1910 outlines a remarkably similar progression of a cold episode followed by intense snowfall, dramatic warming, and eventually rain. The two days before the avalanches were reported as fair, with morning temperatures of -33°C and -40°C, rising to -27°C and -23°C by midday. On the day the slides started, the morning temperature was -21°C rising to -7°C with "continued hard snowfall." The following morning temperatures had risen to -3°C with snow, then rose further to 0°C with rain in the afternoon (Beals, 1910). This sequence parallels the pattern we describe for the significant avalanche cycles in 1977-2004. Similarly, most accounts of avalanches in the Walton Ranger station logbooks describe a mix of cold temperatures, heavy snowfall, warming and rain preceding avalanches that disrupted traffic on the highway or railroad. Indeed, in 1961 a ranger commented "we had rain last night and hell this morning" (Glacier National Park, 1961).

Butler and Malanson (1985) noted major avalanche winters in Stevens Canyon and Rogers Pass often occurred concurrently and suggested that common synoptic circulation might be a primary cause of that similarity. Our analysis reinforces this connection. The development of significant avalanche cycles in John Stevens Canyon is consistent with patterns that characterize catastrophic avalanches in Rogers Pass, B.C. Fitzharris and Schaerer (1980) describe a sequence that starts with "prolonged intense outbreaks of Arctic air...followed by a major storm, with rapid warming to above 0° C, heavy snowfall, and sometimes rain." They give a threshold of 110mm of SWE in six days.

4. IMPLICATIONS FOR MITIGATION PLANNING

Our analysis demonstrates the need for direct observations of snow conditions in the starting zones for precise and accurate hazard assessments. The January 2002 cycle highlights the need for direct observations of the strength and distribution of weak layers and slabs in the starting zones. Similarly, the temperature differences between Pike Creek and Snowslip reveal that conditions in the canyon are highly variable with elevation during significant avalanche cycles.

Our analysis of significant avalanche cycles suggests that each one combines a series of infrequent events, no one of which creates the cycle without the reinforcement of the others. When an element in this sequence is missing or weakened, fewer or smaller avalanches will result. Fitzharris and Schaerer (1980) observe that for numerous large avalanches to occur in a few days there must be "weather sequences that maximize all the principal causes of avalanches." Rosenthal and Elder (2002) suggest that individual avalanches are chaotic systems in which small variations in initial conditions develop into large differences in outcomes. Events involving multiple medium to large magnitude natural avalanches would seem at least as chaotic and unpredictable as individual avalanches. Forecasting such events is problematic (Foehn et al., 2002) because of inaccurate precipitation forecasts and insufficient knowledge of the formation of catastrophic natural avalanches.

Despite their complex, unpredictable, and perhaps chaotic nature, significant avalanche cycles in John F. Stevens Canyon occur regularly. They are thus natural hazards whose danger and costs can be mitigated through planning and protection. A lack of detailed information currently hampers planning efforts. This paper starts to address that deficiency. Several factors argue for more urgency in that effort. These include the financial and economic costs of traffic disruptions, the possible environmental consequences of an avalanche accident, and the close calls that have occurred in recent years.

6. ACKNOWLEDGEMENTS

The authors would like to thank Karen Holzer and Stephen Willis for their support and assistance with field observations. We are grateful to Dave Butler for sharing his field notes, Dave Hamre for sharing his expertise, Darwon Stoneman for sharing his aerial photographs, and Leo Yudysky for sharing his many years of experience in the canyon. The staff at the Glacier National Park archives was wonderfully helpful. Thanks to Tessie Bundick for her work in at the Minnesota Historical Society and to Andy Cagle, Lisa McKeon and Ali White for their assistance with graphics and data.

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