Regional comparison of old-deep slab avalanches

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ABSTRACT

Deep slab avalanches are rare events that are often responsible for property damage and highway closures. A better understanding of their characteristics will aid forecasting and mitigation efforts. We analyzed avalanche data from 17 winters between 1991 and 2010, comparing characteristics of deep slab avalanches from four regions: Coast, North Columbia, South Columbia and Rocky Mountain. We found that deep slab avalanches usually involve a persistent weak layer that formed during the early winter season. Such avalanches tend to occur most often in January. Each region has particular years with significant deep slab avalanche activity independent of other regions.

RÉSUMÉ

Avalanches de plaque épaisse sont des événements rares, qui sont souvent responsables de dégâts matériels et les fermetures de l'autoroute. Une meilleure compréhension de leurs caractéristiques contribueront aux efforts de prévision et d'atténuation. Nous avons analysé les données d'avalanche de 17 hivers entre 1991 et 2010, comparant les caractéristiques des avalanches de plaque épaisse de quatre régions: la Côte, du Nord-Britannique, du Sud-Britannique et des Rocheuses. Nous avons constaté que avalanches de plaque épaisse impliquent généralement une faible couche de persistance qui est développé au cours de la saison début de l'hiver. Ces avalanches ont tendance à survenir plus souvent en Janvier. Chaque région a des années notamment avec une importante activité d'avalanche profonde dalle indépendante des autres régions.

1 INTRODUCTION

Deep slab avalanches are a unique and difficult to forecast natural hazard. Little effort has been applied to their study, especially in the mountainous regions of southwestern Canada. Recent research indicates that slab properties such as stiffness and depth are positively correlated with weak layer fracture propagation (van Herwijnen and Jamieson, 2007).The depth of the failure layer usually makes human triggering less frequent. The long burial time of the weak layer as well as the large overburden pressures acting on the weak layer suggests that this layer would be gaining strength (Brown et al., 2001).

Previous studies on forecasting methods and characteristics of deep slab avalanches have been region specific. They were mainly focused on transitional (Jamieson et al., 2001; Savage, 2006; Comey and McCollister, 2008) and continental snow climates (Bradley and Bowels, 1967). These studies suggest that deep slab avalanches are larger (Comey and McCollister, 2008) and that occurrence of the deep slab avalanches correlate better with trends in weather over several days (Jamieson et al., 2001; Savage, 2006). Problems with these earlier studies are that each study has its own definition for deep slab avalanches making comparisons between studies difficult.

The Canadian Avalanche Centre (CAC) defines a "persistent deep slab avalanche" as a deeply buried hard slab avalanche that often fails on or near the ground (Klassen et al., 2010). While this definition is very effective at communicating the essence of a difficult to forecast deep slab avalanche, a quantitative definition is needed for a study of historical database information. In an effort to adapt the CAC definition to work with a large dataset, Tracz and Jamieson (2010) defined old deep slab avalanches those that meet or exceed the 80th percentile of both weak layer age and average crown depth. This definition works well with large datasets and produces a subset that is representative of difficult to forecast avalanches. Their study was limited to observations mainly in the Columbia Mountains.

Many studies have investigated the difference in climates among the mountain ranges of western North America (e.g. Armstrong and Armstrong, 1987; Johnson, 2000) and avalanche climates (Haegeli and McClung, 2007). Generally the mountainous regions of southwestern Canada are divided into four main regions, the Coast, North Columbia, South Columbia and Rocky Mountains (Figure 1). The Coast Mountain region is representative of a coastal or maritime snow climate characterised by relatively warm temperatures, large amounts of precipitation and frequent midwinter rainfall events. Both the North and South Columbia Mountains are representative of a transitional snow climate that is characterised by periods of intense snowfall with intermittent periods of cold clear weather brought about by high pressure arctic outbreaks. However, the South Columbia Mountains show more often warmer temperatures and rainfall events compared to the North Columbia Mountains. The Rocky Mountains are representative of a continental snow climate typified by less precipitation, long periods of cold clear conditions and a relatively thin snowpack.

This study builds on the work of Tracz and Jamieson (2010) to compare various slab, start zone and weak layer characteristics as well as trends in monthly and yearly occurrences of old deep slabs in four mountain regions of southwestern Canada.

Figure 1. Study area and boundaries (dashed line) separating the four mountain regions.

2 DATA

Data for this study were provided by the Canadian Avalanche Association (CAA). They maintain a database of daily avalanche occurrences and stability assessments from avalanche industry professionals. This database is known as the information exchange (InfoEx), which was developed for sharing observations from the previous day between many Canadian avalanche safety operations. A dataset of this type offers a unique chance to analyse avalanche events over several years in many areas of Canada's southwest. Contributors to the InfoEx include mechanised and non-mechanised backcountry skiing operations, lift access ski resorts, parks, highway avalanche control and natural resource companies.

The data used for this study were provided in two separate databases. The first covers the 1991/92 to 2001/02 winter seasons and has been parsed from daily InfoEx text reports by Gruber et al. (2004). Starting in the 2004/05 winter season the CAA introduced an online reporting format that allowed subscribers to report avalanche observations online and data were stored in a tabular format.

Both databases have a similar structure. Daily observations between the months of October to April were tabulated and present avalanche data such as: observation date, occurrence date, burial or formation date of the weak layer, number of avalanches, trigger type, start zone aspect (from/to), avalanche size (min/max) (CAA, 2007), start zone elevation (min/max), start zone inclination (min/max), crown width (min/max), length slab traveled (min/max), vertical crown depth (min/max), a primary weak layer grain form, a secondary weak layer grain form, and unique to the 2004/05 to 2009/10 data, bed surface level and bed surface grain form. In the 1991/92 to 2001/02 data the bed surface layer is documented as part as a primary or secondary weak layer grain form. The number of avalanche observation reports and the corresponding number of avalanche occurrences are shown in Table 1.

3 METHODS

Extreme events are generally found at the tails of distributions (Bier et al., 2004). The concept of selecting extreme events based on a non-exceedance probability has been practiced for years in the environmental and engineering sciences; examples are the 1:100 year flood, or a 1:300 year avalanche. The selection of the non-exceedance probability is arbitrary and done so to best suit the needs of a particular study (Zhu and Toth, 2001) and often it is necessary to define non-exceedance probability by geographical regions (IPCC, 2007).

Table 1. Number of avalanche observations (records) and the corresponding number of avalanches for each region and dataset. Obs.: observation, Ava.: avalanche, Region: All Avalanches reported in a region, ODS: old deep slab dataset. C: Coast Mountains, NC: North Columbia Mountains, SC: South Columbia Mountains, R: Rocky Mountains.

Reg.		All reported			ODS		
		1991/92-2001/02	2004/05-2009/10	**Tot.**	1991/92-2001/02	2004/05-2009/10	**Tot.**
C	Obs.	70	354	**424**	9	51	**60**
	Ava.	190	673	**863**	33	110	**143**
NC	Obs.	804	2207	**3011**	246	269	**515**
	Ava.	2323	4773	**7096**	446	469	**915**
SC	Obs.	355	2043	**2398**	313	98	**411**
	Ava.	941	4113	**5054**	567	194	**761**
R	Obs.	134	536	**670**	75	49	**124**
	Ava.	270	1193	**1463**	176	94	**270**

This study defines old deep slabs as any avalanche with a depth that meets or exceeds the 80th percentile of depth on a regional basis and involved a weak layer that is at least 14 days old. Weak layer age is calculated by counting the days between the avalanche occurrence and the weak layer's estimated burial date. By selecting the 80th percentile of depth it ensures that the subset will represent avalanches that are deep for the region and the weak layer age of 14 days excludes large storm snow avalanches. The method of selecting old deep slab avalanches in the Columbia Mountains used by Tracz and Jamieson (2010) was adapted in this study for the Rocky and Coast Mountain regions. This study is further limited to dry slab avalanches.

The source database allows multiple avalanches to be reported in a single record with a range of values (maximum, minimum) for variables such as slab thickness, elevation, etc. Where a maximum and minimum were reported, an average of the two was used for all the avalanches in the record. If only one value was reported as the "minimum", it was taken to be the average.

Continental snow climates are known for having a snowpack with a weak basal layer of depth hoar or large faceted crystals (Bradley and Bowles, 1967) which form in the presence of a strong temperature gradient (Akitaya, 1974). Unfortunately basal weak layers are rarely assigned a burial weak layer date and these potentially important avalanches cannot be included in the analysis without one. For this reason, avalanche observations in the Rocky Mountains that were reported to have failed on the ground and do not have a weak layer date are assigned with a weak layer date of November 10th.

A two-tailed Mann-Whitney U test (Spiegel and Stephens, 1999) is performed on continuous and ordinal variables to determine if a significant difference exists between two different regions. The null hypothesis was chosen so that no location shift exists between the two distributions, i.e. a small p-value indicates that one of the samples tends to have larger values then the other. Where the p-value was less than 0.05 we assumed that the location shift was significant. When a difference was determined to be significant, descriptive statistics were compared to assess the difference.

Variables that could not be analysed using the Mann-Whitney U test such as the start zone aspect, weak layer grain type, bed surface, trigger type and occurrence month and occurrence year of avalanche events are normalized by dividing the result by the total number of avalanche events in the region and qualitative comparison were made.

4 RESULTS

In all four mountain regions, the avalanche size, width, length, slab thickness and age in the old deep slab subsets were significantly larger than in the original datasets containing all reported avalanches (Table 2). This was also true for the elevation and inclination data; however, the accuracy of both these variables questions the validity of these results. A comparison of old deep slabs by region is also shown in Table 2.

The Mann-Whitney U test was performed for each pair of regions for the characteristic shown in Table 2. The p-value associated with each test is shown in Table 3. By combining the results of Tables 2 and 3 several inferences can be made. Old deep slabs in the Coast Mountains tend to occur on less steep slopes and have larger slab thickness compared to the other regions. The old deep slab avalanche events reported in the Rocky Mountains tend to involve weak layers that are older than the other mountain regions; however, the formation date was assumed to be 10 November.

The percentage of avalanches that released on ground and the percentage of avalanche events involving a specific grain form are shown in Table 4. Ground avalanches were relatively more frequent in the Rocky Mountain region then other regions. In all regions faceted crystals and crusts were reported more frequently and surface hoar crystals were less frequently reported in the old deep slab avalanche subsets.

Avalanche triggers by region for both the old deep slab subsets and the entire avalanche datasets are shown in Table 5. In the complete datasets for each of the four regions, skier triggered avalanches were most frequently reported, followed by naturally triggered avalanches. Natural avalanches were reported most frequently in the old deep slab subsets for all regions except the Rocky Mountains where explosive triggers were most frequently reported.

The start zone aspect reported for all avalanches reported by region and the old deep slab subsets are shown in Figure 2. The old deep slab subsets follows a very similar trend to that of all avalanches reported in their respective regions. Northerly aspects were more commonly reported than southerly aspects.

A comparison of the percentage of avalanche occurrences by month is shown in Figure 3. While some interesting regional trends can be seen in the distributions of all avalanches reported by regions, the most notable observation is the consistent January spike of old deep slabs in the Coast, North Columbia and South Columbia Mountains and the December spike for the Rocky Mountains.

The percentage of avalanches classified as old deep slabs per season and region are presented in Figure 4. No deep slab avalanches were reported during the winter season of 92/93, whereas no data was available for the winter seasons of 02/03 and 03/04. Relatively more old deep slab avalanches were reported during the 91/92 - 01/02 winter season; however, this is likely a bias in the data as discussed subsequently. The Rocky Mountain region consistently reports relatively more old deep slabs than the other regions. The Coast Mountain region reports relatively less deep slab avalanches than the other regions except for the 96/97 and 08/09 seasons. The North Columbia Mountain region follows a similar yearly avalanche trend to that of the South Columbia Mountain region. However, the South Columbia Mountain region typically reported more old deep slabs than the North.

Table 2. Descriptive statistics for various avalanche characteristics and the Mann-Whitney U test p-value from a comparison of the regional data and the old deep slab subset. Bold values are significant ($p < 0.05$). Descriptive statistics presented are the number of avalanches N, minimum Min., first quartile Q1, median Med, third Quartile Q3 and maximum Max. for data representing Size: avalanche size, Elev: elevation, Incl: inclination, Width: crown width, Length: distance from crown to toe of debris, Thick: avalanche crown height measured vertically and Age: days from weak layer burial date to the avalanche occurrence. Regions presented are C: Coast Mountains, NC: North Columbia Mountains, SC: South Columbia Mountains, R: Rocky Mountains.

	Reg.	All reported						Old deep slab						Mann Whitney
		N	Min	Q_1	Med	Q_3	Max	N	Min	Q_1	Med	Q_3	Max	p-value
Size	C	837	0.5	1.5	2	2.5	4	142	1.5	2	2.5	3	4	**< 0.001**
	NC	6919	0.5	1	1.5	2	5	876	1	2	2.5	3	5	**< 0.001**
	SC	4963	0.5	1	1.5	2	4	731	0.5	2	2.5	3	4	**< 0.001**
	R	1428	0.5	1	1.5	2	4	244	0.5	2	2.25	2.5	4	**< 0.001**
Elev (m)	C	720	400	1500	1850	2100	2700	114	400	1700	1800	2100	2450	0.423
	NC	6377	600	1700	1981	2200	3500	844	600	1850	2080	2300	2850	**< 0.001**
	SC	4480	600	1900	2100	2282	2900	687	1000	1940	2150	2400	2900	**< 0.001**
	R	1233	1000	1875	2000	2300	3000	194	1300	1900	2100	2400	2800	**< 0.001**
Incl °	C	718	12	32.5	35	39	55	111	12	30	35	37.5	45	**0.002**
	NC	5749	10	35	35	40	70	751	20	35	38	40	70	**< 0.001**
	SC	4131	15	35	37.5	40	70	596	20	35	40	40	70	**< 0.001**
	R	1215	15	35	37.5	40	60	200	20	35	37.5	40	60	0.079
Width (m)	C	718	5	25	50	105	3500	129	20	100	150	300	3500	**< 0.001**
	NC	5936	5	20	40	100	4000	789	10	70	100	225	4000	**< 0.001**
	SC	4113	5	15	30	60	1500	624	5	40	100	200	1500	**< 0.001**
	R	1203	5	20	40	80	1500	227	15	50	100	200	1500	**< 0.001**
Length (m)	C	661	5	42.5	100	255	2500	111	40	225	255	500	2000	**< 0.001**
	NC	5598	3	40	87.5	250	2900	781	10	175	300	650	2900	**< 0.001**
	SC	4049	2	30	80	185	2500	608	2	100	263	550	2500	**< 0.001**
	R	1136	3	50	150	300	1700	193	3	200	300	500	1700	**< 0.001**
Thick (cm)	C	863	5	30	50	80	300	143	95	110	125	150	250	**< 0.001**
	NC	7096	5	32	45	65	400	915	75	85	100	130	400	**< 0.001**
	SC	5054	5	30	40	65	300	761	70	80	100	125	300	**< 0.001**
	R	1463	5	25	40	65	400	270	75	80	100	144	400	**< 0.001**
Age (days)	C	863	0	4	9	22	119	143	15	20	24	39	119	**< 0.001**
	NC	7096	0	4	8	15	130	915	14	18	25	37	130	**< 0.001**
	SC	5054	0	4	8	16	149	761	14	18	24	35	138	**< 0.001**
	R	1463	0	5	14	35.5	148	270	14	30	43.5	82.5	148	**< 0.001**

Table 3. Regional comparison of old deep slab avalanche characteristics. Shown are the p-values from the Mann-Whitney U test. Bold numbers show significant values ($p < 0.05$). Same abbreviations as in Table 2.

	NC	SC	R	NC	SC	R	NC	SC	R	NC	SC	R
	Avalanche size			Start zone elevation			Start zone inclination			Crown width		
C	0.494	**0.035**	**0.002**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
NC		**< 0.001**	**< 0.001**		**< 0.001**	**< 0.001**		0.290	0.922		**< 0.001**	**0.016**
SC			0.209			0.412			0.226			0.248
	Length			Thick			Age					
C	0.312	0.078	0.601	**< 0.001**	**< 0.001**	**< 0.001**	0.697	0.281	**< 0.001**			
NC		**< 0.001**	0.136		**< 0.001**	0.258		0.245	**< 0.001**			
SC			**0.047**			0.051			**< 0.001**			

Table 4. Bed surface and failure layer grain form for the all reported avalanches and old deep slab subsets, by region (Reg.). The maximum value in each column is written in bold text. All: All Avalanches reported in a region, ODS: old deep slab subset. DF: defragmented precipitation particles. C: Coast Mountains, NC: North Columbia Mountains, SC: South Columbia Mountains, R: Rocky Mountains.

	Ground		Crust		Faceted crystals		Depth hoar		Surface hoar		DF	
Reg.	All (%)	ODS (%)	All (%)	ODS (%)	All (%)	ODS (%)	All (%)	ODS (%)	All (%)	ODS (%)	All (%)	ODS (%)
C	0.0	0.0	**34.1**	26.6	**32.7**	**64.3**	0.7	0.7	35.5	11.9	7.8	0.0
NC	0.2	0.3	14.5	23.2	19.8	39.8	0.1	0.0	**54.0**	**40.0**	**12.4**	**8.1**
SC	0.1	0.7	14.1	20.8	21.8	40.1	0.0	0.0	48.2	33.4	6.4	2.0
R	**19.3**	**48.1**	27.5	**37.0**	20.3	27.4	**2.4**	**3.0**	31.5	5.2	2.2	0.4

Table 5. Avalanche trigger type by region for all avalanches reported and the old deep slab subset. All: All Avalanches reported in a region, ODS: old deep slab dataset. M: machine, helicopter or vehicle, N: natural or spontaneous, S: skier, X: explosive.

	Coast		North Columbia		South Columbia		Rocky	
	All (%)	ODS (%)	All (%)	ODS (%)	All (%)	ODS (%)	All (%)	ODS (%)
M	2.1	1.8	3.6	4.4	4.3	13.0	4.3	1.2
N	38.8	**72.3**	42.1	**62.2**	29.0	**43.3**	32.0	32.7
S	**50.0**	20.5	**48.6**	11.9	**50.6**	15.8	**32.6**	6.9
X	9.1	5.4	5.7	21.5	16.1	27.9	31.0	**59.3**

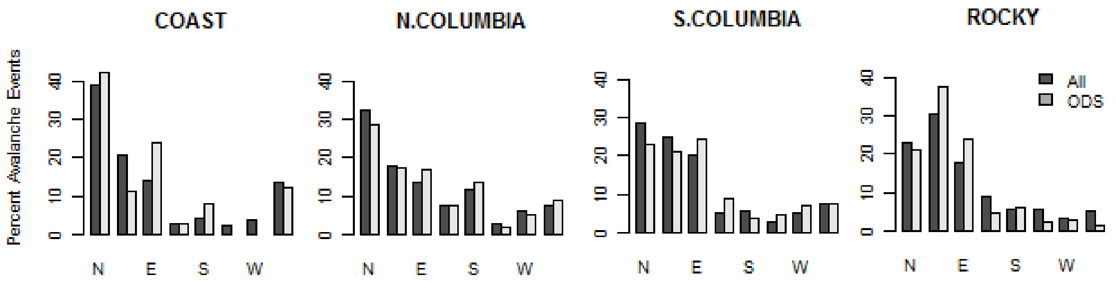

Figure 2. Percentage of avalanche occurrences by the eight cardinal aspects (north, northeast, east, southeast, south, southwest, west, northwest) for all four mountain ranges. Dark grey bars: all avalanches, grey bars: old deep slabs.

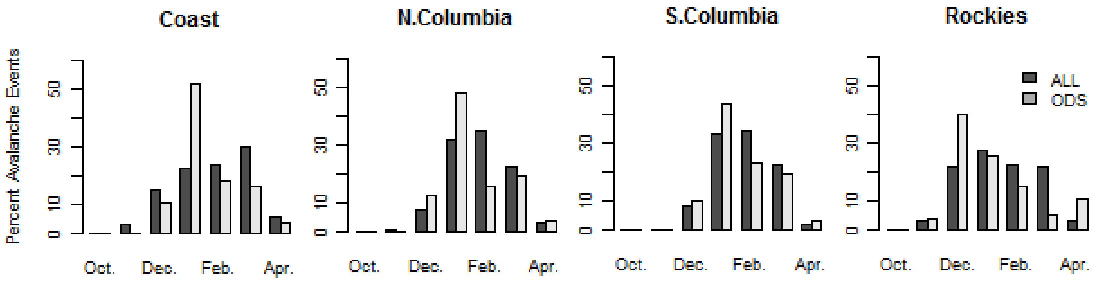

Figure 3. Percentage of avalanche occurrences by month for all four mountain ranges. Dark grey bars: all avalanches, grey bars: old deep slabs (ODS)

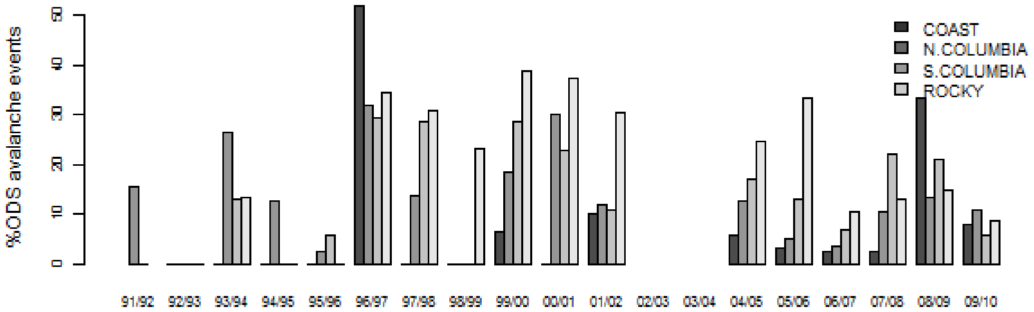

Figure 4. Percentage of old deep slab avalanches by year. Each bar represents the number of old deep slabs avalanches divided by the total number of avalanches. No data were available for the 02/03 and 03/04 winters.

5 DISCUSSION

5.1 Dataset

The InfoEx was intended for sharing observations from the previous day and not for research. Gruber et al. (2004) point out that environmental factors such as poor visibility and large operational tenures prevent many avalanche events from being observed, making the dataset incomplete. Each type of operation has different avalanche concerns based on what is at risk and makes observations accordingly. The operating season for many of the participating operations begin in December or January and runs until March or April. This means very few operations are reporting to the InfoEx in early and late season. Finally, many of the reported avalanche dimensions reported are estimated from distances ranging from tens of meters to hundreds of meters away. While all these issues are acceptable for the intended purpose of the InfoEx, errors and biases may affect the results presented in this study. The reported weak layer grain form was assumed to be correct because approximate crown depths and frequent field observations reliably indicate which layer most likely released the avalanche.

An artificial weak layer date of November 10th was assigned in the Rocky Mountain region if a ground avalanche was reported without a weak layer date. This was done because a weak layer of well developed facets or depth hoar is known to typically form in the lower snowpack during early winter months in the Rocky Mountains (LaChapelle, 1966: Bradley and Bowles, 1967; Haegeli and McClung, 2007) which has not been documented in the other regions. By using this rule only for the Rocky Mountains it potentially biases the data. A query of the Rocky Mountain data (after this rule was implemented) reveals that 20% of all the avalanche observations were on a November 10th weak layer, whereas 35% of old deep slab observations were on a November 10th weak layer.

5.2 Inter regional comparisons

The characteristics of old deep slab avalanches for each region were found to be significantly larger and more destructive when compared to all other avalanche events in the corresponding region (Table 2). This is in agreement with previous studies by Comey and McColllister (2008) and Tracz and Jamieson (2010). Table 2 indicates significant differences between old deep slab and the all reported avalanches for start zone elevation and inclination; however, the differences in medians are less than the assumed error associated with the estimates of start zone elevation (± 100 m) and inclination (± 2°). Another problem with the reported start zone inclination is an inconsistency in the way it was reported. Old deep slabs tend to propagate wider than other avalanches (Table 2, width) and terrain can vary substantially in the start zone. The wider width of the crown indicates that much of the terrain in the start zone is involved, where more frequent smaller avalanches that do not propagate as far would only involve the steeper areas of the start zone. However, when reporting start zone inclination only the steepest inclination should be reported, which would be the same for both small and large avalanches.

5.3 Average slab thickness

The old deep slab avalanches reported in the Coast Mountain region tend to have thicker slabs ($p < 0.001$) when compared to the other regions; specifically the median of the slab thickness was found to be 25 cm larger. The Coast Mountains receive frequent heavy precipitation events (Armstrong and Armstrong, 1987), which will increase the snowpack depth quickly. It is possible that thin weak layers in the upper fifty centimetres become rapidly buried by heavy snowfall and fail near the end of the storm. An analysis of weather events associated with old deep slab avalanche events is beyond the scope of this study.

5.4 Median age of failure layers

The median age of the failure layers of old deep slab avalanches from the Coast, North and South Columbia Mountain regions were found to be 24, 25, and 24 days respectively. The median weak layer age in the Rocky Mountain region was 44 days. The p-value derived from the Mann-Whitney test was found to be less than 0.001 for each region when compared to the Rocky Mountain region. The first quartile of the weak layer age in the Rocky Mountain region is greater than the medians of the other regions and the interquartile range is more the one and a half times larger than the next closest region indicating that the Rocky Mountain region deals with a old deep weak layer that is often present throughout the entire reporting season (November through April).

5.5 Average start zone inclination

Old deep slabs tend to occur on less steeper slopes in the Coastal Mountain region when compared the other regions. The differences in the median reported inclinations is approximately 3°, between the Coastal Mountains and the other regions and was found to be significant ($p < 0.001$). However, the interquartile range is larger for the Coast Mountain old deep slab subset indicating more variability of the data.

5.6 Failure layer grain form and bed surface

For the data set with all avalanches as well as for the old deep slab subset, the Rocky Mountain region showed relatively more ground avalanches than the other regions. Even when all avalanches assigned with a November 10th failure layer date are removed from the Rocky Mountain deep slab subset ground avalanches account for over 38% of the avalanches. All other regions report very few ground avalanches which is likely due to the lack of weak layers of depth hoar near the ground. Haegeli and McClung (2007) found that a crust typically forms in the Coast Mountain region in early to mid winter due to mild temperatures and rain events. These crusts are often associated with avalanche activity and evidence of this can be seen in Table 4. It is however, surprising to see the number of avalanches reported involving crusts in the Rocky Mountains. Johnson (2000) reports an average of 0 mm of rain during winter months (November - March), Mock and Birkeland (2000) report the same for the Rocky Mountains of the United States but do not present data for the month of November. Nevertheless, we suspect that when an early season rain or significant warming event forms a crust in the Rocky Mountain region it is important for subsequent releases of old deep slab avalanches. It can also be noted from Table 4 that all old deep slab avalanche subsets from each region except the Coast Mountain region experience an increased association with crusts when compared to all avalanches from the respective region.

Faceted crystals are associated with 64% of old deep slab avalanches in the Coast Mountains. This is two times more than for all avalanches reported in this specific region. Similar trends are found in the North and South Columbia Mountain. However, this is not experienced in the Rocky Mountains. One explanation for this is that often no weak layer grain type was reported for avalanches in the Rocky Mountain which released on the ground. It is likely that the basal layer grain type was either well developed faceted crystals or depth hoar.

Surface hoar crystals are most prevalent in the Columbia Mountains being associated with approximately 50% of the avalanches in each sub region. It is very interesting to note that in each region the percentage of surface hoar avalanches reported in the old deep slab subsets is less than percentages reported in the complete avalanche data. However, in the North and South Columbia Mountain regions surface hoar layers are reported in 40% and 33% of old deep slab avalanches, respectively.

5.7 Initiation

All regions show skier triggering as most frequent for all avalanches reported and natural and explosive triggered avalanches as most frequent for the old deep slab subsets. Only in the Rocky Mountain region do explosive triggered avalanches outnumber natural avalanches in the old deep slab subset. This is most likely because of the relatively shallow average maximum snow depth of 132 cm (Johnson, 2000), consistent annual basal weakness and the high percentage of reporting operation in the Rocky Mountain regions that use explosives to control avalanche hazard. The high percentage of old deep slab avalanches that are naturally occurring in all regions suggests that particular weather events or succession of weather events precede the initiation of old deep slab avalanches. Jamieson et al. (2001) documented a particular weak layer, crust and faceted crystals combination, during the winter season of 1996/97 which produced many old deep slab avalanches in the North and South Columbia Mountains (see Figure 4). They found that snowfall accumulation over several days and changes in air temperature over 4-5 days were significantly correlated with avalanche activity. A broader study looking at the effects of weather may prove insightful for the prediction of old deep slab avalanches on a regional basis.

5.8 Start Zone Aspect

In each region old deep slab avalanches follow similar trends compared to all avalanches reported. North and east aspects are more common than south and west aspects in each region. Each region shows a modest increase in the percentage of old deep slab avalanches reported on east aspects. This is likely due to the prevailing wind in the area as well as reduced direct solar radiation on north and east-facing slopes. It is possible that during certain winters, special circumstances could have caused a week layer to form on south or west-facing slopes which produced many old deep slab avalanches during that particular winter.

5.9 Timing of old deep slabs

Old deep slab avalanches tend to occur most often in January for all regions except the Rocky Mountains where activity peaks in December. This is a distinct change from the trends shown by data representing all avalanche activity. Haegeli and McClung (2007) found that each of the four regions will usually develop an early season weakness of faceted crystals that will produce avalanche activity. This January and December spike may be a result of an early season weakness reaching its critical load and failing. Once the peak has passed the weak layer may gain strength due to densification and pressure sintering caused by the increased load (Brown et al., 2001). Johnson (2000) found that average monthly snowfall rates peak in December for the Rocky Mountains and January for the Columbia Mountains coinciding with the respective peaks in old deep slab activity.

Old deep slab avalanche activity separated by year and region is shown in Figure 4. It appears that more old deep slabs occurred before the 01/02 winter season. However, it is likely that reporting habits changed and more thorough reporting of smaller and more common events started in 2004. One season stands out more than the others in terms of avalanche activity, the 96/97 winter season. Jamieson et al. (2001) already identified this season as significant in terms of deep slab avalanche activity and documented the weather events that led to the formation of a very persistent weak layer. They suggested that this pattern recognition in the early months of the winter season could aid in forecasting for deep slab avalanches. Figure 4 shows that there are seasons where one or more regions have a higher percentage of old deep slab avalanches than other regions and that the Rocky Mountains constantly show more regional old deep slab avalanche activity when compared to the other regions. The increased old deep slab avalanche activity of the Rocky Mountains may be attributed to the basal weakness that is present most winters.

6 CONCLUSIONS AND OUTLOOK

By reviewing over twenty thousand avalanches from the InfoEx database, we found that many of the characteristics for old deep slab avalanches are similar for all four regions. They tend to propagate wider, run further down slope and are more destructive based on the CAA avalanche size classification. These characteristics alone make them a major hazard. Furthermore, deep slab avalanches tend to be more often naturally triggered with crusts as the bed surface and faceted crystals as the failure layer when compared to all other avalanches reported in a region. The aspects on which old deep slab avalanches occur are similar to trends seen for all avalanches in a particular region. These findings have not been verified on a seasonal basis and particular winters may show different trends.

Old deep slab avalanches tended to occur most often during the early season, January in the Coast, North and South Columbia Mountain ranges and December in the Rocky Mountain range. It is believed that this is the result of an early season weak layer, often involving faceted crystals, reaching a critical load and failing naturally. Further studies that investigate weather patterns and avalanche occurrences for years with many old deep slabs contrasted with years with few old-deep slabs might provide early recognition of potential hazardous avalanche conditions and critical loading patterns which lead to naturally occurring of old deep slab avalanches.

The Rocky Mountain region is unique in that it had a higher tendency for ground avalanches during the reporting months of November to April. There was also a large number of old deep slab avalanches reported in this region involving a crust. Previous studies suggest rainfall events are rare during the early season of the Rocky Mountains but that such events are important for formation of old deep slabs in this region. A more thorough analysis of the early season weather is required.

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