In situ and photogrammetric measurements of avalanche crown transects

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ABSTRACT: We present results on the geometry and depth distributions for transects along the crowns of small to large avalanches. Previous research suggests that power laws in aggregate distributions of crown depths result from observers recording maximum depth. We therefore studied individual crown transects to obtain information about the parent distributions, using *in situ* and photogrammetric measurements. The geometry shows that crowns are thinnest and decreasing toward the flanks. Depth distributions of individual crowns do not follow power laws. Instead, we find transects fit normal distributions. To reconcile this finding with observed aggregate distributions, we propose a mixture of maxima, taken from normally distributed crown depths, with power law mean parameters. We suggest normally distributed transects arise from spatially-correlated new snow depths.

KEYWORDS: photogrammetry, crowns, power laws, distributions

1 INTRODUCTION

Detailed measurements of avalanche slabs are important for run-out models and fracture research. Because the avalanche destroys it, the slab is difficult to measure. A reasonable proxy is the crown face. After asserting that power laws in aggregate crown-depth distributions may result from observers recording maximum depth (Bair et al., 2008), we decided to investigate parent distributions of these maxima by measuring depth transects across individual avalanche crown faces. Two researchers have noted slab taper (Perla, 1977; McClung, 2009), yet they treat slab depth as a scalar rather than a distributed variable. Both comment on a lack of measurements across crown faces. A few recent studies have used laser scanning and photogrammetry to construct snow depth difference maps before and after avalanches (Vallet et al., 2001), but none have reconstructed the slab. Slab depth has been called the "fundamental scaling parameter" (McClung, 2005), yet there are almost no field observations of its distribution for individual transects.

To our knowledge, there have been no *in situ* studies published for avalanche crown depth transects. One study that uses photogrammetry (Vallet et al., 2001) reported just one crown depth transect. They did not find a tapering crown, nor was a statistical distribution fit to the depths. The avalanches they photographed were very large (ca. $10^5 m^3$), with crown depths ranging from 1.0 to 3.5 m. The measurements had an accuracy of $\pm$ 0.35m, which is not fine enough to capture a crown face that tapers to very small depths.

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2 METHODS

We limit our examination to geometry and depth distributions of crown transects. We do not examine slab length, slab volume, or total avalanche volume because of the difficulty in completely measuring these variables. The crown is easier to measure both *in situ* and by photogrammetry, since it is not partially or completed destroyed by the avalanche as are the flanks, stauchwall, and slab.

2.1 In situ methods

During the winter of 2008-2009, we directly measured two crown line faces, both within one day of the avalanche. The measurements were orthogonal to the bed surface and made at 0.10 and 1.00 m spacing, respectively. They covered the crown face from flank to flank, across the slope. The main source of error was finding the exact depth to the bed surface, especially after it was covered with wind-transported snow. Still, we believe the error was only 1-2cm.

2.2 Two-dimensional photogrammetry

We used 2-d photogrammetry to measure transects for eight other avalanches. Since crown faces are often the most intact scar left by an avalanche, we are able to take advantage of digital photographs of them. We selected images where the crown face is oriented orthogonally to the central line of sight and where lens distortion appears minimal.

Using a known length of some reference object in the photograph, such as person or a measured maximum crown depth, we scale

Table 1. Summary of measurements. Avalanches from 4 different states or provinces were measured. Depths range over 3 orders of magnitude.

#	Location	Method	width (m)	max depth (cm)	min depth (cm)	μ	σ	confined?	*N*	R^2 normal	class size
1	Paranoid 4, Mammoth, CA	*in situ*	7	20	1	10	6	yes	73	0.90	R1
2	Kayla's Brothers & The Right Stuff, Yellowstone Club, MT	*in situ*	130	140	7	79	36	yes	130	0.96	R5
3	Unknown, Columbia Mountains, BC	photo	149	100	28	70	14	yes	168	0.97	R3
4	Unknown backcountry, CO	photo	42	72	7	39	17	no	81	0.96	R3
5	Crown Butte, Daisy Pass, Cooke City, MT	photo	84	63	20	44	9	yes	88	0.99	R3
6	Dropout 1-3, Mammoth, CA	photo	100	213	29	129	30	no	87	0.92	R3
7	Climax, Mammoth, CA	photo	230	122	10	73	22	no	150	0.99	R4
8	Paranoid 4, Mammoth, CA	photo	69	200	24	98	46	yes	111	0.97	R4
9	Dropout 1-3, Mammoth, CA	photo	100	655	148	446	147	no	80	0.91	R5
10	Dave's, Mammoth, CA	photo	385	457	42	288	90	no	77	0.96	R5

our measurements. The enlarged area in Figure 3a shows an example of photogrammetric measurements, taken for avalanche 9. Photogrammetric methods are less accurate than *in situ* measurements. Sources of error include image resolution, distortion, look angle, and distinguishing the bed surface. We estimate the error to be at least the resolution of the image, or on average 10-20cm. Keeping these limitations in mind, we find photogrammetry essential for increasing our sample size, which is otherwise restricted by the labour required to directly measure the distribution of sizes in the crown.

Photogrammetry is especially useful for examining general geometry and comparing transects. Given that we are only making 2-d, rather than 3-d measurements, we can avoid using fixed control points, stereo plotters, and other more advanced photogrammetric tools.

2.3 *Statistical distributions of crown depths*

We fit nine candidate statistical distributions using maximum likelihood. The distributions fit were the: exponential, normal, two-parameter Fréchet, generalized extreme value, truncated power law, lognormal, uniform, Cauchy, and Gumbel. We select distributions by comparing squared correlation coefficients, R^2, for linear regressions on probability plots, as Table 1 shows. We find that the normal distribution provides the best fit (see section 3.2).

3 RESULTS AND DISCUSSION

3.1 *Geometry*

Transects are generally thinner at the flanks and decrease in depth toward the flanks. Based on others' observations (Perla, 1977; McClung, 2009), we might expect that confined paths, such as those abutted by rock walls or dense trees, show more tapering than unconfined paths. Our measurements show that a smooth taper towards the flanks is observed in some fractures (1, 4, 8, & 9) but not in others, regardless of whether the path is confined. Consider the photographs and transects for avalanches 4 and 5. The transect for avalanche 4 shows smooth tapering on both sides (Figure 1). It is not confined by trees or rock outcroppings on either side (Figure 2).

The slope appears convex in the horizontal direction, which is atypical of a defined avalanche path. The transect for avalanche 5 does not show smooth tapering, although it is generally thinner at the flanks

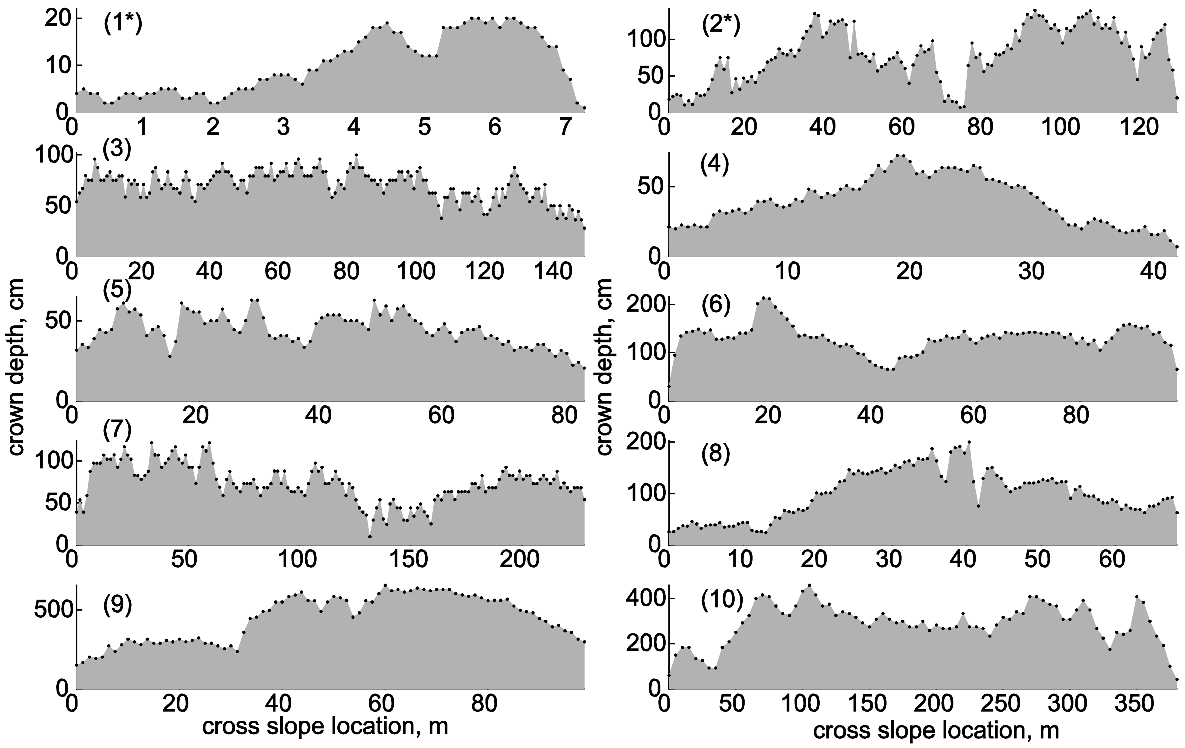

Figure 1. Depth Transects. Transects measured in situ (first two with stars), or by photogrammetry. The numeric labels correspond to avalanche numbers in Table 1.

(Figure 1). There are rock outcroppings to the left and right of the main area of the fracture, suggesting that this fracture may have been confined by the terrain (Figure 3b). This example shows that confinement does not necessarily play a role in crown taper.

Avalanches 1 and 8 are from the same path, as are avalanches 6 and 9. Although avalanche 1 is small compared to avalanche 8, both taper at the flanks (Figure 1). Likewise, avalanches 6 and 9 also taper at the flanks.

3.2 Depth distributions

We find that transects are best fit by a normal distribution with R^2 values ranging from 0.90-0.99 (Table 1 & Figure 4). None of the transects is fit by heavy-tailed distributions such as the Fréchet or power law, as Bair et al. (2008) predict. How can we reconcile this finding? We suggest that transects are driven by spatial distributions of new snow. Normal distributions may result from a Gaussian process (Cressie, 1993), where measurements are spatially correlated. The most likely process that causes spatial heterogeneity is wind transport of new snow.

We cannot suggest a simple mechanism for the observed power laws in aggregate crown depths. A rough model is that they are a mixture of maxima (Bair et al., 2008) drawn from normal distributions, with means distributed as power laws. A logical thought is that these means are driven by precipitation. However, 24-hr new snow and SWE, measured at Mammoth’s patrol plot, are both exponentially distributed; they alone cannot cause the means to be heavy-tailed. Micro- and slope-scale processes—such as sintering, temperature gradients, and wind deposition—cause complex interactions that lead to large spatial variance. Rosenthal and Elder (2003) have proposed that these factors may drive observed power laws in aggregate crown depth distributions.

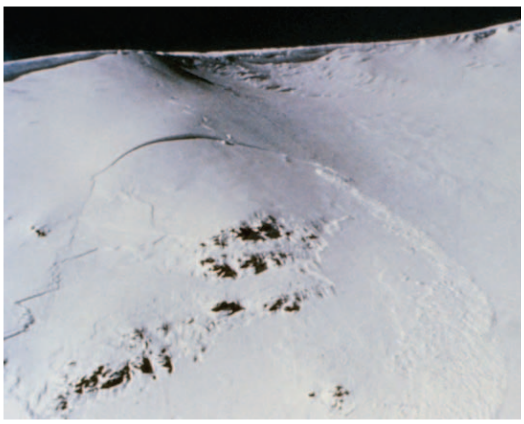

Figure 2. Avalanche 4. Crown taper on an atypical path with a cross-slope convexity. Photo courtesy of the National Avalanche Center.

(a) (b)

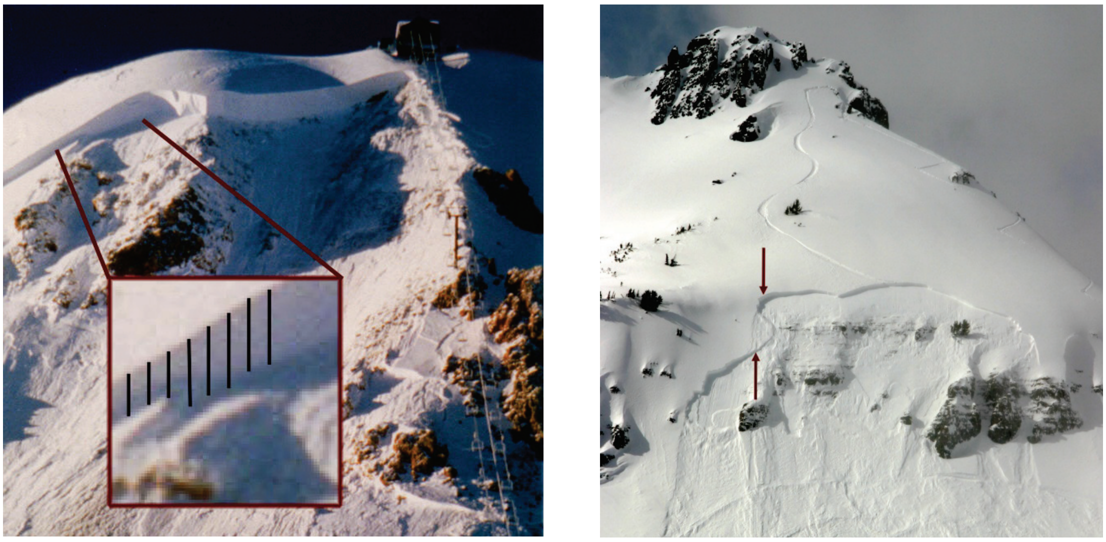

Figure 3. Avalanches 9 & 5. Crown transects show substantial changes associated with the underlying topography, which we suggest are caused by wind redistribution. Image (a) shows avalanche 9, with the area near coordinate 3m enlarged. The substantial increase in depth is caused by an abrupt transition from one convex gully to another. The black lines show depths measured photogrammetrically. Photo courtesy of Mammoth Mountain Ski Patrol. Image (b) shows avalanche 5, with the arrows near coordinates 15-16m. The decrease and then increase in crown depth is associated with a change in the path of the crown fracture. The main fracture on the right crosses over into the path on the left. Photo courtesy of the Gallatin National Forest Avalanche Center.

3.3 *Transect shape*

A majority of our transects are roughly convex (e.g. 1, 2, 4, 8, 9 & 10), suggesting that underlying terrain features are cross- slope concavities, features previously correlated with avalanche starting zones (Gleason, 1994). Wind-transported snow likely contributes to this profile shape. It smoothes terrain by filling depressions and scouring ridges (Elder et al., 1991; Winstral et al., 2002), causing a convex distribution of snow depths over terrain concavities.

There are several reasons to expect avalanche starting zones in concave terrain. If the concave portion of a gully is a deposition area, one would expect denser snow and greater accumulation rates in those areas. Both factors contribute to unstable slab formation (Schweizer et al., 2003). Further, convex features have barriers on their sides that interrupt the spatial structure of the weak layer, such as large rocks. These barriers can prevent the formation of uniform weak layers by breaking up their spatial structure. Kronholm and Birkeland (2005) support this finding; they used a cellular automata model to show that fracture propagation is likely to be arrested in areas with weak spatial structure. A few of our transects are not concavities (e.g. 3, 6 & 7); we hypothesize they are caused by wind redistribution of snow on underlying terrain features that load heavily. Transects of these terrain features might be approximated by the inverse of the crown depth transect.

4 CONCLUSION

Crown depths along these 10 transects are normally distributed. Though we know of

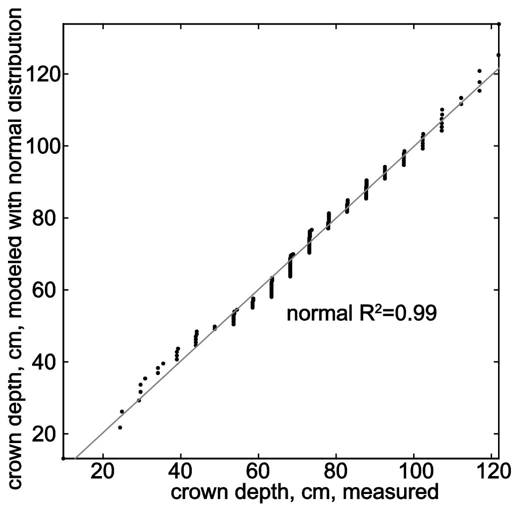

Figure 4. Avalanche 7 normal probability plot. We use R^2 values on probability plots to compare distributions.

no detailed reconstructions of slab depth in the literature, our results suggest that depth in such reconstructions would be normally distributed, with noticeable tapering at the flanks. Wind redistribution of snow, which could be a spatially correlated Gaussian process, may be responsible. A recommendation for future work is to use a combination of terrestrial laser scanning and synthetic aperture radar to measure distribution of snow depths in avalanche starting zones (Schaffhauser et al., 2008).

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