ON THE SUSTAINABILITY AND ARREST OF WEAK LAYER FRACTURE IN WHUMPFS AND AVALANCHES

Dave Gauthier*[1], Bruce Jamieson[1,2]

[1]Department of Civil Engineering, [2]Department of Geoscience, University of Calgary, Alberta, Canada

ABSTRACT: Recent theoretical and practical descriptions of weak layer fracture have focused on the mechanics of achieving a state of propagation, which is assumed to be self-sustaining. Arrest of weak layer fracture has been addressed for shear-based models, but has often been overlooked for collapsing weak layers. Regardless of the failure mode, discrete weak layer crystals must fail in sequence during propagation. This means that the slab is responsible to 'communicate' the fracture laterally as part of the propagation process. This communication ability is lost, and weak layer fracture propagation should arrest, if the continuity of the slab is destroyed by a fracture through its thickness. Often this is the case, for example in perimeter slab fractures in whumpfs; however, these perimeter fractures are difficult to explain without considering weak layer collapse, slab bending, and the spatial variability of the slab. In addition, it is unclear how weak layer fracture continues to propagate despite the en-echelon slab fractures sometimes observed during avalanche release. We propose several simple mechanisms by which perimeter fractures in whumpfs may occur, how weak layer fracture may repeatedly advance beyond the en-echelon slab fractures, and how these processes could be linked. We argue that fractures should propagate downward through the slab, and investigate the interaction or competition between the weak layer and slab fractures that may determine the arrest condition. In addition, we propose that a sustainability term is required to properly describe propagation propensity.

1. INTRODUCTION

In early February of 2007, a significant surface hoar layer formed in the Columbia Mountains of British Columbia, Canada. About two weeks later, once this layer was buried by about 0.5 m of new snow, University of Calgary researchers were searching for suitable sites to work on the propagation saw test (PST). Approaching one such site, we triggered a whumpf, which propagated across a creek, spread across some flat terrain, and some distance away released an avalanche from a small slope. We searched the flat area for some indication of how far the whumpf had propagated and found a long vertical 'perimeter crack' through the slab. The slab had fractured along a set of old ski tracks across the flats, and we assumed that was where the weak layer fracture arrested. Later, however, we determined that the weak layer fracture had progressed past this break in the slab. We knew the slab fracture must have occurred during or after the whumpf, but when we started thinking about it we wondered how the weak layer fracture could keep propagating after the slab had broken. It seemed that the ski-tracks had something to do with why the slab fractured where it did, but what made it fracture at all? In this paper we present some conceptual arguments and empirical evidence to try to explain these and other questions about strange observations of propagation and arrest, and try to relate them to current theory and what we mean by the term 'propagation propensity'.

2. FRACTURE INITIATION AND PROPAGATION

Recent research has advanced our understanding of how weak layer fracture starts, and what is required for it to achieve a state of rapid, self-sustaining propagation that could lead to the release of slab avalanches. Most of this research focuses on 'anticracks', with collapsing weak layers and associated bending and vertical movement of the slab (Johnson, 2001; Heierli, 2005; Heierli and Zaiser, 2006, 2008; Heierli et al., 2008a,b; Harvey and Heierli, 2009), as opposed to the more traditional slope-parallel shear-based approach (e.g. McClung, 1979). Heierli et al. (2008a,b) have recently unified the weak layer fractures occurring on slopes and on horizontal terrain during avalanches and whumpfs, so that the two cases can be treated as a continuum. The actual release and sliding of the slab due to gravity is the most important distinction between them.

*Corresponding author address: Dave Gauthier, Dept. of Civil Engineering, University of Calgary, Calgary, AB, Canada T2N 1N4; tel: 403-220-7479; e-mail: davidmgauthier@gmail.com

The focus of the analytical models is to describe how a two-dimensional cross-section of a slab and weak layer configuration can *achieve* a state of self-sustaining fracture in the weak layer (e.g Heierli et al., 2008a,b). As with all fracture mechanics, the analysis begins with some small flaw or crack in the weak layer, which grows to reach a critical size. Once the crack reaches that critical size, rapid propagation may occur without the need to add additional load or driving force. In the case of human-triggered or other artificial avalanches, the load from the 'trigger' (e.g. skier, explosives, etc.) starts a small crack in the weak layer and causes it to expand (we often call this initiation). If it reaches the critical size for that particular snowpack configuration, the crack will grow rapidly without any additional input from the trigger (we often call this propagation). The fact that external forces need only expand the crack to the critical size, beyond which the 'body' or intrinsic forces take over, is one reason why avalanche size in a given snowpack is not proportional to the trigger energy.

The critical crack length required to achieve self-sustaining propagation is really an expression of the 'critical energy release rate' or 'specific fracture energy' of the snowpack configuration. In terms of avalanche release, self-sustaining propagation should be easier to achieve if the critical energy release rate is lower, and therefore critical crack length is shorter. The critical energy release rate can be estimated or measured in the laboratory (e.g Sigrist and Schweizer, 2007), or it can be measured in the field using the propagation saw test (PST) or similar methods (e.g. Sigrist and Schweizer, 2007; Gauthier and Jamieson, 2008). With some adjustment for geometry (Sigrist and Schweizer, 2007; Heierli and Zaiser, 2008), the PST measures the critical crack size through the cut length when the cut (i.e. the crack) propagates across the test column.

Gauthier and Jamieson (2008) showed that on skier-tested slopes where the weak layer was fractured by the skier (i.e. initiation occurred), slopes that did not whumpf or release an avalanche had significantly lower critical energy release rates than those that did (Mann Whitney U Test, $p < 0.01$). (A minor formulation error was included in Gauthier and Jamieson (2008), based on the equation presented in Sigrist (2006). Figure 1 shows the correct values, which match better those of Sigrist (2006).The distinction between cases with and without propagation remains clear.) Heierli and Zaiser (2008) presented a more detailed formulation for calculating the critical energy release rate for the PST configuration, which tends to result in slightly larger values than those in Figure 1.

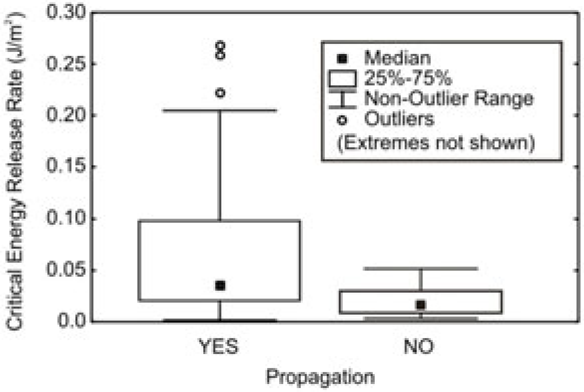

Figure 1. Corrected critical energy release rates for skier-tested slopes with confirmed fracture initiation. Slopes with no observed propagation had significantly lower energy release rates.

Figure 1 shows that the snowpacks with the lowest critical fracture energy release were often the ones least able to achieve propagation following initiation. Often, the propagation arrested in the PST in those same snowpacks, usually slab fractures in the test column. Combined with the observation that the critical energy release rates of the two groups of snowpacks in Figure 1 overlap, this suggests that a propagation criterion based solely on fracture energy is missing some crucial information for identifying the snowpacks that are able to whumpf or release avalanches. It appears that in some cases, although propagation may be easy to achieve, it is not sustainable for any reasonable distance to cause a whumpf or release an avalanche.

Since all weak layer fractures must stop or arrest *somewhere*, in every case there must be a limit to the sustainability of propagation. For avalanche release, we observe this arrest at fractures through the thickness of the slab at the crown and along the flanks. In whumpfs, we often can find perimeter cracks, again through the thickness of the slab, marking the presumed location of weak layer fracture arrest. Understanding the sustainability and arrest of weak layer fractures is the focus of this paper.

3. FRACTURE SUSTAINABILITY AND ARREST

Any progressive weak layer fracture requires that the slab communicate the disturbance or fracture from place to place. Take for example a cross-section of a thick surface hoar layer. It is actually composed of a sequence of discrete crystals that break or fail individually - but in succession - during weak layer fracture. The slab is the intermediary between weak layer crystals, 'informing' the next in line that its neighbour has failed and that it must now carry an extra load. If the next crystal cannot do this, it too fails, and so on across a slope. To perform this communication function, the slab must possess the capacity to transmit or transfer the forces (or energy) driving the progressive failure of weak layer crystals. The energy transfer associated with this task occurs via displacement and strain energy of slab bending. If the slab is unable to meet the energy transfer requirement, weak layer fracture propagation must arrest since there is no means of delivering the driving force or energy along the weak layer. When the demands of propagation (e.g. bending, displacement, etc.) on the slab exceed its capacity, it should fail, usually by fracturing. Given that in every avalanche, the perimeter of the released area is defined by slab fractures, the energy transfer required for propagation must eventually exceed the energy transfer capacity of the slab in all cases in nature.

Based on the weak layer collapse descriptions of Heierli (2005) and Heierli and Zaiser (2006, 2008) and the more refined anticrack theory of Heierli et al., (2008a,b) and Harvey and Heierli (2009), the weak layer fracture and associated slab bending occur over a relatively small area, equivalent to the 'wavelength' of the collapse. This actual length is related to the slab properties and collapse height in the weak layer, and is probably about 1 m long with average slab and weak layer properties (e.g. Heierli, 2005), while the critical crack length to start the collapse may shrink to near zero with localized external loads (Heierli and Zaiser, 2008; Harvey and Heireli, 2009). In any case, on flat terrain and assuming spatially consistent slab and weak layer properties, propagation should only arrest adjacent to the trigger point, within the first wavelength of the collapse, as beyond that distance the energy transfer required for propagation should not increase (Heierli and Zaiser, 2006). In other words, with uniform slab and weak layers, properties whumpfs should propagate forever! On slopes, however, the slab is also affected by the weight of the slab behind the fracture trying to slide down slope, although friction between the slab and bed surface along the fractured weak layer may reduce the added load near the propagating fracture. Preliminary measurements of the friction coefficients during and immediately after collapse have been performed (van Herwijnen and Heierli, 2009). In this case, there is an obvious mechanism to cause the slab to fracture after some real amount of propagation, although not all slab fractures cause the arrest of fracture propagation in the weak layer.

This idea of energy transfer capacity in the slab is similar to concepts for slab strain energy capacity (Jamieson and Johnston, 1992) or mode-I fracture resistance in the slab (e.g. McClung and Schweizer, 2006) in defining the limit of weak layer propagation distance, although in general slab bending associated with anticracks has not been considered.

4. THE RACE

Van Herwijnen (2005) looked at the interaction between a propagating weak layer fracture and one through the thickness of the slab that might lead to its arrest, and suggested that there was a race between the two to arrive first at a given point along the weak layer. He argued that weak layer fracture arrest would occur if the slab were bisected completely by a fracture through its thickness *before* the weak layer fracture arrived.

In a simple, two-dimensional description of propagation via weak layer collapse on flat terrain, strain from bending of the slab peaks near the 'crack tip' or the leading edge of the propagating fracture. The slab is thought to bend like a beam, with its upper part in tension and its lower park in compression. Since slab stiffness and density usually increase with depth, the 'neutral surface' where tension turns into compression should be near the base of the slab. This means that most of the thickness of the slab is in tension even on horizontal terrain, with the peak stress near the surface. Fractures through the thickness of the slab are therefore expected to start near the snow surface (Figure 2, stage 1) where tensional stresses are highest and the snow is least resistant, and propagate down through the slab (Johnson, 2001).

Of course, the fracture through the entire thickness of the slab cannot occur instantaneously; it must propagate at some finite speed and therefore some time must elapse between it starting near the surface and arriving at the weak layer. During this time, the weak layer fracture should continue, since the continuity of the slab and its energy transfer capacity is not yet interrupted; i.e. propagation is still sustainable (Figure 2, stage 2). Tension-fracture speeds in slab layers were measured by Sigrist (2006), with values ranging between 8 m/s and 23 m/s. Fracture speeds in the weak layer have also been measured, with consistent values of around 20 m/s (Johnson et al., 2004; van Herwijnen and Jamieson, 2005; van Herwijnen et al., 2008). For convenience, if we assume 20 m/s fracture speeds in both the slab and weak layer, it is clear that the weak layer fracture should advance a distance similar to the slab thickness before the slab fracture arrives at the weak layer (Figure 2, stage 3). At that point, two possibilities exist. If, at the time that the slab fracture completely bisects the slab, the weak layer fracture has not advanced far enough to reach the critical length for self-sustaining propagation, it should arrest (Figure 2, stage 4a). Alternatively, if it advanced a distance equal to or greater than the critical length, it should continue to propagate (Figure 2, stage 4b).

One implication of this 'race' is that even when a weak layer fracture arrests because of a fracture through the thickness of the slab, the weak layer *should* be damaged beyond the slab fracture (Figure 2, stage 4a). Therefore, in an avalanche we would expect to discover fractured weak layer above the fracture line, since the weak layer fracture should have continued while the crown was forming. This is not usually observed (e.g. Perla, 1975); however, a provision *is* often included in observation standards stating that profiles and snowpack tests should be performed at least 1.5 m from a fracture line (e.g. OGRS; CAA, 2007). At the fracture line, lack of visible damage to weak layer may not exclude its existence, because the damage could be very subtle and difficult to detect. For example, using Heierli's (2005) model calculations based on the experiments of Johnson et al. (2004; 0.40 m thick slab, vertical collapse of 1.5 mm) for a whumpf site, the total bending in the slab occurs over a length of approximately 0.89 m (Heierli, 2005). In this configuration, by the time a slab fracture reaches the weak layer the slab directly ahead of it would have displaced vertically less than 1 mm. This displacement would be very difficult to observe, especially since the slab would likely rebound to its original position after it fractures (Figure 2, stage 4a). In that case, the damaged weak layer microstructure would be the only evidence of the weak layer fracture having progressed beyond the perimeter of the whumpf. Note that the bulk crushing of the weak layer often observed is expected to happen after the fracture has passed, especially when the slab slides down slope (e.g. van Herwijnen et al, 2009). Heierli and Zaiser (2006) calculated a critical fracture length of between 0.20 and 0.65 m for this configuration, suggesting that the weak layer fracture *could* have advanced far enough beyond the perimeter to keep propagating.

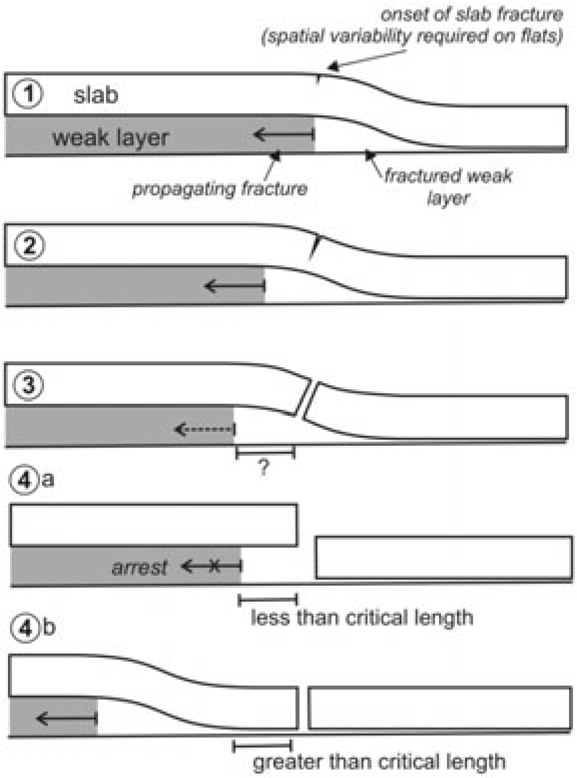

Figure 2. Schematic of the anticrack model showing 'the race' between slab and weak layer fractures. At stage 1 the slab fracture starts near the surface; at stage 2 both fractures continue to propagate; at stage 3 the slab is completely bisected by fracture; weak layer fracture arrest (stage 4a) or continued propagation (stage 4b) depends on whether the weak layer fracture exceeded the critical length for propagation at stage 3.

Jamieson and Johnston (1992) suggest that in the case of avalanche release a propagating crown fracture coupled with the weak layer fracture would consume significant energy and limit that available in the weak layer. For whumpfs, a similar process may be expected, both in terms of the slab fracture consuming and limiting available energy, and in a reduction of its ability to transfer or communicate the energy associated with the weak layer collapse to intact weak layer ahead of the slab fracture. Both of these are possible, and may limit the advancement of the weak layer fracture with the progression of the vertical slab fracture, making it more difficult to observe in situ.

In cases with very thick slabs, we may expect that the weak layer fracture would be more likely to advance a greater distance while the slab fracture occurs, and might have a better chance of winning the race. While this may be true, the critical crack length and the capacity of the slab to sustain propagation should also scale with slab thickness, so we may expect avalanche size to also scale with slab thickness.

5. ARREST IN WHUMPFS

On slopes, we know that as the weak layer fracture progresses, the slab is not only responsible for transmitting the forces required for propagation to continue, but as the fractured area increases so does the pull on the slab from unsupported areas trying to slide down slope. It is reasonable to assume that at some point those combined forces will exceed the capacity of the slab to sustain them and it will fail, often causing the arrest of weak layer fracture. But on flat terrain, as the weak layer fracture progresses, the demands on the slab should stay the same, since there is no additional pull from fractured areas. In fact, as described above, in the weak layer collapse models the capacity of the slab to transfer the propagation energy is tested within the first wavelength of the collapse. If the slab is capable of communicating the disturbance in the first metre or two of propagation, it should have that capability everywhere, and the weak layer fracture should never arrest. However, infinite propagation is not a behaviour observed commonly in whumpfs, although Johnson (2001) describes reports of ‘firn-quakes’ propagating several kilometers from the trigger in high-latitude snowpacks. In most familiar cases, a perimeter crack is evident where the weak layer fracture presumably arrested.

One possible explanation for this apparent paradox is that the snowpack usually changes from place to place, meaning that while the energy transfer requirements in the slab might not change as the fracture propagates, its ability to sustain the energy transfer may change. This is partly the focus of recent research into the spatial variability of the snow cover, although in general weak layer properties have been investigated in more detail (see Schweizer et al., 2008). As an extreme example, were the propagating fracture to encounter a tree or protruding rock, the energy transfer capacity of the slab would be reduced to near zero locally, and the slab would quickly fail and arrest propagation. Spatial variations in any of the slab or weak layer properties could have the same influence – in that either or both of the energy release rate or energy transfer capacity would be expected to change with distance across both flat terrain and slopes. This fracture arrest explanation can be extended to slopes as well, in which case slab fractures (crown or flanks) may be expected to occur frequently near trees or rocks, or at the extent of confined terrain; this is a common of feature of avalanches observed in the field.

Much of the recent work on spatial variability of the snowpack has focused on indentifying the patterns and locations of areas particularly susceptible to triggering weak layer fractures. Heireli (2005) and Heierli and Zaiser (2006, 2008) suggest that while a spatially variable snowpack is not required for the initiation or propagation of weak layer fractures, some variability in the slab and weak layer must be present for the arrest of weak layer fractures on flat terrain.

Where spatial variability may limit the possible extent of propagation and lead to fracture arrest, the lack of variability may have the opposite effect. For example, in February 2007, not far from the whumpf site described in the introduction to this paper, we remotely triggered a large avalanche from approximately 150 m away. The propagation path from the trigger point to the released area traversed several small slopes and dense timber, and eventually reached a large slope steep enough to release an avalanche. A series of snowfalls buried the surface hoar, leaving it and the slab uniform over the terrain, i.e. they were not affected by wind or sun, etc. Therefore, once the weak layer fracture began propagating, it was able to continue over a large distance without encountering any barrier to sustainable propagation, since there was little spatial variability. Weak layer fracture arrest finally occurred at the periphery of an open area near dense timber, where it appears that slab discontinuity associated with trees contributed to the occurrence of the slab fracture.

Heierli (2005) mentions that propagation may arrest if a large enough area lacking ‘meta-stability’ is encountered; in this context meta-stability refers to an ‘appropriately collapsible’ slab-weak layer stratification. This type of fracture arrest would not implicitly require a slab fracture at its termination, but instead propagation may become ‘energy starved’ (Heierli pers. comm., 2007) due to the reduction in collapsibility in the system, determined by both slab and weak layer properties. Nonetheless, spatial variability is also *required* for fracture arrest in this scenario.

6. EN ECHELON SLAB FRACTURES

Van Herwijnen (2005, pp. 246-248) describes a rarely documented phenomenon called ‘en echelon’ fracturing, in which during propagation in the weak layer on a slope a series of evenly spaced slab fractures appear, separated by distances on the order of a few metres to tens of metres, apparently coupled to the weak layer fracture. This usually occurs when the weak layer fracture is propagating upslope, i.e. where an avalanche is triggered from below.

In previous sections, we discussed the ability of the weak layer fracture to advance beyond a slab fracture, often far enough that the critical length for propagation is exceeded allowing propagation to continue. With the estimates for fracture speeds in the slab and weak layer, it would seem like this should be a relatively common occurrence. One mitigating factor that might reduce the likelihood of weak layer fractures continuing past slab fractures is that on slopes – especially steep ones – the fracture through slab may have a slight head start on the weak layer fracture. It is convenient to consider displacements in coordinates either parallel or perpendicular to the slope; however, the weak layer collapse is vertical, and so is the overall slab displacement. With vertical collapse in the weak layer and vertical displacements in the slab, in the slope-normal axis the slab near the surface is in bending before the base. This gives the slab fracture an effective slope dependant advance on the weak layer fracture in slope parallel/normal coordinates. Therefore, it may be less likely for the weak layer fracture to advance beyond the slab fracture on steeper slopes.

While possibly a rare occurrence, when en echelon slab fractures occur it seems that the weak layer fracture repeatedly advances a distance greater than the critical length for propagation beyond evenly spaced slab fractures (Figure 3). The consistency in the spacing of the en-echelon slab fractures would arise because on a consistent slope the slab should reach its capacity to sustain the bending and displacement that drives the fracture *plus* the pull of the unsupported slab down slope after a similar distance each time. The spacing of the slab fractures would be defined by the stiffness and toughness of the slab, the collapse associated with propagation, and the friction between the slab and bed surface following fracture. Some combination of slab and weak layer properties that allows the weak layer fracture to win the race repeatedly is required for this.

This explanation could be tested by observing the en-echelon phenomenon on a concave or convex slope. With consistent slab and weak layer properties, the spacing of the slab fractures should

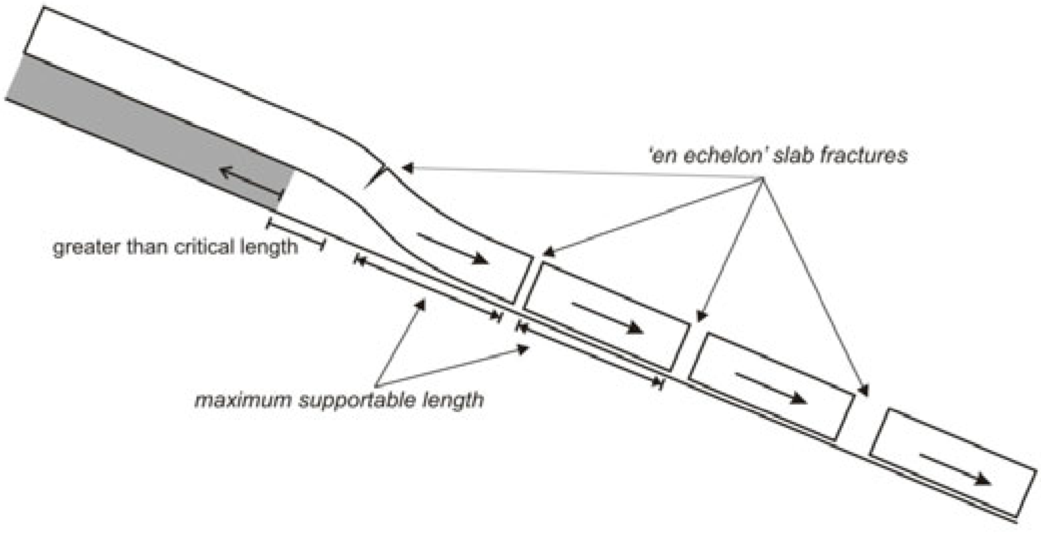

Figure 3. Schematic of the conceptual process for the occurrence of en echelon slab fractures during avalanche release. Repeatedly, after a similar propagation distance, the slab is unable to sustain the demands of propagating the anticrack and the down slope pull of unsupported slab, causing it to fracture. At each stage, the weak layer fracture must exceed the critical length for propagation.

be smaller on steeper parts of the slope as the down slope pull of the unsupported slab increases faster as slope angle increases.

7. PROPAGATION PROPENSITY

In the preceding discussion, we suggested that the traditional approach to the propagation problem, i.e. determining the critical energy release rate, is insufficient on its own to predict the extent of propagation in the weak layer during avalanche release. The critical energy release rate is better at describing the propensity for what we usually call fracture initiation (before self-sustaining propagation), whereas the practical definition of the propagation propensity of a given slab-weak layer system must include the capacity of the slab to transfer the energy required for propagation over some real distance. On slopes, the slab must be able to effectively transfer the energy required to fracture the weak layer, *and* due to the macro-scale slope parallel loading resulting from the reduced shear support of the weak layer following fracture. We also suggested that the interaction between the two can be complex, yet can account for many ordinary and extraordinary observations of slab avalanche release. In general, the critical fracture energy release rate must be low enough to allow propagation to initiate, yet the slab must be able to sustain and transmit the driving energy. Where the slab is thin and soft, initiation and sometimes propagation is easy but not sustainable by the slab; alternatively, where the slab is very thick and the weak layer is not susceptible to fracture, the energy barrier to propagation is too high to be exceeded by normal means. Intermediate levels of both are required for propagation and avalanche release. The *value* of propagation propensity is not defined only by the specific energy associated with weak layer fracture, meaning that a relative scale that relates the energy release due to fracture and the energy transfer required to propagate it with the energy transfer capacity of the slab may be more appropriate. For avalanche forecasting, it may be more useful to describe ‘high’, ‘low’ or ‘no’ propagation propensity of a given slab-weak layer configuration, rather than quote an energy release value. Note that the initial energy barrier for initiation and propagation, or the absolute value of the input required to initially fracture the weak layer and extend that fracture to some critical size for self-propagation is not included describing propagation and sustainability.

8. CONCLUSIONS

In this paper, we have tried to go beyond the initiation and onset of the propagation of weak layer fracture, and focus on its sustainability and arrest. We reported on data showing that snowpacks with very low critical fracture length for propagation often cannot sustain the demands of the propagation process for any distance, meaning that fracture energy alone cannot predict avalanche release. Since many weak layer fractures during whumpfs and avalanches arrest near fractures through the thickness of the slab, we have advanced previous thoughts (van Herwijnen, 2005) on ‘the race’ between the two and the scenarios where the weak layer fracture arrests or continues to propagate. In doing so, we have proposed that on flat terrain spatial variability is not only convenient for triggering fractures but is a mandatory feature of their arrest. Combined, these two ideas can help explain how and why we found fractured weak layer beyond the perimeter crack of a whumpf, and why that crack was located under old ski-tracks. We proposed that the weak layer fracture won the race and exceeded its critical length for propagation before the slab’s energy transfer capacity was destroyed by the vertical crack that occurred where, because of the ski tracks, it could not sustain the demands of the propagating fracture. In addition, the rare observation of en-echelon slab fractures can be explained if the race between the two fractures is considered.

All of the arguments and ideas presented in this paper are based on a very much simplified view of the detailed and precise theoretical and analytical models for anticracks, collapsing weak layers and fracture propagation (e.g. Heierli et al., 2008a,b; Harvey and Heierli, 2009). The models themselves are restricted to two-dimensional sections of hypothetical snowpacks, and therefore so are the ideas proposed in this paper. Incorporating the third dimension represents an alluring - but likely very complex - goal for future research.

The descriptions, arguments, and evidence presented in this paper should be regarded as a preliminary exploration of a few possible interpretations or implications of the models. Some of the ideas we propose here are testable in the field with simple experiments and observations, although whumpfs and en echelon fractures can be elusive at the best of times, especially when one is searching for them!

9. ACKNOWLEDGEMENTS

Karl Birkeland and Ron Simenhois contributed their thoughts and ideas on fracture. For support, we thank the Natural Sciences and Engineering Research Council of Canada, HeliCat Canada, the Canadian Avalanche Association, Mike Wiegele Helicopter Skiing, Teck Mining Company, Canada West Ski Areas Association, the Association of Canadian Mountain Guides, Backcountry Lodges of British Columbia, the Canadian Ski Guides Association and Parks Canada.

10. REFERENCES

Observation Guidelines and Recording Standards for Weather, Snowpack and Avalanches. Canadian Avalanche Association, Revelstoke, Canada, 2007.

Gauthier, D. and Jamieson, B., 2008. Fracture propagation propensity in relation to snow slab avalanche release: Validating the Propagation Saw Test, Geophys. Res. Let., 35, L13501, doi:10.1029/2008GL034245

Jamieson, B., and Johnston, C., 1992. A fracture-arrest model for unconfined dry slab avalanches. Canadian Geotechnical Journal, 29, 61-66.

Harvey, S.,Heierli, J., 2009. Interpretation of prevalent avalanche scenarios on the basis of the anticrack model. Proceedings: ISSW 2009, Davos, Switzerland.

Heierli, J., 2005. Solitary fracture waves in metastable snow stratifications, J. Geophys. Res., 110, F02008, doi:10.1029/2004JF000178.

Heierli, J., and M. Zaiser, 2006. An analytical model for fracture nucleation in collapsible stratifications, Geophys. Res. Let., 33, doi:10.1029/2005GL025311.

Heierli, J., and M. Zaiser 2008. Failure initiation in snow stratifications containing weak layers: Nucleation of whumpfs and slab avalanches, Cold Reg. Sci. Tech., 52, doi:10.1016/j.coldregions.2007.02.07

Heierli, J., Gumbsch, P., Zaiser, M., 2008a. Anti-crack nucleation as triggering mechanism for slab avalanches. Science, 321, 240-243.

Heireli, J., van Herwijnen, A., Gumbsch, P., Zaiser, M., 2008b. Anticracks: A new theory of fracture initiation and fracture propagation in snow. Proceedings: ISSW 2008, Whistler, BC, Canada

Johnson, B., 2001. Remotely triggered slab avalanches, M.Sc. Thesis, 98pp., University of Calgary, Calgary, 8 January.

Johnson, B., Jamieson, B., and Stewart, R., 2004. Seismic measurement of fracture speed in a weak snowpack layer. Cold Reg. Sci. Tech., 40, 21-45.

McClung, D., 1979. Shear fracture precipitated by strain softening as a mechanism of dry slab avalanche release, J. Geophys. Res., 84, 3519-3526.

McClung, D., and Schweizer, J., 2006. Fracture toughness of dry snow slab avalanches from field measurements. J. Geophys. Res., 111, F04008, doi:10.1029/2005JF000403.

Perla, R., 1975. Stress and fracture of snow slabs, IAHS Publication, 114, 208-221.

Schweizer, J., Kronholm, K., Jamieson, B., and Birkeland, K., 2008. Review of spatial variability of snowpack properties and its importance for avalanche formation. Cold Reg. Sci. Tech., 51, 253-272.

Sigrist, C., 2006. Measurement of Fracture Mechanical Properties of Snow and Application to Dry Snow Slab Avalanche Release. Ph.D. Thesis, Swiss Federal Institute of Technology, Zurich., 139pp.

Sigrist, C., and J. Schweizer, 2007. Critical energy release rates of weak snowpack layers determined in field experiments, Geophys. Res. Let., 34, L03502, doi: 10.1029/2006GL028576

van Herwijnen, A., 2005. Fractures in Weak Snowpack Layers in Relation to Slab Avalanche Release. PhD thesis, University of Calgary, 296pp.

van Herwijnen, A., Heierli, J., Schweizer, J., 2008. Field study on fracture propagation in weak snowpack layers. Proceedings: ISSW 2008, Whistler, BC, Canada.

van Herwijnen, A., Heierli, J., 2009. Measurement of crack-face friction in collapsed weak snow layers. Geophys. Res. Let., L23502, doi:10.1029/2009GL040389