AN INVESTIGATION OF THE SPATIAL VARIABILITY AND EFFICACY OF THE EXTENDED COLUMN TEST

by

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ABSTRACT

Most avalanche accidents are the results of an avalanche triggered by the victim, or a member of the victim’s party. Many of these accidents are the result of uncertainty regarding the stability of the snowpack. Spatial variability of snow stability is a significant cause of this uncertainty. There has been significant previous work on the spatial variability of snow stability at multiple spatial scales, but most of these studies have focused on measures of fracture initiation. This study investigates the spatial variability of Extended Column Test (ECT) results (an index of fracture propagation).

We measured the spatial variability of ECT results in 23 grids across southwest Montana over the course of two winters. These slopes were all topographically uniform, wind sheltered clearings, with snowpacks relatively undisturbed by skiers or snowmobiles. Twenty eight ECTs were spaced across each grid in a standardized layout with a 30 m x 30 m extent.

Our results are consistent with previous work, with some grids showing high levels of variability as well as other grids with relatively homogenous results. We found no consistent spatial pattern to our test results. We tested slopes with a variety of weak layers (surface hoar, depth hoar, new snow, and near surface facets), slab characteristics (slab hardness, slab depth), and snow depths and found no correlations with ECT results.

We found a relationship between the forecasted regional avalanche danger and the percent of ECTs showing propagation in a grid. As the regional danger increases the percent of ECTs propagating in a grid does as well. ECT results are most variable under moderate danger. When the regional avalanche danger is either considerable or low, results are likely to be more consistent.

The key practical implication of our results is that ECTs, like all other stability tests, should be interpreted with an appropriate level of caution and in consideration of all other relevant variables. The spatial variability of this test has the potential to be high on some slopes, while on other slopes test results will be entirely in agreement.

INTRODUCTION

Background

Avalanches in the United States cause more fatalities annually than earthquakes and landslides combined (Voight et al., 1990). During the recent 2013–14 season, 35 people were killed in avalanches in the United States (Colorado Avalanche Information Center, 2014). Despite increasing avalanche education and new technologies, avalanche fatalities continue to rise. In 90% of accidents, the avalanche victims or members of their own party trigger the avalanche in which they are caught (e.g., McCammon and Haegeli, 2006; McClung, 2014). This makes understanding the spatial distribution of snowpack weaknesses important to both avalanche practitioners and backcountry travelers. Through the last thirty years, spatial variability of snow stability has been investigated in many studies across a range of scales, from the slope scale to the mountain range scale, with wildly varying results (Schweizer et al., 2008). Fracture initiation and fracture propagation are both necessary for avalanche formation and are independent of one another (Gauthier and Jamieson, 2006). Previous research has mostly focused on tests relating to fracture initiation (Schweizer et al., 2008). This work focuses on the spatial variability of the Extended Column Test (ECT), an index of fracture propagation, at the slope scale.

Slope Scale Spatial Variability

Conway and Abrahamson (1984) were the first to look at variations in stability in a spatial context, they investigated the representativity of point stability tests to the stability of whole slopes. They used shear frames to measure shear strength variability along recently triggered avalanche fracture lines, as well as on slopes that had not failed. They found that if there was one location with a low shear strength, there were often more on the same slope, and they considered the slope to be unstable. They proposed wind as a primary driver of variability in shear strength, citing as evidence the significant variation in bulk snow properties across a slope.

Jamieson and Johnston (1993) performed 36-76 evenly spaced Rutschblock tests on six relatively uniform slopes, free of rock outcrops, with slope angles of 28-33° and slope angle variation of less than 4°. They found that that 97% of their tests fell within +/-1 score of the median score for the slope. In contrast, Landry et al. (2004) found using a stability index that 25% to 39% of their sites were not statistically representative of the stability of the slope.

Different snowpack properties have been shown to have different amounts of variability. Kronholm (2004) showed that layer properties are more continuous than stability scores and most often layers existed throughout a slope of given aspect and elevation. Rutschblock release type proved to be more consistent than Rutschblock scores, especially for low median scores (Campbell and Jamieson, 2007).

Schweizer et al. (2008) proposed that shear quality (Johnson and Birkeland, 2002) and fracture character (van Herwijnen and Jamieson, 2002) will show less variability than Compression Test scores. The results of Campbell and Jamieson (2007) show this low variability in fracture character. As Johnson and Birkeland (2002) stated that shear quality may provide a qualitative measure of how well a fracture will propagate through a given weak layer, this led researchers to hypothesize that fracture propagation is also less variable than fracture initiation.

Spatial Variability of Fracture Propagation

There is limited previous work on the spatial variability of tests relating to fracture propagation, and the existing work shows variable results. Simenhois and Birkeland (2006) developed the ECT, as a stability test that incorporates an index of fracture propagation into its design. The ECT provides information on propagation potential (ECTP or ECTN) as well as information on the force required for fracture initiation (ECT test score). Initial work by Simenhois and Birkeland (2006; 2007; 2009) showed low levels of spatial variability in ECT results. Near Mount Hutt in New Zealand, Simenhois and Birkeland (2006) conducted 21 ECTs in a 30 m by 15 m grid, on a relatively planar 32° slope, and found spatially uniform results, all pits produced ECTN results. Simenhois and Birkeland (2007) conducted 24 ECTs in a grid on Tucker Mountain in Colorado and found a clear line on the grid differentiating between the ECTP and ECTN results. The pits with ECTP results had an obvious wind slab which did not exist lower down the slope. Simenhois and Birkeland (2007) was the first work that showed significant spatial variability of ECT results at the slope scale (30 m by 20 m), but this variability went along with an obvious change in slab property.

On six slopes in New Zealand and Montana, Hendrikx and Birkeland (2008) found results ranging from no spatial variability on a slope (zero ECTPs out of 12 ECTs performed) to very high variability (eight ECTPs out of 16 ECTs performed). Hendrikx and Birkeland (2008) hypothesized that these differing results may be related to the different processes responsible for the instability. The very low variability results from New Zealand came from a snowpack that had experienced a rain event the week previously, this rain and subsequent refreezing may have had a homogenizing effect on the snowpack. Hendrikx and Birkeland (2008) showed that there are conditions under which considerable spatial variability exists in ECT results, but could only hypothesize about the factors influencing the level of variability.

Hendrikx et al. (2009) analyzed a subset of the Hendrikx and Birkeland (2008) ECT data using statistical techniques to look for spatial clustering in the data, as well as changes in the clustering through time. Two slopes in southwest Montana were each sampled twice (four to ten days between sampling) for this study: one slope in Beehive Basin and one on Cedar Mountain. Hendrikx et al. (2009) used Moran's I as a measure of spatial autocorrelation. Moran's I is a weighted correlation coefficient used to detect departures from spatial randomness, with these departures indicating spatial patterns such as clusters (Moran, 1948). While Hendrikx et al. (2009) showed some patterns in the spatial variability of ECT propagation results (an increase in spatial organization over time), it was a small case study, only using two sites. As propagation/non-propagation is a binary response, Hendrikx et al. (2009) used an indicator variable for the Moran's I test. An indicator variable is necessary because ECT test scores are a measure of the load required for fracture initiation at a point rather than potential for propagation (Simenhois and Birkeland, 2006). However, as the Moran's I test is not appropriate for binary data

(Cliff and Ord, 1973), it was not used in this study.

Geostatistics

While Hendrikx et al. (2009) used the Moran's I with an indicator variable as a measure of the spatial autocorrelation of ECT results, as propagation/non-propagation is a binary response, we instead used join count statistics (Moran, 1948; Cliff and Ord, 1973). To calculate a join count statistic, a binary variable is mapped in two colors (Black & White). A join links two adjacent (neighboring) areas. The possible types of joins are black-black (BB), black-white (BW), and white-white (WW). For point data, a neighborhood distance is defined in order to determine adjacency, in this study 10 m was used. The number of BB, BW, and BW joins are compared to the expected numbers of BB, BW and WW joins under the null hypothesis of no spatial autocorrelation. The black-black join count test (Cliff and Ord, 1973) was used in this study, in order to determine if test results in two neighboring pits are more likely to be the same than on a slope with no spatial autocorrelation.

Early efforts to conduct explicit geostatistical analyses on snow spatial variability primarily used the semi-variogram as a measure of spatial autocorrelation (Cressie, 1993; Kronholm and Schweizer, 2003). However, sample sizes for snow stability work are often much smaller than those recommended for semi-variograms (Webster and Oliver, 1992). For instance, Kronholm and Schweizer (2003) used semi-variograms with a sample size of 17-26 point stability tests for each slope, despite Webster and Oliver's (1992) suggestion of a minimum sample size of at least 150 for semi-variograms. Semi-variograms were not used in this study, as appropriate sample sizes were impractical due to logistical and time constraints.

Sampling

In addition to physical factors, sampling strategy also has a potentially huge effect on the results of spatial variability studies. Blöschl and Sivapalan (1995) reviewed potential effects of sampling methods in snow hydrology. This work introduced the idea of the "scale triplet": spacing, extent, and support. Spacing is how far apart from each other sampling points are located. With a large spacing, fine resolution variability will not be captured. Extent is the size of the area over which all the sampling points are located. With a small extent, variability that occurs over a large area will not be sampled. Support is the the area over which a sampling "point" is actually distributed. For example, the ECT involves isolating a snow column that is 30 cm x 90 cm. This means that a data point from an ECT actually represents the area within the size of that column. A larger support (each point is greater in area) will make variability seem smoother than the true distribution. Blöschl and Sivapalan (1995) suggest that spacing should be minimized, extent should be maximized, and support should also be minimized in order to best capture spatial signatures. In addition, Blöschl (1999) concluded that errors of up to two orders of magnitude can be introduced simply by the scale triplet of the sampling design. This helps to explain why the results from previous spatial variability of snow stability studies (Schweizer et al., 2008) have been so varied. Skøien and Blöschl (2006) stress the important of adjusting sampling design to the scale of the underlying process you are attempting to capture. However, the underlying processes leading to snow stability variability are unknown so in this study we used a sampling design attempting to capture variability at a wide range of scales.

False Stability

The probability that an individual test result will accurately reflect the stability of the slope as a whole is an important measure of the efficacy of a stability test. Using a highly controlled dataset of 324 ECTs collected by a single observer, Simenhois and Birkeland (2009) found a false stable rate of 1% for the ECT, as well as a false unstable rate of 2%. This indicates that performing an ECT on slopes which are unstable will only produce a test result indicating stability 1% of the time. Simenhois and Birkeland (2009) characterized stable versus unstable slopes by applying explosives and ski cutting to the slopes, if the slope avalanched within one day of the test it was characterized as unstable, otherwise it was classified as stable. Simenhois and Birkeland (2007; 2009) and Birkeland and Simenhois (2008) analyzed a dataset of ECT results from the SnowPilot database, showing a 6% false stability rate, and 18% false unstable rate, from 311 ECTs conducted by nearly 20 observers in a wide range of snow climates. The SnowPilot analysis relied upon the “similar slopes” stability rating chosen by the observer (Simenhois and Birkeland, 2009). Winkler and Schweizer (2008) found both false stable and false unstable rates of 20% for the ECT from a dataset of 225 tests. Winkler and Schweizer (2008) classified slopes as stable or unstable using the presence of recent avalanche activity, whoomphing or cracking, and analysis of the snowpit hardness profile.

Comparison With Other Tests

Overall, the false stability rates for the ECT from previous studies are comparable with the 10% false stability rate found by Birkeland and Chabot (2006) for tests based on measures of fracture initiation (e.g. Rutschblock Tests, Compression Tests, and Stuffblock Tests). However, Hendrikx and Birkeland (2008) found slopes where 50% of ECTs propagated and 50% did not, indicating that there are slopes where the ECT has up to a 50% false stability rate.

The Propagation Saw Test (PST) is the only other standardized, widely adopted, stability test that attempts to measure propagation potential (Gauthier and Jamieson, 2006). The PST is conducted by using a standard snow-saw to cut along a weak layer within a completely isolated column of snow, measuring 30 cm across-slope by 1 m or greater upslope. Tests with cut lengths of less than half the length of the column, followed by uninterrupted propagation to the end of the column, are considered to indicate high propagation propensity (Gauthier and Jamieson, 2010). Previous studies show much higher false stability rates for the PST: 44% (Simenhois and Birkeland, 2009) and 30% (Gauthier and Jamieson, 2008). These same studies show false unstable rates of 0% (Simenhois and Birkeland, 2009) and 5% (Gauthier and Jamieson, 2008) for the PST.

Research Motivation

This research was motivated by the very limited previous work on the spatial variability of tests relating to fracture propagation. There are only two peer reviewed journal articles (Simenhois and Birkeland, 2009; Hendrikx et al., 2009), and several related conference proceedings articles, examining spatial datasets of ECTs. There are no articles looking at the spatial variability of other tests attempting to capture fracture propagation (e.g. the Propagation Saw Test). In addition, the small body of previous work shows variable results. While some explanations for these variable results have been proposed in earlier studies, no study has gathered a large enough dataset to meaningfully analyze the spatial variability of the ECT and look for correlations with other factors.

This research aimed to address three primary objectives. First, to determine the amount of spatial variability present in ECT results across a range of different slopes. Second, to determine spatial patterns in that variability. Third, to determine if that variability in ECT results can be correlated with other factors (e.g. weak layer type, slab hardness). This research builds off the work done by Hendrikx and Birkeland (2008), using a much larger and more diverse dataset while maintaining a constant sampling scheme.

These aims have been addressed in one paper titled “Spatial Variability of Extended Column Test Results at the Slope Scale” which is presented in Chapter 2.

REFERENCES CITED

Birkeland, K. W., Chabot, D. (2012). Changes in stability test usage by snowpilot users. *Proceedings of the 2012 International Snow Science Workshop, Anchorage, Alaska,* 1065-1068.

Blöschl, G. (1999). Scaling issues in snow hydrology. *Hydrological Processes* 13 (14-15):2149-2175.

Blöschl, G., Sivapalan, M. (1995). Scale issues in hydrological modelling: A review. *Hydrological Processes*, *9*, 251–290.

Campbell, C. P., Jamieson, B. (2007). Spatial variability of slab stability and fracture characteristics within avalanche start zones. *Cold Regions Science and Technology*, *47*(1-2), 134–147. doi:10.1016/j.coldregions.2006.08.015

Cliff, A. D., Ord, J. K. (1973). Spatial autocorrelation. London : Pion, London, UK. 178 pp.

Colorado Avalanche Information Center. (2014) *US Avalanche Fatalities*. http://avalanche.state.co.us/accidents/us/

Conway, H., Abrahamson, J. (1984). Snow stability index. *Journal of Glaciology*, *30*(106), 321–327.

Cressie, N.A.C. (1993). Statistics for spatial data. Wiley series in probability and mathematical statistics. John Wiley & Sons, Inc., New York, 900 pp.

Gauthier, D., Jamieson, B. (2006). Understanding the Propagation of Fractures and Failures Leading to Dangerous and Destructive Snow Avalanches : Recent Developments. In *Proceedings of the 2006 Annual Conference of the Canadian Society for Civil Engineering, First Specialty Conference on Disaster Mitigation, 23/05/2006, Calgary, Alberta.*

Gauthier, D., Jamieson, B. (2008). Evaluation of a prototype field test for fracture and failure propagation propensity in weak snowpack layers. *Cold Regions Science and Technology. 51* (2–3), 87–97.

Gauthier, D., Jamieson, B. (2012). The Propagation Saw Test (PST): A review of its development, applications, and recent research. *Proceedings of the 2012 International Snow Science Workshop, Anchorage, AK*, 1047–1053.

Hendrikx, J., Birkeland, K. W. (2008). Slope scale spatial variability across time and space: comparison of results from two different snow climates. *Proceedings of the 2008 International Snow Science Workshop, Whistler, BC,* 155–162 .

Hendrikx, J., Birkeland, K. W., Clark, M. P. (2009). Assessing changes in the spatial variability of the snowpack fracture propagation propensity over time. *Cold Regions Science and Technology*, *56*(2-3), 152–160. doi:10.1016/j.coldregions.2008.12.001

Jamieson, J.B., Johnston, C.D. (1993). Rutschblock precision, technique variations and limitations. *Journal of Glaciology*, 39(133), 666-674

Johnson, R., Birkeland, K.W. (2002). Integrating shear quality into stability test results. *Proceedings of 2002 International Snow Science Workshop, Penticton, British Columbia, Canada*, 514-520

Kronholm, K. (2004). *Spatial variability of snow mechanical properties with regard to avalanche formation*. Ph. D. thesis, 187 pp., University of Zurich, Zurich, Switzerland

Kronholm, K., & Schweizer, J. (2003). Snow stability variation on small slopes. *Cold Regions Science and Technology*, *37*(3), 453–465.

doi:10.1016/S0165-232X(03)00084-3

Landry, C., Birkeland, K. W., Hansen, K. J., Borkowski, J., Brown, R. L., Aspinall, R. (2004). Variations in snow strength and stability on uniform slopes. *Cold Regions Science and Technology*, *39*(2-3), 205–218. doi:10.1016/j.coldregions.2003.12.003

McCammon, I., Haegeli, P. (2006). Evaluation of a rule-based decision aid for recreational travelers in avalanche terrain. *Proceedings of the 2006 International Snow Science Workshop, Telluride, CO*, 234–243.

McClung, D. M. (2014). Risk analyses for dry snow slab avalanches released by skier triggering. *Natural Hazards*, *72*(2), 1139–1158. doi:10.1007/s11069-014-1060-4

Moran, P.A.P. (1948). The interpretation of statistical maps. *Journal of the Royal Statistical Society B* 10, 243–251

Schweizer, J., Kronholm, K., Jamieson, B., Birkeland, K. W. (2008). Review of spatial variability of snowpack properties and its importance for avalanche formation. *Cold Regions Science and Technology*, *51*(2-3), 253–272. doi:10.1016/j.coldregions.2007.04.009

Simenhois, R., Birkeland, K. W. (2006). The Extended Column Test: A field test for fracture initiation and propagation. *Proceedings of the 2006 International Snow Science Workshop, Telluride, Colorado*, 79–85.

Simenhois, R., Birkeland, K. W. (2007). An update on the Extended Column Test : New recording standards and additional data analyses. *The Avalanche Review*, *26*(2).

Simenhois, R., Birkeland, K. W. (2009). The Extended Column Test: Test effectiveness, spatial variability, and comparison with the Propagation Saw Test. *Cold Regions Science and Technology*, *59*(2-3), 210–216. doi:10.1016/j.coldregions.2009.04.001

Skøien, J. O., & Blöschl, G. (2006). Sampling scale effects in random fields and implications for environmental monitoring. *Environmental Monitoring and Assessment*, *114*(1-3), 521–52. doi:10.1007/s10661-006-4939-z

Voight, B., Armstrong, B., Armstrong, R., Bachman, D., Bowles, D., Brown, R., Faisant, R., Ferguson, S., Fredston, J., Kennedy, J. (1990). Snow avalanche hazards and mitigation in the United States. National Academy Press, Washington, DC, USA

Webster, R., Oliver, M.A. (1992). Sample adequately to estimate variograms of soil properties. *Journal of Soil Science*, 43(1): 177-192.

Winkler, K., Schweizer, J. (2008). Comparison of different snow stability tests including the Extended Column Test. *Proceedings of the 2008 International Snow Science Workshop, Whistler, British Columbia*, 393–400.

CHAPTER TWO

SPATIAL VARIABILITY OF EXTENDED COLUMN TEST RESULTS AT THE SLOPE SCALE

Contribution of Authors and Co-Authors

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Co-Author: Kathryn M. Irvine
Contributions: Provided statistical advice through the development and implementation of the study and comments on the manuscript.

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SPATIAL VARIABILITY OF EXTENDED COLUMN TEST RESULTS AT THE SLOPE SCALE

Abstract

Fracture propagation is required for avalanche release, making understanding its spatial variability critically important. Previous work on spatial variability of snow stability at the slope scale primarily focused on tests related to fracture initiation. The small number of studies examining spatial variability of fracture propagation test results (utilizing tests such as the Extended Column Test (ECT)) are inconsistent. Some work reports spatially homogenous ECT results, while other studies show results that are more variable and difficult to explain. Because of these inconsistencies, we measured the spatial variability of ECT results on multiple slopes in southwest Montana over the course of two winters. We sampled 23 grids, with each grid containing 28 ECTs, for a total of 644 ECTs, using a predefined standarized layout with a 30 m by 30 m extent. We tested slopes with a variety of weak layers (surface hoar, depth hoar, new snow, and near surface facets), slab characteristics (slab hardness, slab depth), and snow depths. Further, we sampled during varying levels of forecasted regional avalanche danger. Our data demonstrate that considerable spatial variability in ECT results exist on many slopes, even without substantial variation in snowpack structure. When the regional avalanche danger is either considerable or low, results are likely to be more consistent, but when the regional danger is moderate, results tend to be more variable. Further, the ratio of ECTPs to ECTNs is correlated with the forecasted danger level. Harder slabs were also correlated with a higher percentage of ECTPs. Our results show that ECTs, like all other stability tests, should be interpreted with an appropriate level of caution.

1.0 INTRODUCTION

Avalanches impact populations and infrastructure in mountainous regions worldwide. On an average annual basis, avalanches in the United States have historically caused more fatalities than earthquakes and landslides combined (Voight et al., 1990). During the recent 2013–14 season, 35 people were killed in avalanches in the United States (Colorado Avalanche Information Center, 2014). Despite increasing avalanche education and new technologies, avalanche fatalities continue to rise. In 90% of accidents, the avalanche victims or members of their own party trigger the avalanche in which they are caught (e.g., McCammon and Haegeli, 2006; McClung, 2014). Most of these avalanches are slab avalanches. In addition, avalanche forecasting methods rely heavily on the evaluation of snowpack information collected in the field, including the use of stability tests. This makes understanding the spatial distribution of snowpack weaknesses and appropriate interpretations of stability test results important both to avalanche forecasting and to inform avalanche safety education.

There are four ingredients necessary for the formation of a slab avalanche: 1) initiation of a crack, 2) growth of that crack to a critical size, 3) crack propagation, and 4) the slab overcoming friction in order to move downslope (Schweizer et al., 2003). These four factors are each necessary for avalanche formation and are independent of one another (Gauthier and Jamieson, 2006). Thus, the results of snowpack tests analyzing only fracture initiation provide limited or no information on the propagation potential of that snowpack.

Previous work has proposed that shear quality (recorded in fracture initiation tests) may function as a proxy for fracture propagation (Johnson and Birkeland, 2002). Schweizer et al. (2008) suggest that shear quality, and related fracture character (van Herwijnen and Jamieson, 2002), should show less variability than fracture initiation test scores. The results of Campbell and Jamieson (2007) show this reduced variability in fracture character. However, shear quality and fracture character are at best a qualitative proxy for fracture propagation propensity, not a true test of propagation potential.

Simenhois and Birkeland (2006) developed the Extended Column Test (ECT), as a stability test that incorporates an index of fracture propagation into its design. The ECT is performed by isolating a 30 cm x 90 cm column of snow and applying increasingly large forces (usually by tapping) to a shovel placed on the top of one side of the column until failure occurs (Greene et al., 2010). The ECT provides both information on propagation potential (ECTP or ECTN), as well as information on the force required for fracture initiation (ECT test score). An ECTP indicates that when failure occurred the fracture propagated all the way to the end of the column, while an ECTN indicates that the fracture arrested before reaching the far end of the column. The ECT is a good measure of slope stability (e.g. Simenhois and Birkeland, 2009) and has become an increasingly popular stability test among avalanche practitioners in recent years (Birkeland and Chabot, 2012). Birkeland et al. (2010b) found that ECT results were independent of slope angle, allowing comparison across test sites with similar stratigraphy, but varying slope angles.

There has been a substantial amount of prior research examining the spatial variability of snow stability on the slope scale (e.g. Conway and Abrahamson, 1984;

Jamieson and Johnston, 1993; Campbell and Jamieson, 2007). However, most of this earlier research focused on measurements of fracture initiation such as shear frames, Compression Tests, Stuffblock Tests, or Rutschblock Tests (Schweizer et al., 2008).

There has only been preliminary work, with small datasets, examining the spatial variability of the ECT (Hendrikx and Birkeland, 2008; Hendrikx et al., 2009; Simenhois and Birkeland, 2009). No research has been published investigating spatial variability of other tests which attempt to measure propagation potential, such as the Propagation Saw Test (PST) (Gauthier and Jamieson, 2006; Gauthier and Jamieson, 2012). As propagation is a necessary ingredient for avalanche release (Heierli et al., 2011), a detailed investigation of its spatial variability is an important missing element in our understanding of spatial snow stability.

Previous work has shown different levels of spatial variability in ECT test results. On two slopes, Simenhois and Birkeland (2009) found very little spatial variability in ECT propagation results, and the variability they did find was attributable to changing wind slab properties as they moved away from a ridgeline. However, Hendrikx and Birkeland (2008) found varying levels of spatial variability for ECT results on six slopes in Montana and New Zealand. The authors suggested that the type of weak layer may be a determining factor in the degree of the spatial variability seen across a slope (Hendrikx and Birkeland, 2008).

Snowpit stability tests based on measures of fracture initiation (e.g. Rutschblock Tests, Compression Tests, and Stuffblock Tests) have false-stability rates around 10% (Birkeland and Chabot, 2006). This means that using fracture initiation based tests on slopes which are actually unstable will produce a test result indicating stability about 10% of the time. For the ECT, Simenhois and Birkeland (2009) found much lower false stable rates (1%, 6%) as well as relatively low false unstable rates (2%, 18%). In contrast, Winkler and Schweizer (2008), found both false stable and false unstable rates of 20% for the ECT. Previous studies show much higher false stability rates for the PST: 44% (Simenhois and Birkeland, 2009) and 30% (Gauthier and Jamieson, 2008). These same studies show false unstable rates of 0% (Simenhois and Birkeland, 2009) and 5% (Gauthier and Jamieson, 2008) for the PST.

This study has two primary goals. First, to determine the amount of spatial variability present in ECT results across a range of slopes through the use of a much larger dataset than has previously been collected. Second, to determine if the variability in ECT results is correlated with other factors (e.g. weak layer type, slab hardness). This builds off the work done by Hendrikx and Birkeland (2008), but using a much larger and more diverse dataset while maintaining a constant sampling scheme.

2.0 STUDY AREA

Sampling teams collected data at 13 study sites during the Northern Hemisphere winters of 2012/13 and 2013/14 in seven areas across southwestern Montana. Sites were located in below treeline, topographically uniform, wind sheltered clearings of at least 40m by 40m to minimize terrain effects on our results as well as to provide enough area for data collection. All sites were approximately planar, with only small variations in slope angle (±5°) and minimal changes in aspect (Fig. 1). Each study site was located in an area undisturbed by previous sampling. During the second winter of data collection some sites that had been sampled in the previous winter were sampled again.

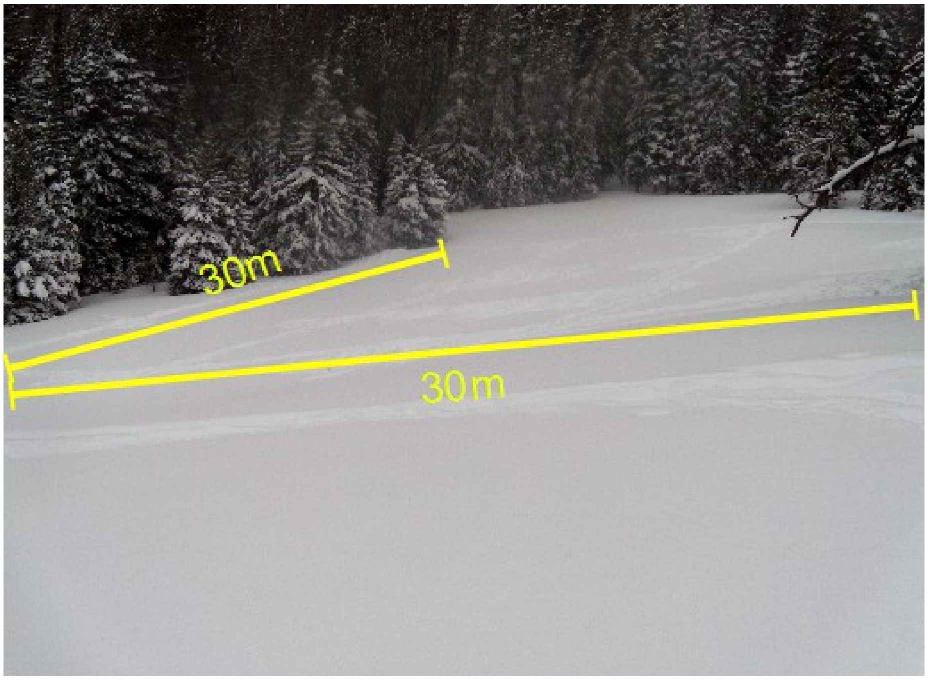

Figure 1. Photo of a typical site after sampling, showing the grid with added dimension lines for scale. We sampled this grid in the Montana's Gallatin Range on February 23rd, 2013.

Study sites were chosen based on accessibility and the existence of snowpacks relatively undisturbed by skiers or snowmobiles. In order to sample a variety of snowpacks within a winter season, sites were located across three mountain ranges with distinctly different snowpacks. The Bridger, Gallatin, and Madison ranges all typically have continental to intermountain avalanche climates (Mock and Birkeland, 2000), but often show marked variety in their snowpack structure. To mitigate avalanche safety concerns while sampling, all study slopes had a slope angle of less than 25º. As shown by Birkeland et al. (2010b), ECT results are independent of slope angle, so varying slope angles and low slope angles should not bias the resulting data.

3.0 METHODS

3.1 Field Methods

This study used a pre-defined sampling scheme, spacing 28 ECTs across each slope in a standardized layout with a 30 m x 30 m extent (Fig. 2). This scheme attempts to maximize extent and minimize the spacing, following Blöschl and Sivapalan's (1995) recommendations to best capture spatial signatures at a range of inter-site distances. As the spatial patterns of ECT results are under investigation, the range of lag distances created by this sampling design was designed to capture spatial patterns from small (1-5 m) to large (20-30+ m) scales. The spacing in this sampling design varies from 1 m to 10 m. The full extent of each grid is 42 m, while the support of the ECT is fixed at 0.27 m^2 (Simenhois and Birkeland, 2006).

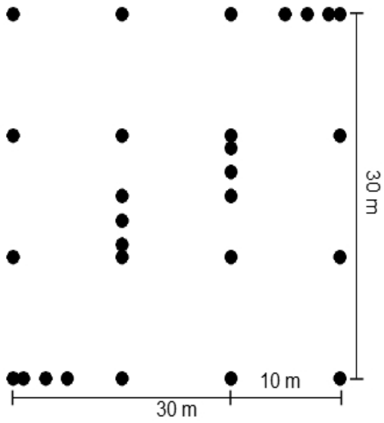

Figure 2. Map view showing the layout of the sampling grid with the black dots indicating the ECT locations. This sampling scheme has been optimized to capture spatial signatures ranging from small (1-5 m) to large (20-30+ m) scales.

Following Hendrikx et al. (2009), we modified the ECT by using the stuffblock test (Birkeland and Johnson, 1999) loading increments rather than standard hand taps. For each ECT we recorded the propagation result (ECTP, ECTN, or ECTX), test score (i.e. drop height), snow depth, and failure height (distance from the ground to the failure), and calculated slab thickness (snow depth minus failure height). When multiple weak layers were present in the snowpack at a site, each weak layer was tracked independently, and the results were analyzed as separate grids. At each site, we obtained a full snow pit profile according to Greene et al. (2010), including a hand hardness profile, temperatures, densities, grain forms and grain size .

A single observer conducted all tests in order to minimize bias introduced due to observer variability. This limited the data collected each day and hence the number of tests in each grid. Due to the rapidly changing nature of snowpack properties, collecting data over more than one day would introduce potential temporal changes into the spatial analysis (Hendrikx et al., 2009). To minimize temporal effects, all grids were performed as rapidly as feasible, generally within a period of approximately five hours.

In total we sampled 23 grids at 13 sites with each grid containing 28 ECTs, for a total of 644 tests. For each grid, the weak layer type was identified: four of these grids had surface hoar as the weak layer, 13 had near surface facets, one was on depth hoar, and five were on interfaces within new snow. For each grid the forecasted regional avalanche danger was recorded. This involved some interpretation of the forecast, as the regional forecasted danger was often broken down by slope-scale factors (e.g. aspect, elevation, wind loading). The avalanche danger assigned to a grid never exceeded the highest forecasted danger in the region, but was regularly lower due to these mitigating slope-scale conditions (e.g. lack of wind loading).

Data Analysis

The fundamental question this study seeks to address is: how much spatial variability in ECT propagation results exists at the slope scale? To address this question, we calculated the percentage of ECTs propagating on a slope as follows:

$$PP = 100 * ECTP / (n - ECTX), \qquad (1)$$

Where PP is the propagation percentage. $ECTP$ is the number of ECTP results in the grid, n is total number of ECTs in the grid, and $ECTX$ is the number of ECTX results.

ECTX results were treated as a non-response because ECTX results indicate a failure to initiate a fracture rather than giving information on the propensity to propagate a fracture if one had been initiated (Simenhois and Birkeland, 2009). These non-responses were removed for the calculation of propagation percentage because ECTX results reflect no initiation rather than no propagation, therefore, it was assumed that the non-response tests were missing completely at random with respect to propagation.

Propagation agreement percentage (PA) was calculated as another tool to measure and visualize the level of spatial variability on a slope. This was calculated as follows:

$$\text{If } PP>50, \text{ then}$$

$$PA = PP \tag{2}$$

$$\text{IF } PP<50, \text{ then}$$

$$PA = 100 - PP \tag{3}$$

Propagation agreement is a measure of the percentage of test results that agree with the predominant result within a grid. Therefore, both grids with 100% ECTP and 100% ECTN will plot as 100% agreement. Grids with 75% ECTP or ECTN results will plot as 75% agreement.

The daily danger rating for each sampling day was obtained from the Gallatin National Forest Avalanche Center (2014). When there were multiple danger ratings given for a region (e.g. wind loaded and non-wind loaded), the danger rating applicable to the snowpack and terrain at the sampling site was used.

As propagation/non-propagation is a binary response, we used join count statistics (Moran, 1948; Cliff and Ord, 1973) as measures of spatial autocorrelation. While Hendrikx et al. (2009) used the Moran's I test for spatial autocorrelation with similar spatial ECT result data, that test is only appropriate for continuous data (Cliff and Ord, 1973). The black-black join count test was used (Cliff and Ord, 1973), in order to determine if ECT test results in two neighboring pits are more likely to be similar than a distribution with no spatial autocorrelation would indicate. We performed this analysis looking for clustering in both ECTP results as well as ECTN results, as clustering in either has implication when trying to minimize false-stable or false-unstable results. The null hypothesis for the join count test is that there is no spatial pattern, with P-values used as a measure of significance for clustering in a grid. We used the statistical package R (R Development Core Team, 2013), with the *joincount.test* tools in the *spdep* package (Bivand et al., 2013) to calculate the join count tests' p-values.

4.0 RESULTS AND DISCUSSION

A wide range in spatial variability is seen in our results, from no variability to very high variability (Fig 3.). This leads to a wide range of propagation percentages across the 23 sampled grids (Fig. 4). The propagation percentage indicates both false-stables and false-unstables in our results. As opposed to previous work (Simenhois and Birkeland, 2009; Winkler and Schweizer, 2008), we do not classify slopes as “truly stable” or “truly unstable,” as we do not have unambiguous information available for characterizing the “true” stability of the slope. The grid with 12 out of 25 of ECTs (Fig. 3) propagating shows that if a sampling location is randomly selected it is possible for some slopes to give results that are 50% false stable (if they are truly unstable) or 50% false unstable (if truly stable). Clearly, under some conditions a substantial amount of variability exists in ECT results (Fig. 3).

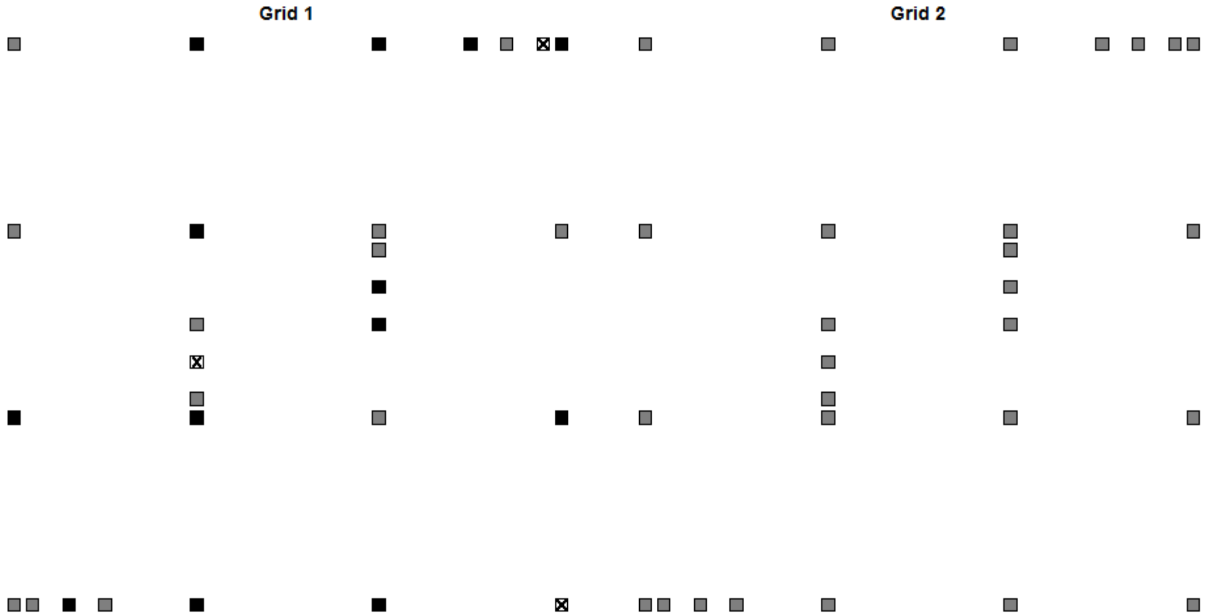

Figure 3. Plots showing the spatial distribution of propagation results for each of the 23 sampling grids, with each square indicating the location of an ECT. Each grid has a 30 m extent and follows the sampling plan laid out in Figure 2. Black squares are ECTP, gray squares are ECTN, and black X's are ECTX.

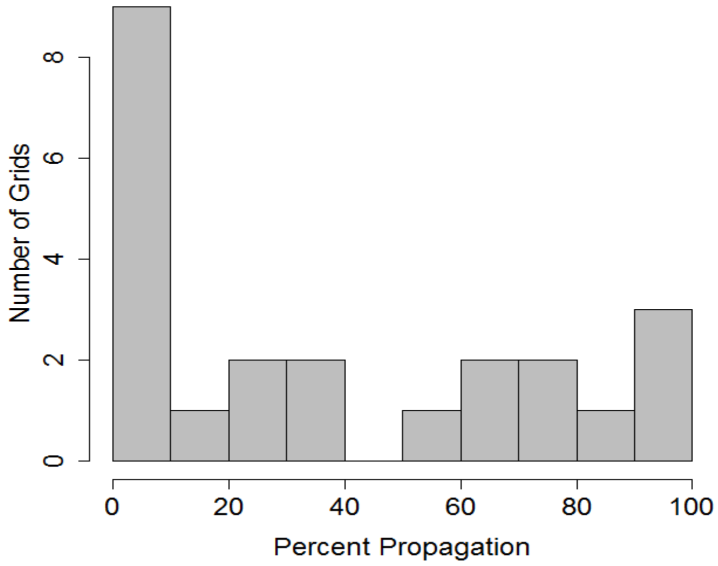

Figure 4. Distribution of propagation percentage for our 23 grids. Each bin contains a 10% range in percent propagation.

A histogram of the percent agreement values shows that 48% (11 out of 23) of grids have greater than 10% of ECT results that are unrepresentative of the slope as a whole (Fig. 5 – the sum of the bars from 50-90% agreement). This follows from both early work on the ECT by Simenhois and Birkeland (2006; 2007), suggesting homogenous ECT results on the slope scale, as well as the findings of Hendrikx et al. (2009), which show more variability in ECT results. Our larger and more diverse dataset shows that while some slopes are highly variable, many slopes (52% or 12 out of 23) show low levels of variability, and on these a single ECT has more than a 90% chance of accurately characterizing the stability. As such, it is unsurprising that a small dataset of only two slopes might only show low levels variability (Simenhois and Birkeland, 2006;

2007). However, grids exhibiting a nearly even mix of ECTP and ECTN results indicate that there are also slopes where a single randomly placed ECT is not a reliable indicator of the distribution of potential ECT results.

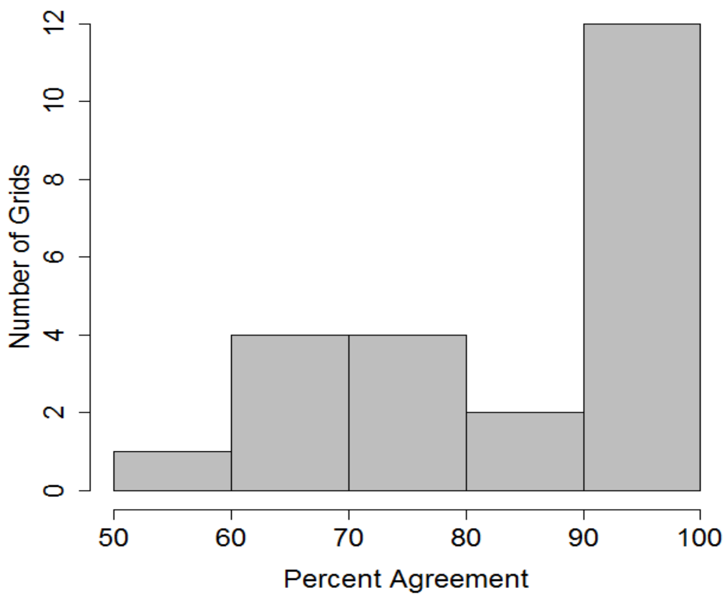

Figure 5. Distribution of the percent of ECTs in each grid that agree with the predominate result of that grid. Each bin contains a 10% range in percent agreement.

The number of grids with a low percent agreement initially appears to contrast with earlier analyses done by Simenhois and Birkeland (2009). Their results show extremely low false stable rates (1%, 6%) and relatively low false unstable rates (2%, 18%), while half of our test grids have less than 90% agreement. The likely explanation for these discrepancies is the difference in our samples. While we used pre-defined grids on sheltered, non-wind affected slopes in this study, the previous work utilized single tests located by experts on or near avalanche slopes. The targeted sampling by these experts may have increased the likelihood of sampling a location more indicative of the stability of the particular slope. Our percent agreement results also line up nicely with the work of Winkler and Schweizer (2008), who found both false stable and false unstable rates of 20% for the ECT.

The variability found in ECT results reinforces the advice given by Birkeland and Chabot (2006) to perform multiple stability tests to reduce the probability of a false-stable result. Because of this potential for false-stable results, observers must always be searching for instability. Unstable tests indicate the potential for unstable conditions, but stable test results do not assure stability.

We analyzed weak layer type, slab thickness, snow depth, and the coefficient of variation of snow depth as possible explanations for this variability (Fig. 6 and Table 1). The only trend found in these analyses was that new snow showed lower variability than other weak layer types. This seems likely to be a result of the relatively low elevation, sheltered, non-wind effected slopes we sampled. In our dataset only two out of 115 tests in five grids in new snow showed propagation, and as the ECT has been shown to capture propagation in new snow (e.g. Bair et al., 2012), this indicates that our sampling strategy missed capturing the full range of new snow propagation potential.

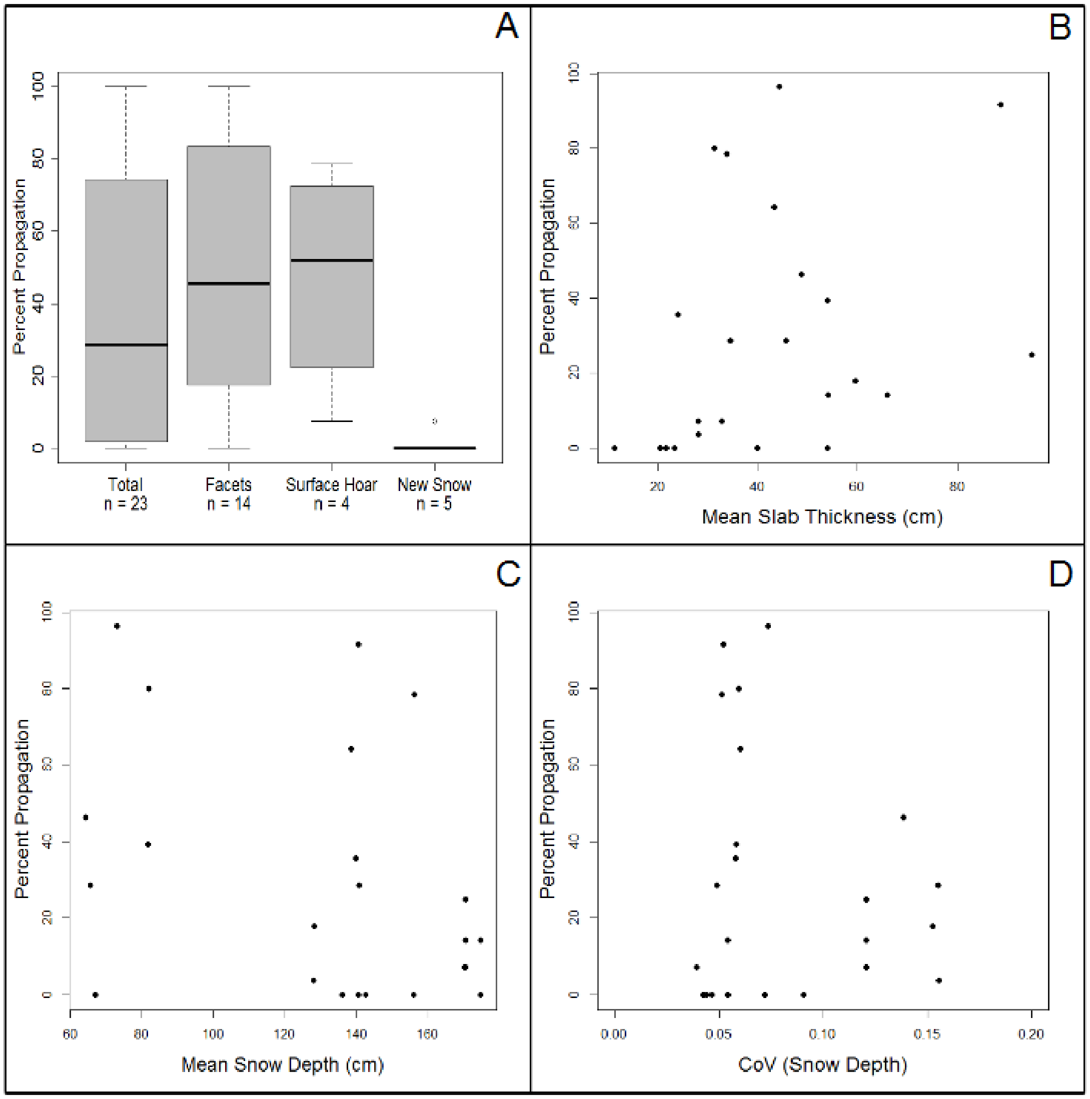

Figure 6. (A) Box and whiskers plot of the propagation percentage broken out by weak layer type: Facets, Surface hoar, and New Snow. The box and whiskers represents the maximum/minimum, median and interquartile range. (B) Scatterplot of the propagation percentage for a grid versus the mean slab thickness for that grid (P-value = 0.14). (C) Scatterplot of the propagation percentage for a grid versus the mean snow depth for that grid (P-value = 0.11). (D) Scatterplot of the propagation percentage for a grid versus the Coefficent of Variation (CoV) for snow depth across that grid, showing a lack of correlation (P-value = 0.52).

Table 1. Summary of data for each grid showing: ECTP, ECTN, ECTX, Regional danger, weak layer type, mean drop height, mean snow depth, mean failure height, propagation percentage (PP), percent agreement (PA), Join Count ECTP P-value, and Join Count ECTN P-value. P-values significant at the 0.05 level are bolded. Rows in dark grey have a clear spatial pattern. Rows in light grey have an indication of a spatial pattern. Rows that are left white have no indicate of a spatial pattern.

Grid #	P	N	X	Regional Hazard	Weak Layer Type	Mean Drop Height	Mean Snow Depth	Mean Failure Height	Propagation Percentage (PP)	Percent Agreement (PA)	Join Count ECTP P-value	Join Count ECTN P-value
1	13	12	3	Moderate	Facets	41	64	15	52	52	0.734	0.963
2	0	28	0	Moderate	Facets	32	67	44	0	100	NA	NA
3	2	25	1	Low	Surface Hoar	31	170	142	7	93	0.670	0.961
4	0	24	0	Moderate	New Snow	3	156	144	0	100	NA	NA
5	22	6	0	Considerable	Surface Hoar	17	156	122	79	79	0.539	0.625
6	4	0	24	Moderate	Facets	55	175	100	100	100	0.118	0.728
7	0	27	0	Low	New Snow	34	175	153	0	100	NA	NA
8	10	17	0	Moderate	Surface Hoar	16	140	116	37	63	0.550	0.072
9	5	1	22	Moderate	Facets	50	128	69	83	83	0.105	0.333
10	1	26	0	Low	Facets	33	128	100	4	96	NA	0.701
11	0	22	0	Low	New Snow	19	136	116	0	100	NA	NA
12	22	2	0	Considerable	Facets	58	140	52	92	92	0.298	0.681
13	0	16	0	Moderate	New Snow	46	140	86	0	100	NA	NA
14	8	20	0	Moderate	Facets	28	141	95	29	71	**< 0.001**	0.454
15	0	22	0	Low	Facets	25	142	102	0	100	NA	NA
16	7	3	18	Moderate	Facets	57	170	75	70	70	0.600	0.079
17	4	19	0	Moderate	Facets	50	170	116	17	83	**0.010**	0.728
18	2	25	0	Moderate	New Snow	21	170	137	7	93	**0.011**	0.590
19	18	9	1	Moderate	Surface Hoar	41	138	95	67	67	**0.002**	**0.038**
20	11	17	0	Considerable	Facets	31	82	28	39	61	0.797	**0.041**
21	20	5	0	Considerable	Facets	24	82	50	80	80	0.476	0.764
22	27	1	0	Considerable	Facets	30	73	29	96	96	0.966	NA
23	8	20	0	Moderate	Facets	33	66	31	29	71	**0.001**	**0.006**

Four individual grids show a significant difference between mean ECTP slab thickness and mean ECTN slab thickness (Fig. 7). On all four of these grids, pits with ECTPs have thicker slabs than pits with ECTNs. On these slopes, ECTs on the thickest part of the slab have the greatest likelihood of an ECTP result. It is important to note that we intentionally chose slopes with low variability in snowpack structure, so these slab thickness differences are small (5-20 cm). This limits the appropriate scope of inference, these results should not be applied to slopes with less homogenous slab thickness. Slopes with larger slab thickness changes may show entirely different results. In addition, the stress a skier/snowmobile transmits to a weak layer decreases with slab thickness (Thumlert et al., 2013), which also indicates that the thickest part of the slab will not necessarily be the most likely place to trigger an avalanche.

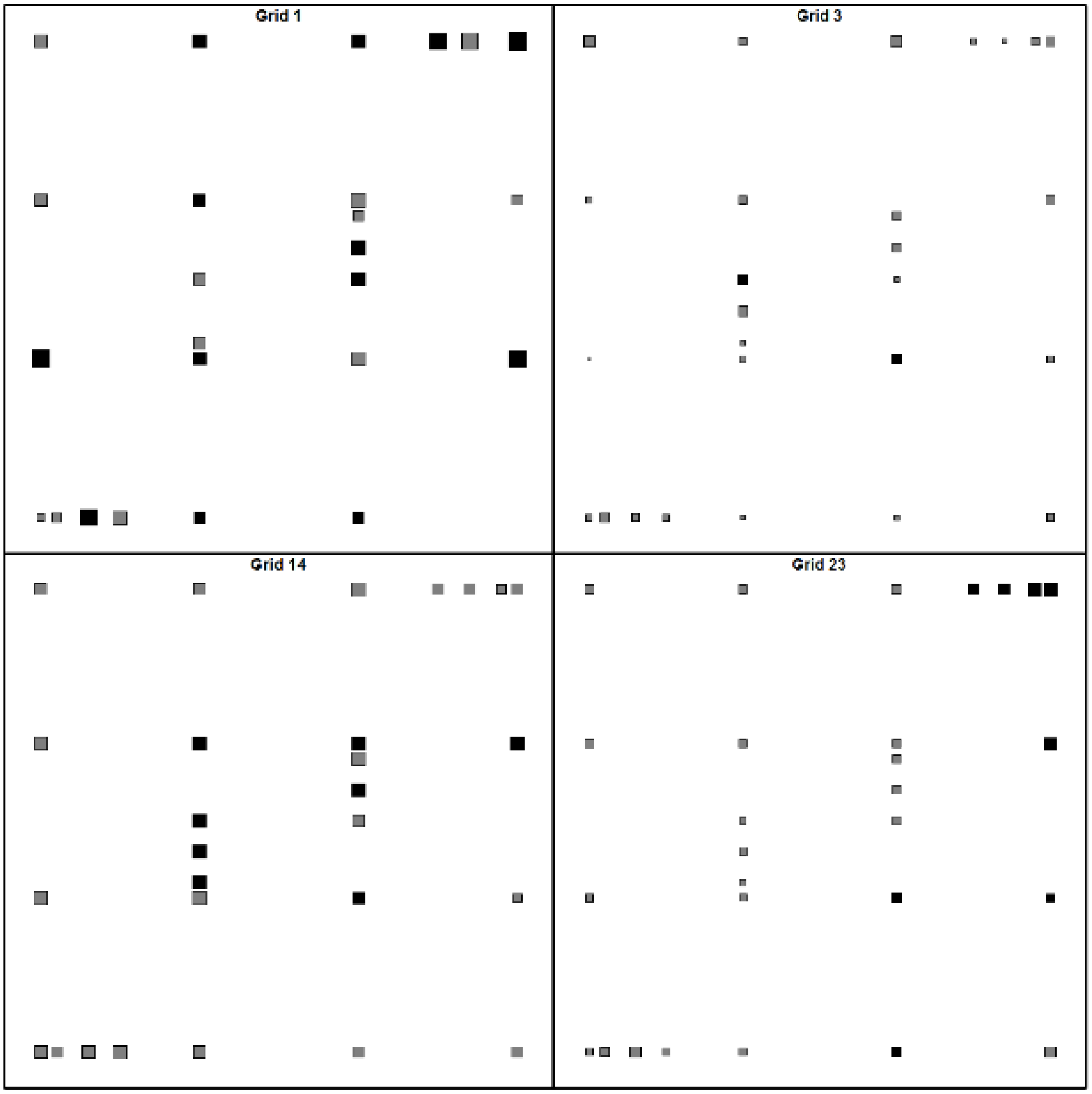

Figure 7. Four spatial grids showing slab thickness differences for ECTP versus ECTN results within individual grids. These four grids were the only to show significant differences between mean ECTP slab thickness and mean ECTN slab thickness. Square represent the location of ECT results. Black squares indicate an ECTP and gray squares represent an ECTN. The sizes of squares are proportional to the slab thickness at that test result.

The join count analysis shows six grids (~30%) with a significant level of clustering for either ECTP or ECTN results at the $p < 0.05$ level (Table 1). At 10 meters, three grids show clustering of ECTP results, one grid shows clustering of ECTN results, and two slopes show clustering of both. As join count statistics only capture clustering within a grid, homogenous results across a grid may indicate clustering at a larger scale than this sampling scheme's extent (40+ m). When these join count results are combined with the slopes that have low/no variability, 20 out of 23 slopes show indications of some sort of spatial patterns. These results show that while there are some conditions under which ECT propagation results do not show significant clustering, there is also often clustering, under a wide range of conditions. This is consistent with the limited data provided by Hendrikx et al. (2009) and Simenhois and Birkeland (2006; 2009). These join count results reinforce the recommendations of earlier work (Birkeland et al., 2010a; Schweizer et al., 2008) to conduct stability tests further apart to minimize the likelihood of two false stable results.

Harder slabs led to the potential for higher propagation percentages (Fig. 8). All but one fist hardness slab had less than 40% propagation, while all grids with greater than 80% propagation had slabs harder than 1 finger. The hardness of the hardest layer above the failure, as determined in the full pit profile, was used as the slab hardness. As slab hardness is not the only ingredient necessary for fracture propagation there continue to be grids which show no ECTP results throughout the range of slab hardnesses. Very soft slabs are also easily destroyed by the impact of the stuffblock during loading, which then does not allow for propagation to occur in an ECT.

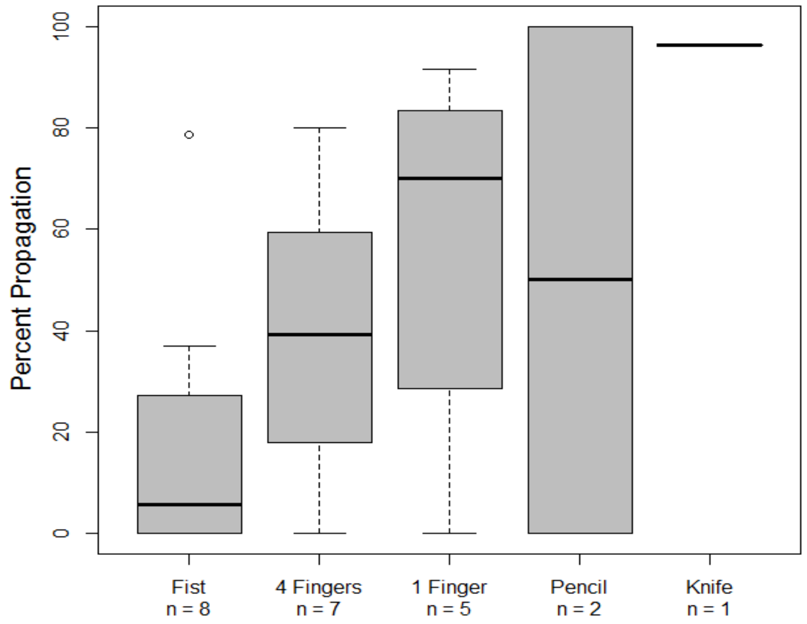

Figure 8. Boxplot of the propagation percentage by the hardness of the hardest layer in the slab. The box and whiskers plot represents the maximum/minimum, median and interquartile range of percent propagation for each hardness. Note the increasing maximum propagation percentage as the hardness of the slab increases.

No grids showed apparent changes in weak layer thickness or hardness between pits. Overall, the snowpack structure of each slope appeared to be fairly uniform. However, fracture propagation is the result of interactions between slab and weak layer properties (Heierli et al., 2011). In order to account for the sometimes high level of spatial variability, there must have been differences across the test slopes which were imperceptible using our field methods.

In our dataset, ECTP results occurred only with slabs thicker than 20 cm (Fig. 6b). The fracture with the thickest slab in our dataset, at 114 cm, also showed propagation. The ECT appears to be effectively capturing propagation for slab thicknesses significantly greater than the 70 cm maximum proposed by Ross and Jamieson (2008) based on work in the Columbia Mountains of British Columbia. Our results are consistent with the work by Simenhois and Birkeland (2009), which show the ECT performing well with slabs up to 100cm thick in Colorado and New Zealand. The minimum slab thickness of 20 cm for propagation in our dataset should not be interpreted to show that thinner slabs do not have a potential for propagation, but only that as slabs get thinner they must also become harder in order to propagate, and we did not test any thin hard slabs in this study. Once a slab thickness of 20 cm has been reached, there is no relationship between fracture propagation propensity and slab thickness.

There is no correlation between the mean drop height of ECT results for a slope and the percentage of fracture propagation (p-value = 0.96) (Fig. 9). There is also no correlation seen between the mean drop height and the forecasted danger level (p-value = 0.56), but there is greater variation in drop height under a moderate danger rating (Fig. 10). This follows Simenhois and Birkeland’s (2006) results, showing that the compression test was not effectively differentiating between many stable and unstable slopes.

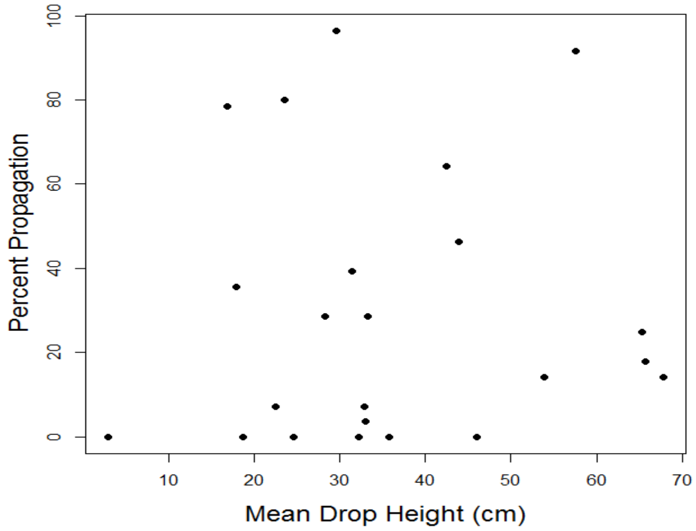

Figure 9. Scatterplot showing the propagation percentage for a grid versus the mean drop height (cm) for that grid. There is no correlation between propagation percentage and drop height (p-value = 0.96).

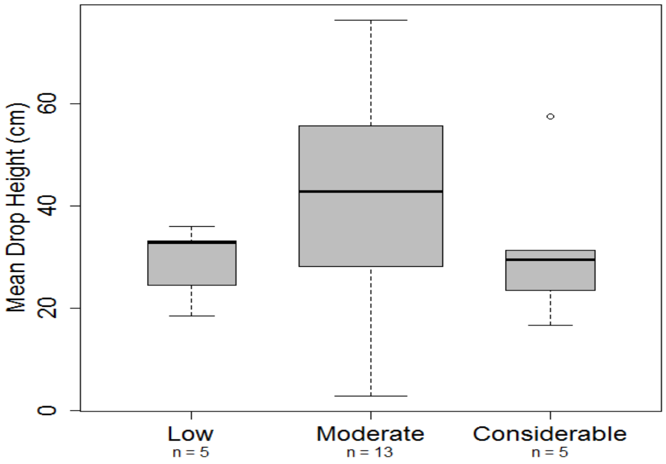

Figure 10. Boxplot of the mean drop height by the regional forecasted danger rating. The box and whiskers plot represents the maximum/minimum, median and interquartile range of percent propagation for each danger rating. Interestingly, drop height does not necessarily decrease as avalanche danger increases.

The important role that fracture propagation plays in avalanche release is further supported when we consider the results of plotting the forecasted regional danger rating against the percentage of ECTs propagating in a grid (Fig. 11). Grids with a low danger rating never showed propagation in more than 7% of ECTs, and in 60% of the grids sampled with a low avalanche danger (3 of 5), all results were ECTN. Grids with a considerable rating exhibited 39% - 97% propagation, with four out of five grids (80%) showing greater than 79% (a range of 79 - 97%). The greatest variability in propagation comes with a moderate danger. Under a moderate danger rating, grids showed between 0% and 65% propagation. Grids with a moderate danger rating showing the greatest variability in propagation results presents challenges for hazard assessment, as moderate danger conditions are where a definitive stability test result would be the most useful. Under low or high forecasted danger it is easier to interpret the snow and weather data, while during moderate danger decision making is most complex (Schweizer and Fohn, 1998).

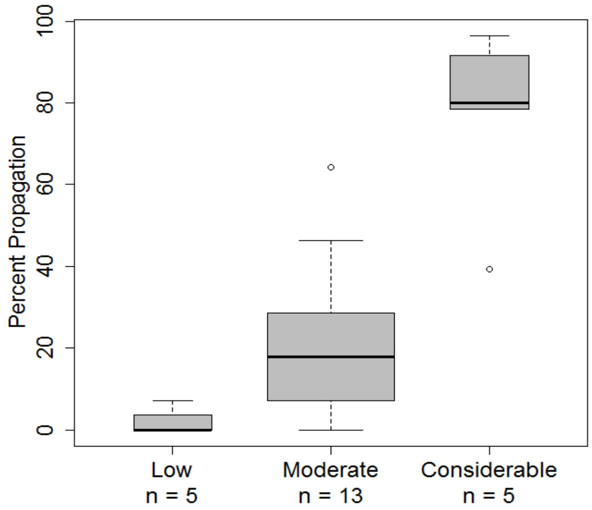

Figure 11. Boxplot of the propagation percentage by the regional forecasted danger rating. The highest degree of variability occurs under moderate danger. The box and whiskers plot represents the maximum/minimum, median and interquartile range of percent propagation for each hazard rating.

5.0 CONCLUSIONS

This study measured the spatial variability of ECT results in 23 grids across slopes in southwest Montana over the course of two winters. Each grid contained 28 ECTs, for a total of 644 individual ECTs. Our data demonstrate that while there are often spatial patterns in ECT results, there is also substantial spatial variability on some slopes, even without large variations in snowpack structure. We tested slopes with a variety of weak layers (surface hoar, depth hoar, new snow, and near surface facets), slab characteristics (slab hardness, slab depth), and snow depths and found no factors correlating with fracture propagation. This dataset is much larger and has a more diverse range of slopes than had previously been analyzed using grids of ECTs. Our results are consistent with previous work, with grids showing both a high level of variability as observed by Hendrikx et al. (2009), as well as other grids with relatively homogenous results similar to the two slopes analyzed by Simenhois and Birkeland (2009). Many of our slopes have larger false-stable and unstable results than numbers from studies analyzing the efficacy of the ECT had previously reported, perhaps due to differences in methodology (e.g. the use of a sampling grid in this study). Significant levels of clustering in ECTP or ECTN results were found in 30% of grids, reinforcing the recommendations of previous work (Birkeland et al., 2010a; Schweizer et al., 2008) that it is better to conduct stability tests further apart. When combined with the slopes with no variability, almost all slopes were seen to have some degree of spatial clustering in ECT result. Overall, this study demonstrates the importance of carefully selecting sampling locations when assessing stability, and also reinforces the importance of not basing a stability assessment on a single test result (Birkeland and Chabot, 2006).

On four slopes there was a significant relationship between slab thickness and ECTP/ECTN results. On each of these slopes, ECTPs were more likely in areas with thicker slabs. While this result may not apply across a wider range of slopes, it does show how snowpack structure variability can drive ECT variability.

When the regional avalanche danger is either considerable or low, results are likely to be more consistent. Our results show the most variability when the regional danger is moderate. In addition, the ratio of ECTPs to ECTNs on a slope increases with an increase in the forecasted danger level.

The key practical implication of our results is that ECTs, like all other stability tests, should be interpreted with an appropriate level of caution and that the spatial variability of this test can be quite high on some slopes, while on other slopes test results may be entirely in agreement.

Acknowledgments

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REFERENCES CITED

Bair, E. H., Simenhois, R., Birkeland, K. W., & Dozier, J. (2012). A field study on failure of storm snow slab avalanches. *Cold Regions Science and Technology*, *79-80*, 20–28. doi:10.1016/j.coldregions.2012.02.007

Birkeland, K. W., Chabot, D. (2006). Minimizing “false-stable” stability test results: Why digging more snowpits is a good idea. *Proceedings of the 2006 International Snow Science Workshop, Telluride, Colorado*, 498–504.

Birkeland, K. W., Chabot, D. (2012). Changes in stability test usage by snowpilot users. *Proceedings of the 2012 International Snow Science Workshop, Anchorage, Alaska,* 1065-1068.

Birkeland, K.W., Johnson, R.F. (1999). The stuffblock snow stability test: comparability with the rutschblock, usefulness in different snow climates, and repeatability between observers. *Cold Regions Science and Technology*, 30(1), 115–123.

Birkeland, K. W., Simenhois, R. (2008). The Extended Column Test: Test effectiveness, spatial variability, and comparison with the Propagation Saw Test. *Proceedings of the 2008 International Snow Science Workshop, Whistler, BC*, 401–407.

Birkeland, K. W., Hendrikx, J., Clark, M. P. (2010a). Instruments and methods - On optimal stability-test spacing for assessing snow avalanche conditions. *Journal of Glaciology*, *56*(199), 795–804.

Birkeland, K. W., Simenhois, R., & Heierli, J. (2010b). The effect of changing slope angle on extended column test results: can we dig pits in safer locations? *Proceeding of the 2010 International Snow Science Workshop, Squaw Valley, California*.

Bivand, R. (2013). *spdep: Spatial dependence: weighting schemes, statistics and models. R package* version 0.5-56. http://CRAN.R-project.org/package=spdep

Blöschl, G., Sivapalan, M. (1995). Scale issues in hydrological modelling: A review. *Hydrol. Process.*, *9*, 251–290.

Campbell, C. P., Jamieson, B. (2007). Spatial variability of slab stability and fracture characteristics within avalanche start zones. *Cold Regions Science and Technology*, *47*(1-2), 134–147. doi:10.1016/j.coldregions.2006.08.015

Colorado Avalanche Information Center. (2014) *US Avalanche Fatalities*. http://avalanche.state.co.us/accidents/us/

Conway, H., Abrahamson, J. (1984). Snow stability index. *Journal of Glaciology*, *30*(106), 321–327.

Fischer, M.M., Scholten, H.J., European, D.U. (1996). Spatial Analytical Perspectives on GIS. Taylor Francis Ltd., London. 267 pp.

Fierz, C., Armstrong, R.L., Durand, Y., Etchevers, P., Greene, E., McClung, D.M., Nishimura, K., Satyawali, P.K., Sokratov, S. (2009). The International Classification for Seasonal Snow on the Ground. IHP-VII Technical Documents in Hydrology, No. 83 (IACS Contribution No. 1), 90 pp.

Gallatin National Forest Avalanche Center. (2014) *Archived Advisories*. http://www.mtavalanche.com/archive/advisory

Gauthier, D., Jamieson, B. (2006). Understanding the Propagation of Fractures and Failures Leading to Dangerous and Destructive Snow Avalanches : Recent Developments. In *Proceedings of the 2006 Annual Conference of the Canadian Society for Civil Engineering, First Specialty Conference on Disaster Mitigation, 23/05/2006, Calgary, Alberta.*

Gauthier, D., Jamieson, B. (2008). Evaluation of a prototype field test for fracture and failure propagation propensity in weak snowpack layers. *Cold Regions Science and Technology. 51* (2–3), 87–97.

Gauthier, D., Jamieson, B. (2012). The Propagation Saw Test (PST): A review of its development, applications, and recent research. *Proceedings of the 2012 International Snow Science Workshop, Anchorage, AK*, 1047–1053.

Greene, E., Birkeland, K., Elder, K., Landry, C., Lazar, B., McCammon, I., Moore, M., Sharaf, D., Sterbenz, C., Tremper, B., Williams, K., (2010). Snow, Weather, and Avalanches: Observational Guidelines for Avalanche Programs in the United States: American Avalanche Association, Pagosa Springs CO, 150 pp.

Heierli, J., Birkeland, K. W., Simenhois, R., Gumbsch, P. (2011). Anticrack model for skier triggering of slab avalanches. *Cold Regions Science and Technology*, *65*(3), 372–381. doi:10.1016/j.coldregions.2010.10.008

Hendrikx, J., Birkeland, K. W. (2008). Slope scale spatial variability across time and space: comparison of results from two different snow climates. *Proceedings of the 2008 International Snow Science Workshop, Whistler, BC,* 155–162 .

Hendrikx, J., Birkeland, K. W., Clark, M. P. (2009). Assessing changes in the spatial variability of the snowpack fracture propagation propensity over time. *Cold Regions Science and Technology*, *56*(2-3), 152–160. doi:10.1016/j.coldregions.2008.12.001

Jamieson, J.B., Johnston, C.D., (1993). Rutschblock precision, technique variations and limitations. *Journal of Glaciology*, 39(133), 666-674

Johnson, R., Birkeland, K.W. (2002). Integrating shear quality into stability test results. *Proceedings of 2002 International Snow Science Workshop, Penticton, British Columbia, Canada*, 514-520

McCammon, I., Haegeli, P. (2006). Evaluation of a rule-based decision aid for recreational travelers in avalanche terrain. *Proceedings of the 2006 International Snow Science Workshop, Telluride, CO*, 234–243.

McClung, D. M. (2014). Risk analyses for dry snow slab avalanches released by skier triggering. *Natural Hazards*, *72*(2), 1139–1158. doi:10.1007/s11069-014-1060-4

Mock, C. J., Birkeland, K. W. (2000). Snow Avalanche Climatology of the Western United States Mountain Ranges. *Bulletin of the American Meteorological Society*, *81*(10), 2367–2392.

Moran, P.A.P. (1948). The interpretation of statistical maps. *Journal of the Royal statistical Society B* 10, 243–251

R Core Team. (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL: http://www.R-project.org/.

Ross, C., Jamieson, B. (2008). Comparing Fracture Propagation Tests and Relating Test Results to Snowpack Characteristics. In C. Campbell (Ed.), *Proceedings of the 2008 International Snow Science Workshop, Whistler, BC* (pp. 376–385).

Schweizer, J., Fohn, P. M. B. (1996). Avalanche forecasting an expert system approach. *Journal of Glaciology*, *42*(141), 318–332.

Schweizer, J., Jamieson, B., Schneebeli, M. (2003). Snow avalanche formation. *Reviews of Geophysics*, *41*(4). doi:10.1029/2002RG000123

Schweizer, J., Kronholm, K., Jamieson, B., Birkeland, K. W. (2008). Review of spatial variability of snowpack properties and its importance for avalanche formation. *Cold Regions Science and Technology*, *51*(2-3), 253–272. doi:10.1016/j.coldregions.2007.04.009

Simenhois, R., Birkeland, K. W. (2006). The Extended Column Test: A field test for fracture initiation and propagation. *Proceedings of the 2006 International Snow Science Workshop, Telluride, Colorado*, 79–85.

Simenhois, R., Birkeland, K. W. (2009). The Extended Column Test: Test effectiveness, spatial variability, and comparison with the Propagation Saw Test. *Cold Regions Science and Technology*, *59*(2-3), 210–216. doi:10.1016/j.coldregions.2009.04.001

Thumlert, S., Exner, T., Jamieson, B., & Bellaire, S. (2013). Measurements of localized dynamic loading in a mountain snow cover. *Cold Regions Science and Technology*, *85*, 94–101. doi:10.1016/j.coldregions.2012.08.005

van Herwijnen, A., Jamieson, J.B. (2002). Interpretating fracture character in stability tests. *Proceedings of the 2002 International Snow Science Workshop, Penticton BC, Canada,* 514–522.

Voight, B., Armstrong, B., Armstrong, R., Bachman, D., Bowles, D., Brown, R., Faisant, R., Ferguson, S., Fredston, J., Kennedy, J. (1990). Snow avalanche hazards and mitigation in the United States. National Academy Press, Washington, DC, USA

Winkler, K., Schweizer, J. (2008). Comparison of different snow stability tests including the Extended Column Test. *Proceedings of the 2008 International Snow Science Workshop, Whistler, British Columbia*, 393–400.

CONCLUSIONS

Summary

While there has been a substantial amount of prior research examining the spatial variability of snow stability on the slope scale, there has not previously been a thorough analysis of the spatial variability of the ECT. The main focus of this thesis has been three-fold: (1) to determine the amount of variability present in ECT results across a range of slopes; (2) to examine spatial patterns in that variability; (3) to determine if this variability is correlated with other factors. The finding of this study as related to each of these goals are summarized below. These findings and conclusions are followed by a section on this study's limitations and ideas for how to address these limitations in future research.

Variability

Some grids in this study show very homogenous ECT results, while other have high levels of variability. There is a wide range of propagation percentages across the grids sampled in this study. Appendix A contains the raw data used in this study, showing this range in variability. Many of our grids have larger false-stable and unstable results than studies analyzing the efficacy of the ECT had previously reported. Eleven out of 23 grids have greater than 10% of ECT results that are unrepresentative of the slope as a whole. This shows the potential for variability, while also showing that often times ECT results are homogeneous across a slope, with more than half of the grids having greater than 90% agreement in ECT results. As a whole, this study demonstrates the importance of carefully selecting sampling locations when assessing stability, and also reinforces the importance of not basing a stability assessment on a single test result.

Patterns of Spatial Variability

The join count tests show that six out of 23 grids have significant clustering in ECT results at the scale of our sampling grid. (Table 1). Appendix B shows the spatial patterns in ECT results for each grid in this study. These spatial plot visually reinforce the results of the join count tests. Combining a visual inspect of the figures in Appendix B with the results of the join count statistics shows that for almost all grids you are more likely to get a similar result with two nearby pits, rather than two pits spaced further apart. This is consistent with the findings of Birkeland et al. (2010) and recommendations of Schweizer et al. (2008) to dig pits further apart to minimize the chance of two false stable results. Join count statistics can not be calculated with entirely homogenous results, but the slope with very homogenous results seem to indicate that the whole slope is potentially part of a cluster on a larger scale.

Causes of Spatial Variability

We analyzed weak layer type, slab thickness, snow depth, and the coefficient of variation of snow depth as explanations for variability in ECT results. The only relationship found in these analyses was that new snow showed lower variability than other weak layer types. This is likely to be a result of site selection, snow climate, and timing (not sampling immediately after new snowfall) leading to our dataset missing the full range of propagation potential for new snow. We found no other physical variables that correlate with variability in ECT results. We also analyzed the relationship between snow depth, slab thickness and where propagation is most likely on that slope. On four slopes there was a significant difference between mean ECTP slab thickness and mean ECTN slab thickness. On each of these slopes, ECTPs were more likely in areas with thicker slabs. There were no slopes where ECTNs had significantly thicker slabs. This indicates that in this dataset, performing ECTS where the slab is thickest on a slope will give the greatest likelihood of an ECTP result. However, it is important to remember that these slopes were intentionally picked for their homogenous snowpacks, the slab thickness differences were only up to 20 cm. Slope with more heterogeneous snowpacks may show different results, especially if there are other snowpack structure (e.g. weak layer thickness, slab hardness) changes associated with the slab thickness changes.

The regional avalanche danger is correlated with the percent of ECTs that propagate on a slope. The higher the forecasted regional avalanche danger, the higher percent of ECTs that propagate. There is also a relationship with the variability of ECT results, when the regional avalanche danger is either considerable or low, results are more consistent. Our results show the most variability when the regional forecasted danger is moderate. This is a very substantial result, in that it identifies a major challenge of using the ECT for hazard assessment during a moderate forecasted danger rating. Under low or high forecasted danger, slope scale stability is generally easier to determine from other snow and weather data. Moderate danger conditions are where a definitive stability test result would be the most useful in correctly characterizing the hazard on a slope, and this is where the ECT shows the most variability.

Limitations and Opportunities for Future Research

Limitations of our research are presented in order to inform recommendations for future research. Hopefully these recommendations can be incorporated into future studies, to further the research outlined in this thesis.

1. The limited snowpack observations recorded at each ECT location in this study present a significant limitation for data analysis and drawing correlations. One full pit profile was conducted on each slope, and this profile was extrapolated to apply to each ECT on that slope. The snowpack observations taken at each ECT consisted of total snow depth and failure height. These observations only allowed for minimal slope scale analysis of snowpack structure variation across a slope or correlating that variation with ECT results. We analyzed the relationship between slab thickness and snow depth across a slope, with propagation results across a slope, and found relationships on six slopes. However, there is clearly some important change in snowpack properties across all the other slopes, as fracture propagation is a result of physical snowpack properties. There are many other factors that could potentially correlate with ECT results. Slab or weak layer hardness, density, weak layer thickness, or weak layer grain size could all potentially explain the variability seen across different slopes. The application of additional technology, perhaps a SnowMicroPen or Avatech SP1, would allow for the collection of additional snowpack data within the inherent logistical and time constraints imposed by field data collection.

2. Any snowpack test that involves excavating down to the weak layer of interest will inherently take a substantial amount of time (due to moving that amount of snow), making a relatively small sample size a logistical necessity for these sorts of tests. A fracture propagation/ stability test that takes less time to perform (perhaps without requiring digging to expose a pit wall), or that can reliably be performed by multiple observers, would mitigate these time constraints, and allow for a larger sample size. A larger sample size (ideally greater than 150, as per the recommendation of Webster and Oliver (1992)) would also allow for the use of semi-variograms, while also making statistically significant spatial patterns easier to detect with other spatial statistics. In addition, using a different test to look at fracture propagation, such as the Propagation Saw Test, would allow for continuous rather than binary information. Continuous data, would allow for the effective use of statistical tests such as Moran's I and semi-variograms and potentially capture subtle spatial patterns in fracture propagation that are missed by binary data.

3. While our sampling scheme attempted to capture spatial patterns at the widest range of spatial scales possible in this context (from 1m to 42 m), it also posed some challenges from a data analysis standpoint. There are a number of spatial statistics that were not used because they can not analyze data with variable sample spacing. For example, the Ripley's K test for spatial autocorrelation could potentially have provided information about the scale and degree of clustering in ECT results, but our sampling grid precluded its use. Our sampling grid was successful in that it led to a very wide range of lag distances, but combined with a small sample size, it also limited the spatial statistics that were appropriate for our study.

REFERENCES CITED

Birkeland, K. W., Hendrikx, J., Clark, M. P. (2010). Instruments and methods - On optimal stability-test spacing for assessing snow avalanche conditions. *Journal of Glaciology*, *56*(199), 795–804.

Schweizer, J., Kronholm, K., Jamieson, B., Birkeland, K. W. (2008). Review of spatial variability of snowpack properties and its importance for avalanche formation. *Cold Regions Science and Technology*, *51*(2-3), 253–272. doi:10.1016/j.coldregions.2007.04.009

Webster, R. and Oliver, M.A. (1992). Sample adequately to estimate variograms of soil properties. *Journal of Soil Science*, 43(1): 177-192.

REFERENCES CITED

Bair, E. H., Simenhois, R., Birkeland, K. W., & Dozier, J. (2012). A field study on failure of storm snow slab avalanches. *Cold Regions Science and Technology*, *79-80*, 20–28. doi:10.1016/j.coldregions.2012.02.007

Birkeland, K. W., Chabot, D. (2006). Minimizing “false-stable” stability test results: Why digging more snowpits is a good idea. *Proceedings of the 2006 International Snow Science Workshop, Telluride, Colorado*, 498–504.

Birkeland, K. W., Chabot, D. (2012). Changes in stability test usage by snowpilot users. *Proceedings of the 2012 International Snow Science Workshop, Anchorage, Alaska,* 1065-1068.

Birkeland, K.W., Johnson, R.F. (1999). The stuffblock snow stability test: comparability with the rutschblock, usefulness in different snow climates, and repeatability between observers. *Cold Regions Science and Technology*, 30(1), 115–123.

Birkeland, K. W., Simenhois, R. (2008). The Extended Column Test: Test effectiveness, spatial variability, and comparison with the Propagation Saw Test. *Proceedings of the 2008 International Snow Science Workshop, Whistler, BC*, 401–407.

Birkeland, K. W., Hendrikx, J., Clark, M. P. (2010a). Instruments and methods - On optimal stability-test spacing for assessing snow avalanche conditions. *Journal of Glaciology*, *56*(199), 795–804.

Birkeland, K. W., Simenhois, R., & Heierli, J. (2010b). The effect of changing slope angle on extended column test results: can we dig pits in safer locations? *Proceeding of the 2010 International Snow Science Workshop, Squaw Valley, California*.

Bivand, R. (2013). *spdep: Spatial dependence: weighting schemes, statistics and models. R package* version 0.5-56. http://CRAN.R-project.org/package=spdep

Blöschl, G. (1999). Scaling issues in snow hydrology. *Hydrological Processes* 13 (14-15):2149-2175.

Blöschl, G., Sivapalan, M. (1995). Scale issues in hydrological modelling: A review. *Hydrol. Process.*, *9*, 251–290.

Campbell, C. P., Jamieson, B. (2007). Spatial variability of slab stability and fracture characteristics within avalanche start zones. *Cold Regions Science and Technology*, *47*(1-2), 134–147. doi:10.1016/j.coldregions.2006.08.015

Cliff, A. D., Ord, J. K. (1973). Spatial autocorrelation. London : Pion, London, UK. 178 pp.

Colorado Avalanche Information Center. (2014) *US Avalanche Fatalities*. http://avalanche.state.co.us/accidents/us/

Conway, H., Abrahamson, J. (1984). Snow stability index. *Journal of Glaciology*, *30*(106), 321–327.

Cressie, N.A.C. (1993). Statistics for spatial data. Wiley series in probability and mathematical statistics. John Wiley & Sons, Inc., New York, 900 pp.

Fischer, M.M., Scholten, H.J., European, D.U. (1996). Spatial Analytical Perspectives on GIS. Taylor Francis Ltd., London. 267 pp.

Fierz, C., Armstrong, R.L., Durand, Y., Etchevers, P., Greene, E., McClung, D.M., Nishimura, K., Satyawali, P.K., Sokratov, S. (2009). The International Classification for Seasonal Snow on the Ground. IHP-VII Technical Documents in Hydrology, No. 83 (IACS Contribution No. 1), 90 pp.

Gallatin National Forest Avalanche Center. (2014) *Archived Advisories*. http://www.mtavalanche.com/archive/advisory

Gauthier, D., Jamieson, B. (2006). Understanding the Propagation of Fractures and Failures Leading to Dangerous and Destructive Snow Avalanches : Recent Developments. In *Proceedings of the 2006 Annual Conference of the Canadian Society for Civil Engineering, First Specialty Conference on Disaster Mitigation, 23/05/2006, Calgary, Alberta.*

Gauthier, D., Jamieson, B. (2008). Evaluation of a prototype field test for fracture and failure propagation propensity in weak snowpack layers. *Cold Regions Science and Technology. 51* (2–3), 87–97.

Gauthier, D., Jamieson, B. (2012). The Propagation Saw Test (PST): A review of its development, applications, and recent research. *Proceedings of the 2012 International Snow Science Workshop, Anchorage, AK*, 1047–1053.

Greene, E., Birkeland, K., Elder, K., Landry, C., Lazar, B., McCammon, I., Moore, M., Sharaf, D., Sterbenz, C., Tremper, B., Williams, K., (2010). Snow, Weather, and Avalanches: Observational Guidelines for Avalanche Programs in the United States: American Avalanche Association, Pagosa Springs CO, 150 pp.

Heierli, J., Birkeland, K. W., Simenhois, R., Gumbsch, P. (2011). Anticrack model for skier triggering of slab avalanches. *Cold Regions Science and Technology*, *65*(3), 372–381. doi:10.1016/j.coldregions.2010.10.008

Hendrikx, J., Birkeland, K. W. (2008). Slope scale spatial variability across time and space: comparison of results from two different snow climates. *Proceedings of the 2008 International Snow Science Workshop, Whistler, BC,* 155–162 .

Hendrikx, J., Birkeland, K. W., Clark, M. P. (2009). Assessing changes in the spatial variability of the snowpack fracture propagation propensity over time. *Cold Regions Science and Technology*, *56*(2-3), 152–160. doi:10.1016/j.coldregions.2008.12.001

Jamieson, J.B., Johnston, C.D., (1993). Rutschblock precision, technique variations and limitations. *Journal of Glaciology*, 39(133), 666-674

Johnson, R., Birkeland, K.W. (2002). Integrating shear quality into stability test results. *Proceedings of 2002 International Snow Science Workshop, Penticton, British Columbia, Canada*, 514-520

Kronholm, K. (2004). *Spatial variability of snow mechanical properties with regard to avalanche formation*. Ph. D. thesis, 187 pp., University of Zurich, Zurich, Switzerland

Kronholm, K., & Schweizer, J. (2003). Snow stability variation on small slopes. *Cold Regions Science and Technology*, *37*(3), 453–465. doi:10.1016/S0165-232X(03)00084-3

Landry, C., Birkeland, K. W., Hansen, K. J., Borkowski, J., Brown, R. L., Aspinall, R. (2004). Variations in snow strength and stability on uniform slopes. *Cold Regions Science and Technology*, *39*(2-3), 205–218. doi:10.1016/j.coldregions.2003.12.003

McCammon, I., Haegeli, P. (2006). Evaluation of a rule-based decision aid for recreational travelers in avalanche terrain. *Proceedings of the 2006 International Snow Science Workshop, Telluride, CO*, 234–243.

McClung, D. M. (2014). Risk analyses for dry snow slab avalanches released by skier triggering. *Natural Hazards*, *72*(2), 1139–1158. doi:10.1007/s11069-014-1060-4

Mock, C. J., Birkeland, K. W. (2000). Snow Avalanche Climatology of the Western United States Mountain Ranges. *Bulletin of the American Meteorological Society*, *81*(10), 2367–2392.

Moran, P.A.P. (1948). The interpretation of statistical maps. *Journal of the Royal statistical Society B* 10, 243–251

R Core Team. (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL: http://www.R-project.org/.

Ross, C., Jamieson, B. (2008). Comparing Fracture Propagation Tests and Relating Test Results to Snowpack Characteristics. In C. Campbell (Ed.), *Proceedings of the 2008 International Snow Science Workshop, Whistler, BC* (pp. 376–385).

Schweizer, J., Fohn, P. M. B. (1996). Avalanche forecasting an expert system approach. *Journal of Glaciology*, *42*(141), 318–332.

Schweizer, J., Jamieson, B., Schneebeli, M. (2003). Snow avalanche formation. *Reviews of Geophysics*, *41*(4). doi:10.1029/2002RG000123

Schweizer, J., Kronholm, K., Jamieson, B., Birkeland, K. W. (2008). Review of spatial variability of snowpack properties and its importance for avalanche formation. *Cold Regions Science and Technology*, *51*(2-3), 253–272. doi:10.1016/j.coldregions.2007.04.009

Simenhois, R., Birkeland, K. W. (2006). The Extended Column Test: A field test for fracture initiation and propagation. *Proceedings of the 2006 International Snow Science Workshop, Telluride, Colorado*, 79–85.

Simenhois, R., Birkeland, K. W. (2007). An update on the Extended Column Test : New recording standards and additional data analyses. *The Avalanche Review*, *26*(2).

Simenhois, R., Birkeland, K. W. (2009). The Extended Column Test: Test effectiveness, spatial variability, and comparison with the Propagation Saw Test. *Cold Regions Science and Technology*, *59*(2-3), 210–216. doi:10.1016/j.coldregions.2009.04.001

Skøien, J. O., & Blöschl, G. (2006). Sampling scale effects in random fields and implications for environmental monitoring. *Environmental Monitoring and Assessment*, *114*(1-3), 521–52. doi:10.1007/s10661-006-4939-z

Thumlert, S., Exner, T., Jamieson, B., & Bellaire, S. (2013). Measurements of localized dynamic loading in a mountain snow cover. *Cold Regions Science and Technology*, *85*, 94–101. doi:10.1016/j.coldregions.2012.08.005

van Herwijnen, A., Jamieson, J.B. (2002). Interpretating fracture character in stability tests. *Proceedings of the 2002 International Snow Science Workshop, Penticton BC, Canada,* 514–522.

Voight, B., Armstrong, B., Armstrong, R., Bachman, D., Bowles, D., Brown, R., Faisant, R., Ferguson, S., Fredston, J., Kennedy, J. (1990). Snow avalanche hazards and mitigation in the United States. National Academy Press, Washington, DC, USA

Webster, R., Oliver, M.A. (1992). Sample adequately to estimate variograms of soil properties. *Journal of Soil Science*, 43(1): 177-192.

Winkler, K., Schweizer, J. (2008). Comparison of different snow stability tests including the Extended Column Test. *Proceedings of the 2008 International Snow Science Workshop, Whistler, British Columbia*, 393–400.

APPENDICES

APPENDIX A

FIELD DATA

Raw data from each of the 23 sampling grids. Summary Table followed by data from each individual grid. The X,Y coordinates for each pit location are based on a Cartesian grid with meters as units, with the (0,0) point located at the bottom left of the grid.

Grid #	Location	Date	Coordinates		Weak layer	Danger Rating
1	Moonlight Basin	12/19/2012	45.303676°	-111.454890°	Depth Hoar	Moderate
2	Moonlight Basin	1/13/2013	45.304114°	-111.455520°	Facets	Moderate
3	Lionhead	1/22/2013	44.708436°	-111.303487°	Surface Hoar	Low
4	Bacon Rind	2/2/2013	44.969970°	-111.095049°	New Snow	Moderate
5	Bacon Rind	2/2/2013	44.969970°	-111.095049°	Surface Hoar	Considerable
6	Bridger Bowl	2/3/2013	45.829691°	-110.928489°	Facets	Moderate
7	Bridger Bowl	2/3/2013	45.829691°	-110.928489°	New Snow	Low
8	Bacon Rind	2/7/2013	44.970019°	-111.095108°	Surface Hoar	Moderate
9	Fairy Lake	2/21/2013	45.905505°	-110.955978°	Facets	Moderate
10	Fairy Lake	2/21/2013	45.905505°	-110.955978°	Facets	Low
11	Fairy Lake	2/21/2013	45.905505°	-110.955978°	New Snow	Low
12	History Rock	2/23/2013	45.480042°	-111.011876°	Facets	Considerable
13	History Rock	2/23/2013	45.480042°	-111.011876°	New Snow	Moderate
14	History Rock	2/23/2013	45.480042°	-111.011876°	Facets	Moderate
15	History Rock	2/23/2013	45.480042°	-111.011876°	Facets	Low
16	Fairy Lake	2/28/2013	45.906014°	-110.956397°	Facets	Moderate
17	Fairy Lake	2/28/2013	45.906014°	-110.956397°	Facets	Moderate
18	Fairy Lake	2/28/2013	45.906014°	-110.956397°	New Snow	Moderate
19	Bacon Rind	3/2/2013	44.969978°	-111.096750°	Surface Hoar	Moderate
20	Bacon Rind	1/6/2014	44.969919°	-111.096641°	Facets	Considerable
21	Bacon Rind	1/6/2014	44.969919°	-111.096641°	Facets	Considerable
22	Cedar Mountain	1/7/2014	45.232329°	-111.475697°	Facets	Considerable
23	Moonlight Basin	1/19/2014	45.304980°	-111.456840°	Facets	Moderate

Grid # 1						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X	Y
1	n	70	63	35	0	0
2	n	60	64	32	1	0
3	p	30	67	5	3	0
4	n	30	58	8	5	0
5	p	30	51	10	10	0
6	p	40	57	17	20	0
7	x	NA	75	NA	30	0
8	p	50	80	17	30	10
9	n	50	70	20	20	10
10	p	10	57	10	10	10
11	n	30	56	13	10	11
12	x	NA	60	NA	10	13
13	n	40	50	8	10	15
14	p	50	72	7	0	10
15	n	30	55	9	0	20
16	p	40	58	12	10	20
17	p	40	66	13	20	15
18	p	40	65	12	20	17
19	n	30	57	18	20	19
20	n	60	63	9	20	20
21	n	50	75	36	30	20
22	p	70	80	17	30	30
23	x	NA	80	NA	29	30
24	n	40	75	17	27	30
25	p	30	70	11	25	30
26	p	30	60	11	20	30
27	p	40	61	12	10	30
28	n	30	55	8	0	30

Grid # 2

Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	50	66	40	0	0
2	n	70	61	33	1	0
3	n	30	61	47	3	0
4	n	50	65	40	5	0
5	n	30	69	41	10	0
6	n	30	63	44	20	0
7	n	30	73	46	30	0
8	n	30	75	51	30	10
9	n	30	64	50	20	10
10	n	20	65	45	10	10
11	n	30	65	44	10	11
12	n	30	66	44	10	13
13	n	30	69	40	10	15
14	n	30	60	40	0	10
15	n	30	65	42	0	20
16	n	20	60	35	10	20
17	n	20	63	43	20	15
18	n	30	65	45	20	17
19	n	30	65	42	20	19
20	n	30	69	45	20	20
21	n	40	75	43	30	20
22	n	30	80	58	30	30
23	n	40	80	55	29	30
24	n	30	75	48	27	30
25	n	30	73	46	25	30
26	n	20	67	45	20	30
27	n	20	62	42	10	30
28	n	40	56	28	0	30

Grid # 3						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	50	160	135	0	0
2	n	40	170	137	1	0
3	n	60	165	135	3	0
4	n	40	165	140	5	0
5	n	20	164	147	10	0
6	n	20	163	144	20	0
7	n	50	163	136	30	0
8	n	20	163	137	30	10
9	p	30	173	135	20	10
10	n	30	171	145	10	10
11	n	20	176	156	10	11
12	n	40	175	140	10	13
13	p	20	183	147	10	15
14	n	20	160	149	0	10
15	n	20	170	145	0	20
16	n	20	167	137	10	20
17	n	30	173	155	20	15
18	n	30	173	143	20	17
19	n	40	175	143	20	19
20	x	NA	160	NA	20	20
21	n	40	180	143	30	20
22	n	50	180	147	30	30
23	n	50	175	144	29	30
24	n	10	170	151	27	30
25	n	10	163	141	25	30
26	n	30	175	135	20	30
27	n	30	173	142	10	30
28	n	30	178	135	0	30

Grid # 4						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	0	158	148	0	0
2	n	0	150	141	1	0
3	n	10	162	154	3	0
4	n	0	160	149	5	0
5	n	0	156	150	10	0
6	n	0	169	156	20	0
7	n	0	168	150	30	0
8	n	0	165	155	30	10
9	n	0	160	152	20	10
10	n	0	153	145	10	10
11	n	0	155	148	10	11
12	n	10	155	135	10	13
13	n	0	149	137	10	15
14	NA	NA	168	NA	0	10
15	n	0	145	135	0	20
16	NA	NA	136	NA	10	20
17	n	10	148	134	20	15
18	NA	NA	166	NA	20	17
19	n	10	165	149	20	19
20	NA	NA	159	NA	20	20
21	n	10	157	140	30	20
22	n	10	158	142	30	30
23	n	10	148	127	29	30
24	n	0	155	143	27	30
25	n	0	156	149	25	30
26	n	0	144	135	20	30
27	n	0	154	143	10	30
28	n	0	150	150	0	30

Grid # 5						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	60	158	125	0	0
2	p	20	150	122	1	0
3	n	20	162	130	3	0
4	p	10	160	126	5	0
5	p	10	156	125	10	0
6	p	10	169	132	20	0
7	p	10	168	120	30	0
8	p	10	165	135	30	10
9	p	10	160	127	20	10
10	p	10	153	119	10	10
11	n	10	155	125	10	11
12	p	20	155	125	10	13
13	p	10	149	118	10	15
14	p	0	168	132	0	10
15	p	10	145	116	0	20
16	p	0	136	107	10	20
17	n	40	148	115	20	15
18	p	10	166	129	20	17
19	p	20	165	127	20	19
20	p	10	159	121	20	20
21	p	40	157	112	30	20
22	p	30	158	120	30	30
23	n	20	148	120	29	30
24	n	40	155	121	27	30
25	p	10	156	125	25	30
26	p	10	144	112	20	30
27	p	10	154	115	10	30
28	p	10	150	119	0	30

Grid # 6						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	NA	193	NA	0	0
2	n	NA	183	NA	1	0
3	n	NA	187	NA	3	0
4	n	NA	194	NA	5	0
5	n	NA	175	NA	10	0
6	n	NA	170	NA	20	0
7	n	NA	167	NA	30	0
8	n	NA	177	NA	30	10
9	n	NA	167	NA	20	10
10	n	NA	180	NA	10	10
11	n	NA	168	NA	10	11
12	n	NA	179	NA	10	13
13	p	60	170	104	10	15
14	n	NA	185	NA	0	10
15	n	NA	180	NA	0	20
16	n	NA	165	NA	10	20
17	p	60	162	95	20	15
18	n	NA	168	NA	20	17
19	n	NA	191	NA	20	19
20	n	NA	182	NA	20	20
21	n	NA	176	NA	30	20
22	n	NA	170	NA	30	30
23	n	NA	171	NA	29	30
24	n	NA	164	NA	27	30
25	p	60	161	95	25	30
26	p	40	170	105	20	30
27	n	NA	175	NA	10	30
28	n	NA	163	NA	0	30

Grid # 7						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	40	193	170	0	0
2	n	40	183	163	1	0
3	n	40	187	165	3	0
4	n	30	194	175	5	0
5	n	40	175	152	10	0
6	n	40	170	146	20	0
7	n	30	167	147	30	0
8	n	40	177	155	30	10
9	n	40	167	145	20	10
10	n	60	180	156	10	10
11	n	50	168	140	10	11
12	n	30	179	163	10	13
13	n	30	170	145	10	15
14	n	30	185	160	0	10
15	n	30	180	161	0	20
16	n	30	165	141	10	20
17	n	30	162	142	20	15
18	n	30	168	141	20	17
19	n	30	191	168	20	19
20	n	30	182	164	20	20
21	n	30	176	153	30	20
22	n	30	170	150	30	30
23	n	30	171	156	29	30
24	n	30	164	140	27	30
25	n	30	161	142	25	30
26	n	NA	170	NA	20	30
27	n	30	175	155	10	30
28	n	30	163	140	0	30

Grid # 8						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	20	136	114	0	0
2	n	20	147	121	1	0
3	p	10	142	116	3	0
4	p	10	144	120	5	0
5	n	10	146	122	10	0
6	n	10	146	124	20	0
7	p	10	135	112	30	0
8	p	10	162	135	30	10
9	p	10	152	127	20	10
10	n	20	140	116	10	10
11	n	20	139	112	10	11
12	n	20	145	119	10	13
13	n	20	139	115	10	15
14	n	10	135	111	0	10
15	x	NA	142	119	0	20
16	n	20	135	110	10	20
17	n	20	142	118	20	15
18	n	20	148	124	20	17
19	n	30	139	114	20	19
20	n	30	150	125	20	20
21	p	10	140	117	30	20
22	n	20	135	110	30	30
23	p	10	130	106	29	30
24	n	20	130	107	27	30
25	p	10	128	105	25	30
26	p	10	132	109	20	30
27	n	20	133	110	10	30
28	p	10	125	105	0	30

Grid # 9						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	p	40	83	41	0	0
2	p	20	90	47	1	0
3	p	50	94	50	3	0
4	n	50	95	51	5	0
5	NA	NA	96	43	10	0
6	NA	NA	141	77	20	0
7	NA	NA	107	50	30	0
8	NA	NA	125	70	30	10
9	NA	NA	130	76	20	10
10	NA	NA	140	78	10	10
11	NA	NA	137	75	10	11
12	NA	NA	150	85	10	13
13	NA	NA	145	79	10	15
14	NA	NA	125	62	0	10
15	NA	NA	138	70	0	20
16	NA	NA	144	75	10	20
17	p	70	137	76	20	15
18	NA	NA	132	75	20	17
19	NA	NA	147	78	20	19
20	NA	NA	140	73	20	20
21	NA	NA	125	70	30	20
22	NA	NA	130	70	30	30
23	NA	NA	136	80	29	30
24	NA	NA	135	70	27	30
25	p	70	140	77	25	30
26	NA	NA	140	76	20	30
27	NA	NA	140	73	10	30
28	NA	NA	149	77	0	30

Grid # 10						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	10	83	65	0	0
2	n	10	90	71	1	0
3	n	10	94	73	3	0
4	n	40	95	74	5	0
5	n	40	96	71	10	0
6	n	30	141	111	20	0
7	n	50	107	83	30	0
8	n	40	125	100	30	10
9	n	20	130	105	20	10
10	n	20	140	115	10	10
11	n	30	137	112	10	11
12	n	20	150	125	10	13
13	p	50	145	111	10	15
14	n	30	125	95	0	10
15	n	30	138	107	0	20
16	n	40	144	110	10	20
17	n	40	137	107	20	15
18	n	40	132	103	20	17
19	n	40	147	116	20	19
20	n	40	140	107	20	20
21	n	40	125	92	30	20
22	n	30	130	101	30	30
23	NA	NA	136	108	29	30
24	n	40	135	100	27	30
25	n	30	140	107	25	30
26	n	40	140	108	20	30
27	n	40	140	107	10	30
28	n	40	149	118	0	30

Grid # 11						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	NA	NA	83	75	0	0
2	NA	NA	90	80	1	0
3	NA	NA	94	82	3	0
4	NA	NA	95	85	5	0
5	NA	NA	96	85	10	0
6	n	20	141	117	20	0
7	n	20	107	90	30	0
8	n	20	125	110	30	10
9	n	10	130	115	20	10
10	NA	NA	140	125	10	10
11	n	10	137	125	10	11
12	n	10	150	137	10	13
13	n	20	145	118	10	15
14	n	20	125	102	0	10
15	n	20	138	112	0	20
16	n	20	144	120	10	20
17	n	20	137	112	20	15
18	n	20	132	109	20	17
19	n	20	147	125	20	19
20	n	20	140	117	20	20
21	n	20	125	105	30	20
22	n	20	130	116	30	30
23	n	20	136	118	29	30
24	n	20	135	107	27	30
25	n	20	140	117	25	30
26	n	20	140	121	20	30
27	n	20	140	121	10	30
28	n	20	149	127	0	30

Grid # 12						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	NA	NA	140	60	0	0
2	NA	NA	140	60	1	0
3	NA	NA	143	66	3	0
4	NA	NA	146	62	5	0
5	p	70	141	57	10	0
6	p	50	135	50	20	0
7	p	60	130	47	30	0
8	p	50	128	43	30	10
9	p	50	140	50	20	10
10	p	60	147	62	10	10
11	p	60	145	51	10	11
12	p	70	143	49	10	13
13	p	50	141	47	10	15
14	p	70	145	49	0	10
15	n	70	153	57	0	20
16	p	60	145	50	10	20
17	p	40	142	50	20	15
18	p	60	140	48	20	17
19	p	50	147	52	20	19
20	p	70	145	56	20	20
21	p	60	152	53	30	20
22	p	50	123	40	30	30
23	p	40	135	61	29	30
24	p	50	135	60	27	30
25	n	70	137	56	25	30
26	p	60	145	52	20	30
27	p	60	143	50	10	30
28	p	50	132	52	0	30

Grid # 13						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	70	140	85	0	0
2	n	60	140	86	1	0
3	n	60	143	86	3	0
4	n	70	146	83	5	0
5	n	50	141	82	10	0
6	n	30	135	88	20	0
7	n	40	130	86	30	0
8	n	30	128	88	30	10
9	NA	NA	140	NA	20	10
10	n	50	147	92	10	10
11	n	60	145	87	10	11
12	NA	NA	143	85	10	13
13	NA	NA	141	83	10	15
14	n	7	145	84	0	10
15	NA	NA	153	95	0	20
16	NA	NA	145	85	10	20
17	n	30	142	90	20	15
18	NA	NA	140	84	20	17
19	NA	NA	147	89	20	19
20	NA	NA	145	85	20	20
21	n	60	152	92	30	20
22	NA	NA	123	75	30	30
23	NA	NA	135	88	29	30
24	NA	NA	135	82	27	30
25	n	50	137	82	25	30
26	NA	NA	145	87	20	30
27	n	30	143	93	10	30
28	n	40	132	79	0	30

Grid # 14						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	30	140	95	0	0
2	n	40	140	97	1	0
3	n	30	143	95	3	0
4	n	30	146	96	5	0
5	n	30	141	95	10	0
6	n	20	135	95	20	0
7	n	30	130	91	30	0
8	n	30	128	95	30	10
9	p	20	140	95	20	10
10	n	20	147	98	10	10
11	p	30	145	95	10	11
12	p	30	143	94	10	13
13	p	20	141	92	10	15
14	n	30	145	95	0	10
15	n	30	153	105	0	20
16	p	30	145	95	10	20
17	n	20	142	96	20	15
18	p	30	140	92	20	17
19	n	20	147	99	20	19
20	p	40	145	94	20	20
21	p	30	152	100	30	20
22	n	40	123	82	30	30
23	n	30	135	98	29	30
24	n	20	135	95	27	30
25	n	30	137	95	25	30
26	n	30	145	94	20	30
27	n	30	143	99	10	30
28	n	20	132	88	0	30

Grid # 15						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	30	140	107	0	0
2	n	30	140	105	1	0
3	n	20	143	102	3	0
4	n	30	146	104	5	0
5	n	20	141	103	10	0
6	NA	NA	135	100	20	0
7	NA	NA	130	102	30	0
8	NA	NA	128	106	30	10
9	n	20	140	100	20	10
10	n	20	147	105	10	10
11	n	30	145	102	10	11
12	n	20	143	101	10	13
13	n	20	141	100	10	15
14	n	30	145	101	0	10
15	n	20	153	111	0	20
16	n	20	145	102	10	20
17	n	20	142	102	20	15
18	n	30	140	100	20	17
19	n	20	147	103	20	19
20	n	30	145	101	20	20
21	n	40	152	109	30	20
22	n	20	123	87	30	30
23	n	20	135	102	29	30
24	NA	NA	135	102	27	30
25	n	30	137	102	25	30
26	NA	NA	145	98	20	30
27	n	20	143	105	10	30
28	NA	NA	132	97	0	30

Grid # 16						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	50	172	78	0	0
2	p	60	171	80	1	0
3	NA	NA	176	80	3	0
4	p	70	179	81	5	0
5	NA	NA	192	90	10	0
6	NA	NA	166	80	20	0
7	n	60	122	47	30	0
8	p	20	144	70	30	10
9	NA	NA	187	78	20	10
10	NA	NA	177	77	10	10
11	NA	NA	174	76	10	11
12	NA	NA	174	74	10	13
13	NA	NA	205	110	10	15
14	p	60	190	78	0	10
15	p	60	184	70	0	20
16	NA	NA	202	75	10	20
17	NA	NA	160	65	20	15
18	NA	NA	190	95	20	17
19	n	70	185	85	20	19
20	NA	NA	172	77	20	20
21	NA	NA	140	55	30	20
22	p	70	124	53	30	30
23	NA	NA	162	67	29	30
24	NA	NA	152	75	27	30
25	p	50	165	82	25	30
26	NA	NA	169	73	20	30
27	NA	NA	181	65	10	30
28	NA	NA	154	73	0	30

Grid # 17						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	40	172	116	0	0
2	n	40	171	113	1	0
3	n	70	176	119	3	0
4	n	60	179	119	5	0
5	n	40	192	134	10	0
6	n	40	166	120	20	0
7	n	40	122	83	30	0
8	NA	NA	144	101	30	10
9	n	40	187	118	20	10
10	NA	NA	177	118	10	10
11	n	40	174	113	10	11
12	n	40	174	112	10	13
13	n	50	205	145	10	15
14	NA	NA	190	116	0	10
15	NA	NA	184	118	0	20
16	p	70	202	137	10	20
17	n	50	160	105	20	15
18	p	70	190	132	20	17
19	n	40	185	127	20	19
20	p	60	172	119	20	20
21	n	50	140	95	30	20
22	n	50	124	83	30	30
23	n	40	162	118	29	30
24	n	50	152	110	27	30
25	NA	NA	165	115	25	30
26	n	70	169	118	20	30
27	p	60	181	131	10	30
28	n	50	154	115	0	30

Grid # 18						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	20	172	135	0	0
2	n	20	171	132	1	0
3	n	20	176	138	3	0
4	n	20	179	140	5	0
5	n	20	192	156	10	0
6	n	20	166	140	20	0
7	n	20	122	103	30	0
8	NA	NA	144	120	30	10
9	n	20	187	145	20	10
10	n	30	177	139	10	10
11	n	20	174	134	10	11
12	n	20	174	133	10	13
13	n	20	205	167	10	15
14	n	30	190	147	0	10
15	n	20	184	147	0	20
16	n	20	202	167	10	20
17	n	20	160	125	20	15
18	n	20	190	155	20	17
19	n	20	185	149	20	19
20	n	20	172	139	20	20
21	n	10	140	114	30	20
22	n	20	124	97	30	30
23	n	30	162	135	29	30
24	p	20	152	126	27	30
25	n	20	165	139	25	30
26	p	30	169	138	20	30
27	n	20	181	152	10	30
28	n	10	154	135	0	30

Grid # 19						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	p	20	146	105	0	0
2	p	30	160	112	1	0
3	p	30	139	95	3	0
4	p	30	143	98	5	0
5	p	30	135	92	10	0
6	n	50	136	93	20	0
7	n	60	138	93	30	0
8	n	60	140	96	30	10
9	p	40	152	108	20	10
10	p	30	139	85	10	10
11	p	30	131	88	10	11
12	p	30	137	95	10	13
13	p	30	130	91	10	15
14	p	30	146	111	0	10
15	p	30	145	101	0	20
16	p	40	136	92	10	20
17	n	40	130	87	20	15
18	p	60	128	86	20	17
19	n	60	137	94	20	19
20	p	70	135	92	20	20
21	n	60	140	96	30	20
22	n	50	115	74	30	30
23	x	NA	135	90	29	30
24	p	50	149	106	27	30
25	n	60	133	90	25	30
26	n	60	139	96	20	30
27	p	10	141	98	10	30
28	p	30	140	98	0	30

Grid # 20						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	30	82	30	0	0
2	n	40	91	38	1	0
3	n	30	86	34	3	0
4	p	20	87	39	5	0
5	p	30	88	34	10	0
6	p	30	90	30	20	0
7	p	20	76	24	30	0
8	p	20	82	29	30	10
9	n	40	80	27	20	10
10	n	40	81	30	10	10
11	n	40	79	26	10	11
12	p	20	80	27	10	13
13	n	40	76	27	10	15
14	n	40	85	34	0	10
15	n	30	82	29	0	20
16	n	40	80	28	10	20
17	p	20	77	28	20	15
18	p	20	78	27	20	17
19	n	30	82	36	20	19
20	n	30	89	3	20	20
21	p	30	72	25	30	20
22	p	30	77	25	30	30
23	n	50	77	21	29	30
24	n	40	78	27	27	30
25	n	20	85	23	25	30
26	n	40	79	20	20	30
27	n	30	85	35	10	30
28	p	30	84	20	0	30

Grid # 21						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	p	10	82	51	0	0
2	p	30	91	61	1	0
3	p	10	86	55	3	0
4	p	10	87	56	5	0
5	p	30	88	55	10	0
6	p	40	90	NA	20	0
7	NA	NA	76	NA	30	0
8	NA	NA	82	NA	30	10
9	p	30	80	48	20	10
10	n	20	81	50	10	10
11	p	20	79	50	10	11
12	n	30	80	49	10	13
13	p	20	76	46	10	15
14	p	30	85	53	0	10
15	p	20	82	47	0	20
16	p	20	80	49	10	20
17	p	20	77	49	20	15
18	n	30	78	47	20	17
19	p	20	82	51	20	19
20	p	20	89	57	20	20
21	n	20	72	43	30	20
22	p	30	77	46	30	30
23	n	20	77	45	29	30
24	p	30	78	46	27	30
25	p	30	85	47	25	30
26	p	30	79	49	20	30
27	p	20	85	52	10	30
28	NA		84	57	0	30

Grid # 22						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	p	50	80	38	0	0
2	p	20	81	25	1	0
3	p	40	76	30	3	0
4	p	40	78	25	5	0
5	p	40	75	24	10	0
6	p	70	74	35	20	0
7	p	20	72	29	30	0
8	p	20	77	34	30	10
9	p	20	72	25	20	10
10	n	50	79	26	10	10
11	p	30	76	30	10	11
12	p	20	73	27	10	13
13	p	30	69	25	10	15
14	p	40	80	23	0	10
15	p	30	84	36	0	20
16	p	20	74	35	10	20
17	p	30	68	27	20	15
18	p	30	68	28	20	17
19	p	20	70	30	20	19
20	p	30	71	27	20	20
21	p	20	65	25	30	20
22	p	30	67	28	30	30
23	p	30	65	27	29	30
24	p	20	70	32	27	30
25	p	20	65	25	25	30
26	p	20	70	27	20	30
27	p	20	67	26	10	30
28	p	20	79	33	0	30

Grid # 23						
Pit #	Propagation Result	Drop Height (cm)	Snow Depth (cm)	Failure Height (cm)	X (m)	Y (m)
1	n	40	56	25	0	0
2	n	30	55	23	1	0
3	n	30	69	27	3	0
4	n	20	61	31	5	0
5	n	10	60	30	10	0
6	p	30	66	31	20	0
7	n	40	79	36	30	0
8	p	30	70	39	30	10
9	p	20	66	29	20	10
10	n	30	62	33	10	10
11	n	30	55	30	10	11
12	n	50	56	27	10	13
13	n	30	55	28	10	15
14	n	60	54	24	0	10
15	n	40	55	23	0	20
16	n	40	63	30	10	20
17	n	10	65	35	20	15
18	n	20	68	37	20	17
19	n	30	63	33	20	19
20	n	30	65	33	20	20
21	p	20	83	36	30	20
22	p	20	87	37	30	30
23	p	20	89	41	29	30
24	p	30	78	35	27	30
25	p	40	76	35	25	30
26	n	50	64	30	20	30
27	n	70	60	28	10	30
28	n	60	55	23	0	30

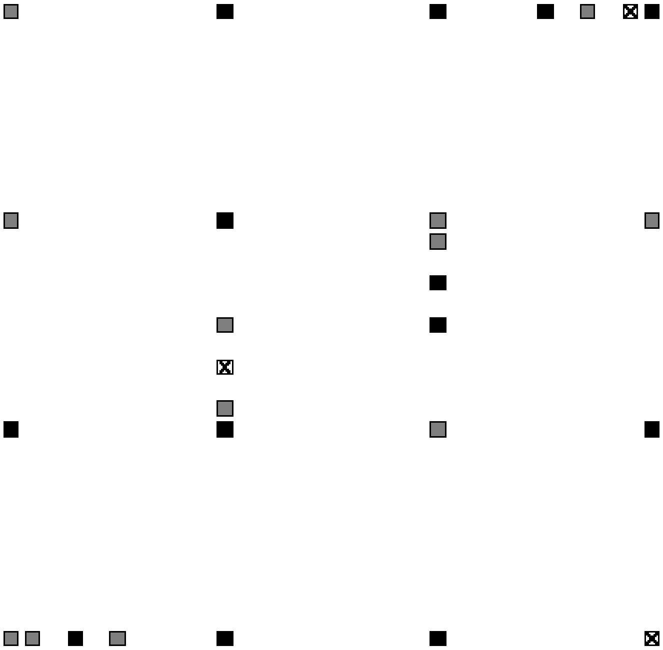
APPENDIX B

SPATIAL PLOTS

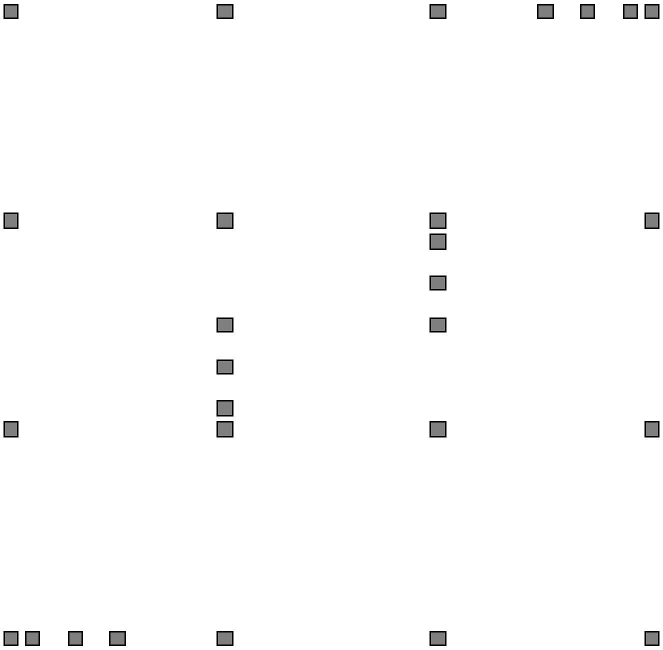
Plots showing the spatial distribution of propagation results for each of the 23 sampling grids, with each square indicating the location of an ECT. Each grid has a 30 m extent and follows the sampling plan laid out in Figure 2. Exact locations of each pit are given in Appendix A. ECTP, ECTN, and ECTX results were all classified according to Greene et al. (2010). “No Result” indicates that no usable test result was collected at that pit, reasons for this include the weak layer of interest not being found in that pit or a failure occurring lower in the pack before the weak layer of interest failed.

Legend
■ **ECTP**
▨ **ECTN**
☒ **ECTX**
☐ **No Result**

Grid 1



Grid 2



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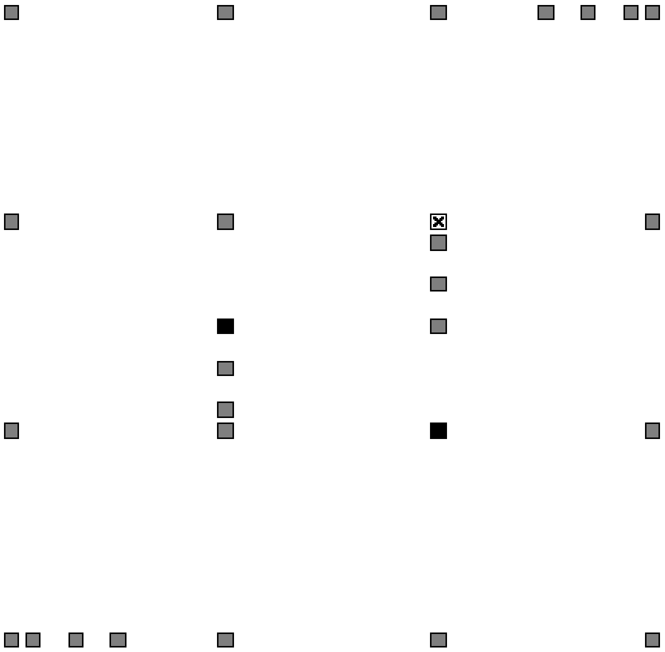

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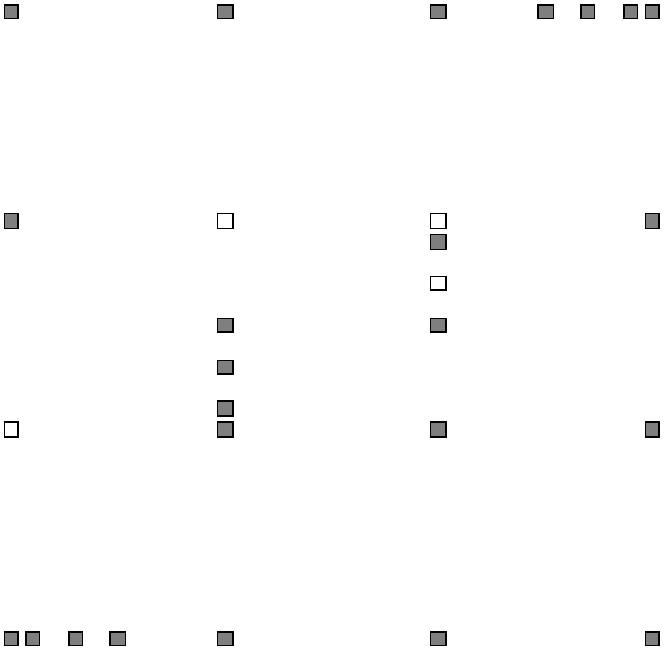

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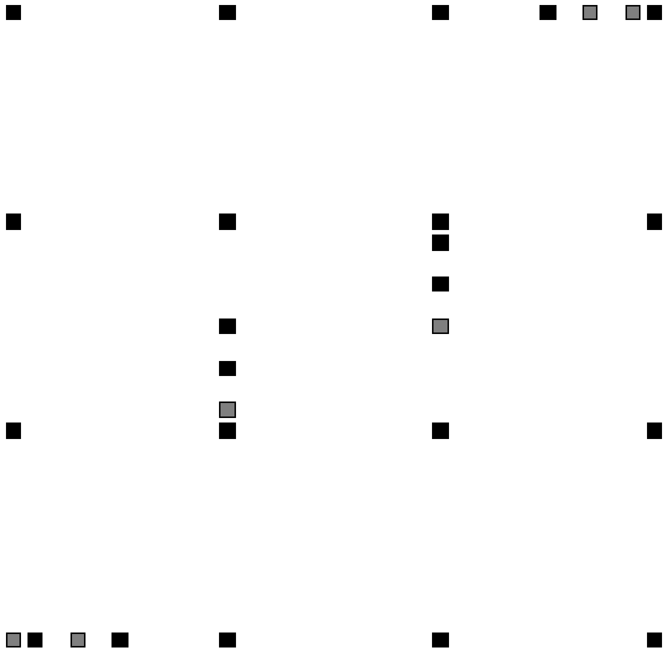

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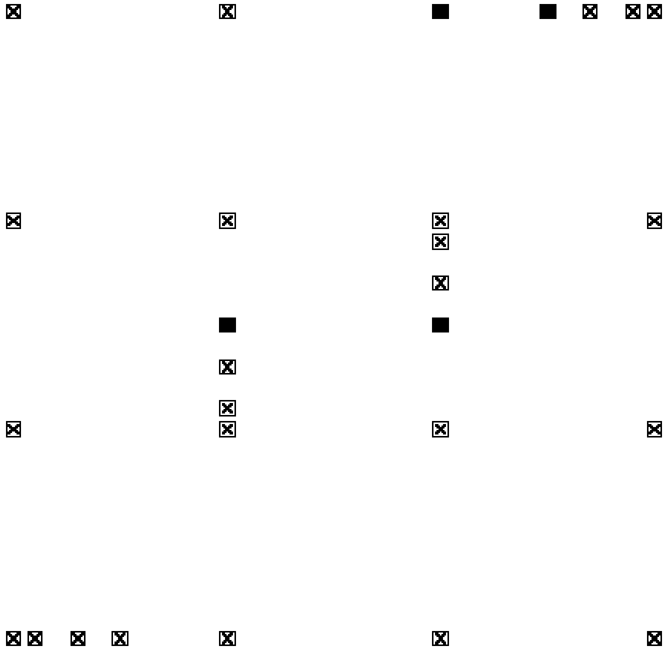

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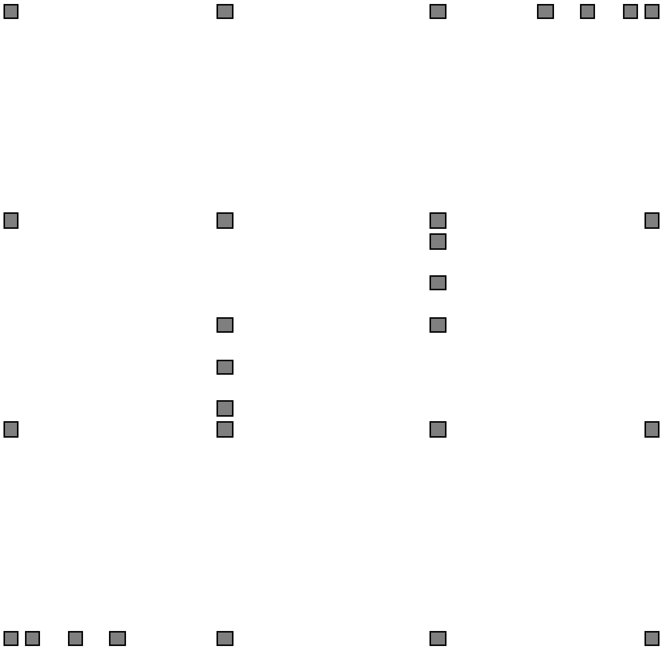

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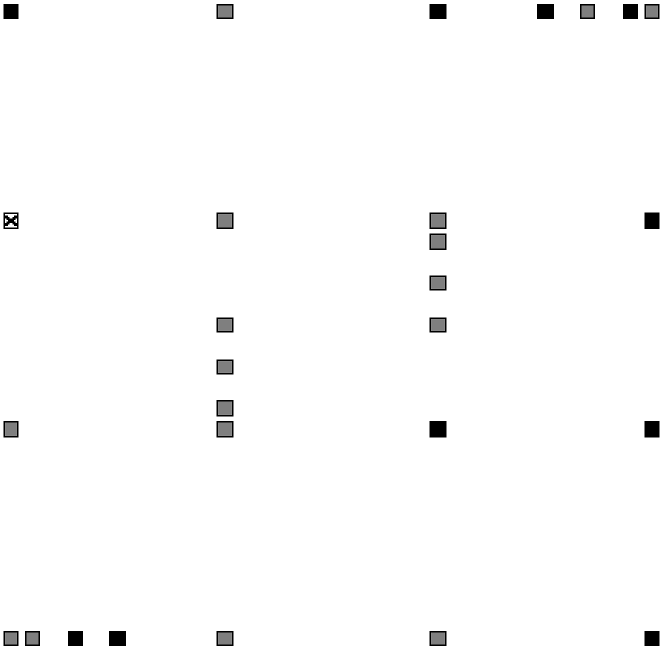

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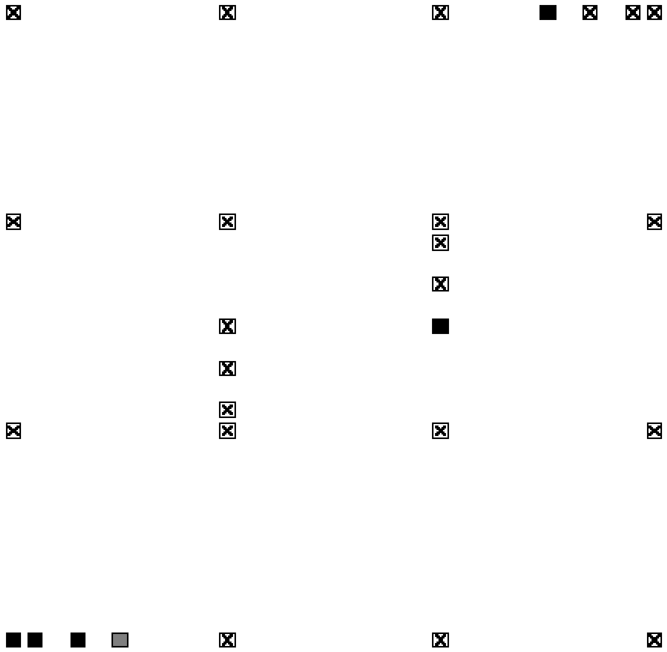

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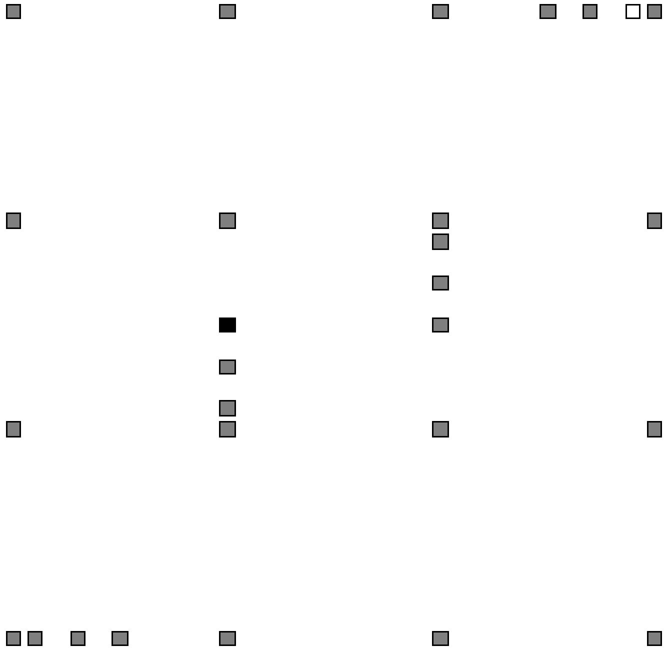

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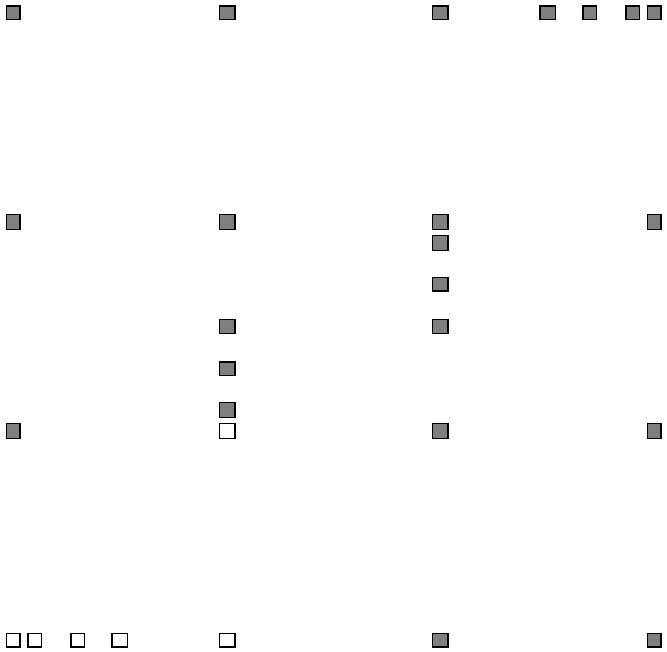

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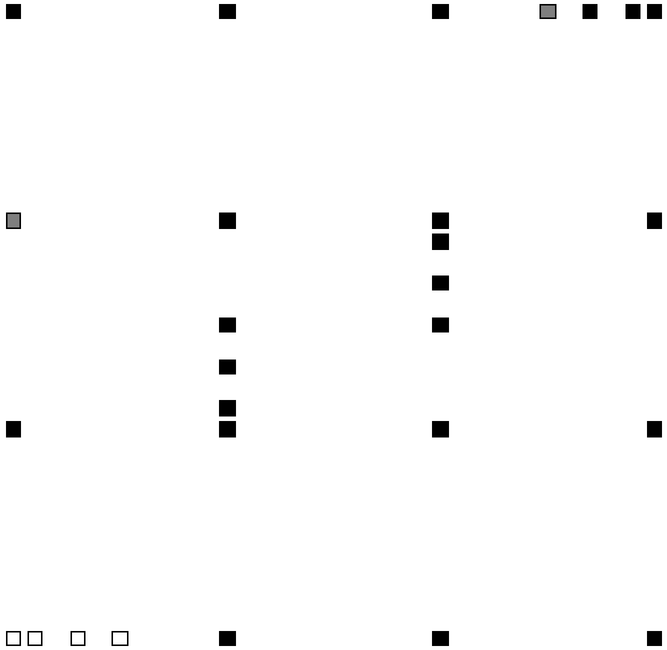

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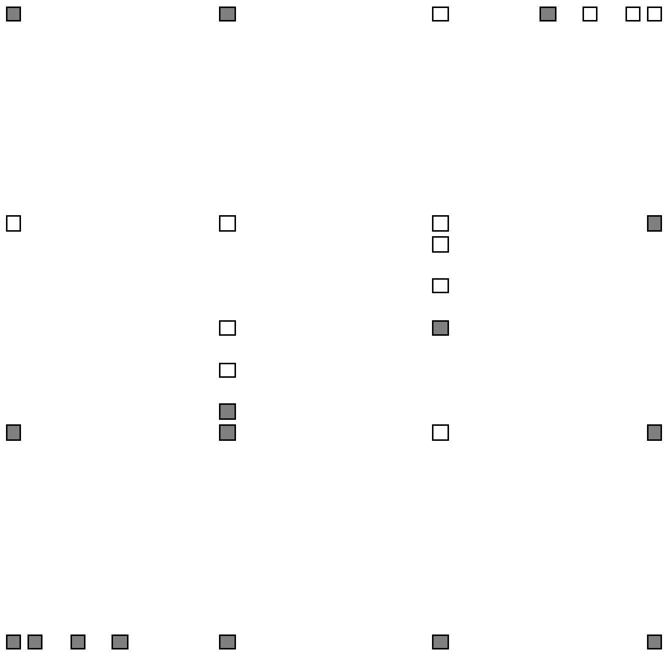

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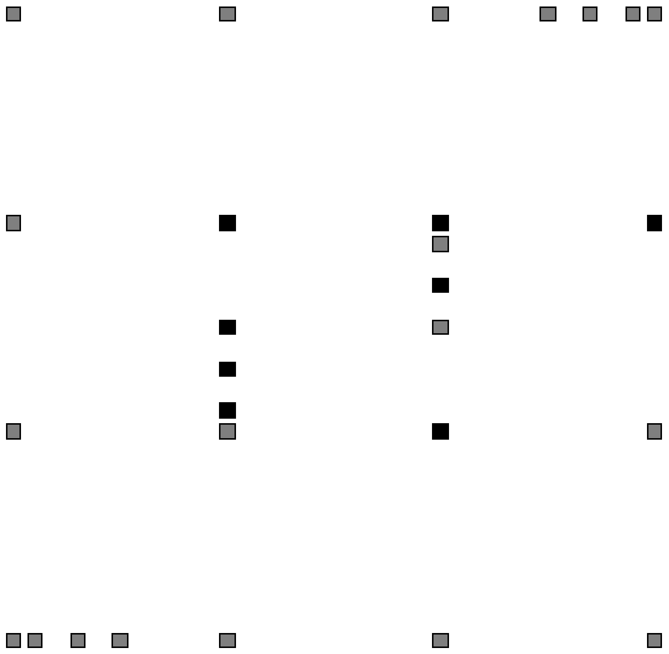

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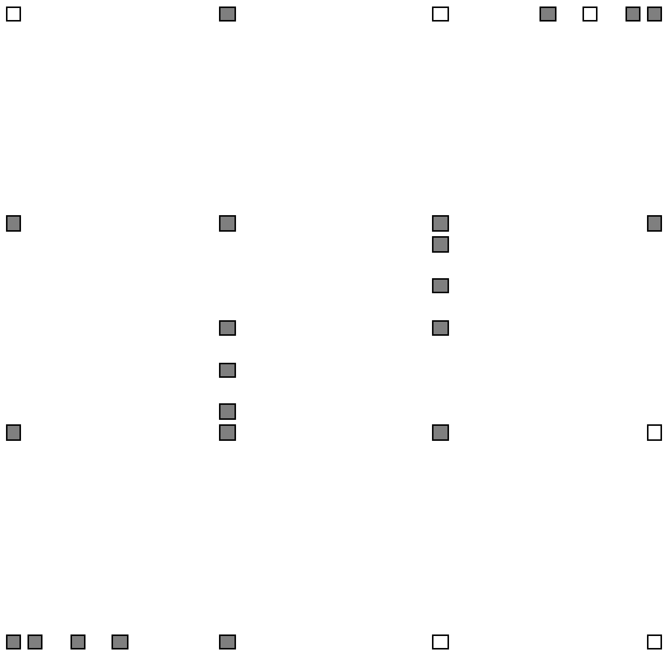

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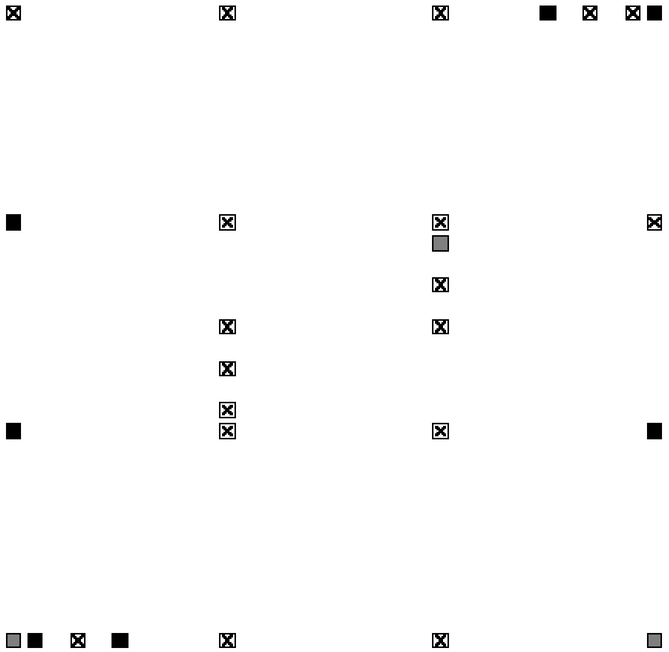

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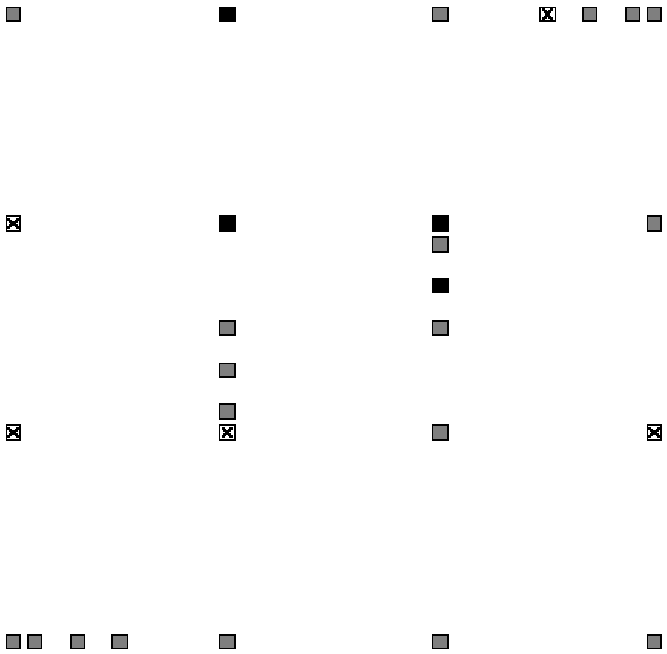

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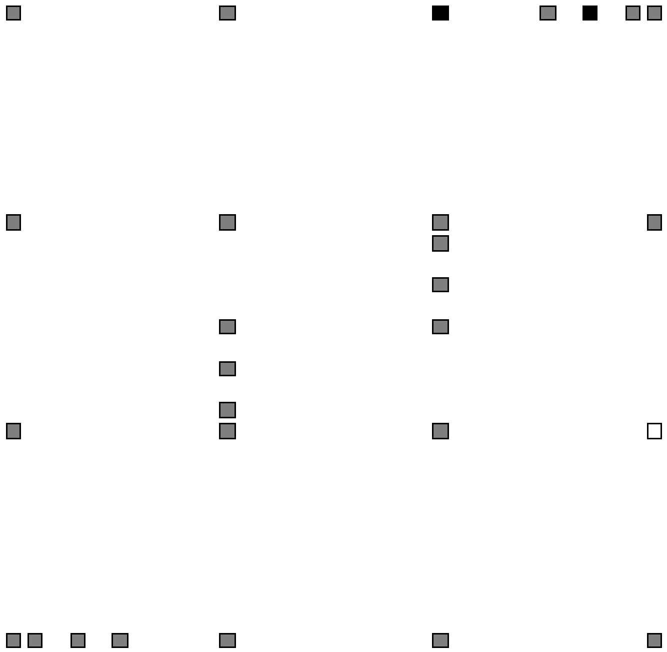

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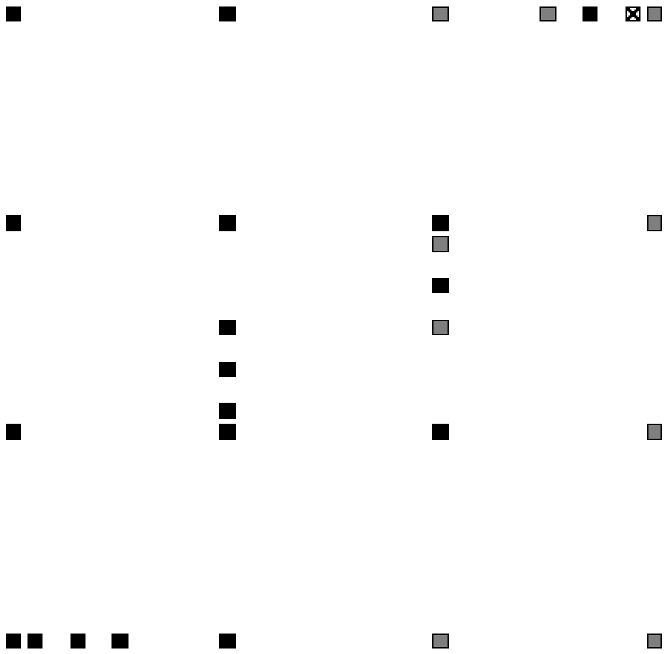

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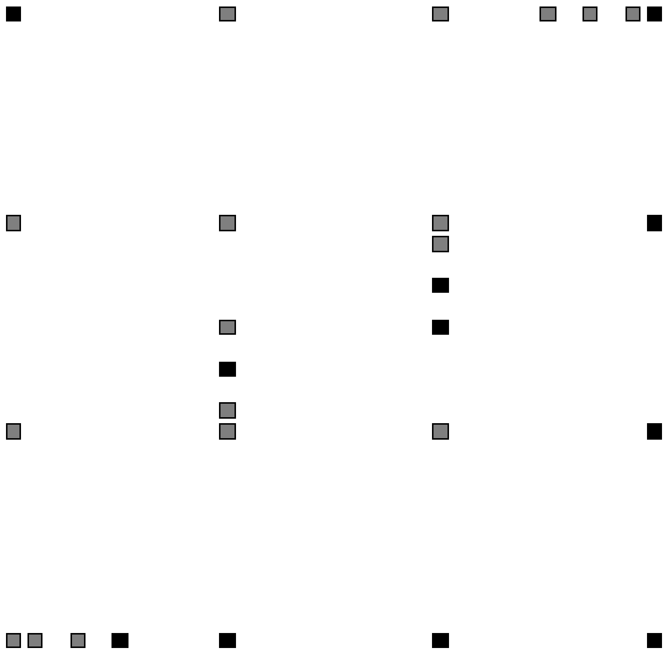

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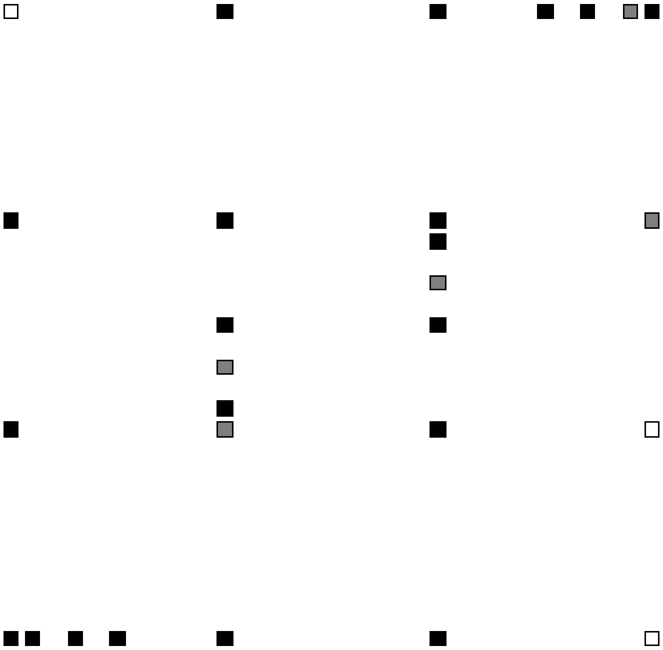

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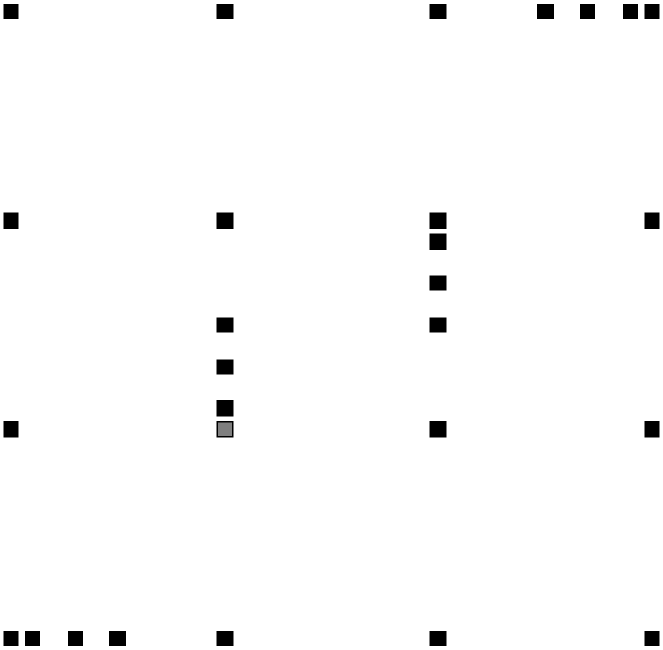

Grid 23