IDENTIFYING MAJOR AVALANCHE YEARS FROM A REGIONAL TREE-RING BASED AVALANCHE CHRONOLOGY FOR THE U.S. NORTHERN ROCKY MOUNTAINS

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ABSTRACT: Avalanches not only pose a major hazard to people and infrastructure, but also act as an important ecological disturbance. In many mountainous regions in North America, including areas with existing transportation corridors, reliable and consistent avalanche records are sparse or non-existent. Thus, inferring long-term avalanche patterns and associated contributory climate and weather factors requires the use of dendrochronological methods. Through the collection of regionally distributed tree-ring data recording avalanche events, we aim to address the following questions: 1) What is the regional and path specific frequency of large magnitude avalanches in the U.S. Northern Rockies?, and 2) Are there specific seasonal weather or climate variables that contribute to large magnitude and regional avalanche events? We collected 617 cross sections and 56 cores from 12 different avalanche paths in four mountain ranges in Glacier National Park and the Flathead National Forest across northwest Montana, USA. Six of these paths affect major transportation corridors, and the other six impact heavily used winter backcountry recreation zones. We identified, cross-dated, and quality ranked damage events recorded within and between samples from each path. We then implemented a double threshold analysis to account for decreasing sample numbers through time and to ensure accurate identification and dating of avalanche events. Finally, we developed an avalanche chronology of large magnitude events for each path, mountain range, and ultimately a composite record for the region. Preliminary samples from five paths in Glacier National Park reveal 1308 growth disturbances over 27 major avalanche years from 1795 to 2017. Within the major transportation corridors of GNP, a large magnitude avalanche (size 3 or greater) is likely to occur every 5 years in at least one of the five avalanche paths. These avalanche years coincide with winters characterized by high regional snowpack anomalies. Using this developing network to understand the spatiotemporal behavior of large magnitude avalanches and the contributory climate and weather factors will ultimately improve avalanche forecasting and backcountry safety efforts within the region.

KEYWORDS: Dendrochronology, Climate, Regional Avalanche Chronology

1. INTRODUCTION

Avalanches affect transportation corridors and settlements throughout the world. In Glacier National Park (GNP), Montana, United States, avalanches impact road clearing operations along the Going to the Sun Road, and a major vehicle and railroad transportation corridor (Peitzsch et al., 2012). In many mountainous regions, including areas with existing transportation corridors, reliable and consistent avalanche records are sparse or non-existent. Reconstructing avalanche chronologies using tree-ring methods has been ongoing for decades (Burrows and Burrows, 1976; Butler et al., 1987; Potter, 1969). Numerous studies used dendrogeomorphic techniques to develop avalanche records for remote regions without historical avalanche records, or in areas with inconsistent avalanche observations (Ballesteros-Canovas et al., 2018; Martin and Germain, 2016; Reardon et al., 2008).

Understanding the spatiotemporal behavior of avalanches and the contributory climate and weather factors in northwest Montana will ultimately improve avalanche forecasting efforts, including operations involving avalanche terrain that impacts transportation corridors. Thus, this study aims to answer these specific questions:

- What is the regional and path specific frequency of large magnitude avalanches in northwest Montana?

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- Are there specific seasonal weather or climate variables that contribute to large magnitude, regional avalanche events?

2. METHODOLOGY

For this study, we define large magnitude avalanches as avalanche events characterized by low and variable frequency with a high capacity for destruction (Germain, 2016). This loosely translates to size 3 on the North American destructive scale (Greene et al., 2016). We sampled 12 avalanche paths in northwest Montana, in the northern Rocky Mountains, United States (Figure 1). The 12 paths were equally distributed in three mountain ranges: the Whitefish, Swan and Livingstone Ranges located within the Flathead National Forest and GNP. However, the preliminary results presented here were generated from the six paths located within GNP. The sites in GNP are along the two major transportation corridors through the park: Going-to-the-Sun Road and U.S. Highway 2 in John F. Stevens Canyon. Elevations of avalanche paths within the study sites range from approximately 1100 m in the runout zones to 2700 m in the starting zones, and these paths cover a range of aspects.

Sample collection was conducted in the runout zones and into the surrounding periphery forest outside the trim line. Germain (2010) examined cumulative distribution functions of avalanche chronologies and reported only slight increases in the probability to extend chronologies with sample depths greater than 40. Thus, we collected 40-136 samples per avalanche path. The paths with more than 55 samples were collected during previous sampling campaigns. In total, we sampled 617 cross sections from dead trees and 56 cores from live standing trees, and processed the samples following general dendrochronological techniques from Stokes and Smiley (1968) and Burrows and Burrows (1976).

We implemented several quality control measures in classifying growth disturbance (GD) within trees, and applied thresholds for minimum number of samples required per path and avalanche year. For the former, we implemented a quality scale for classifying GDs as per Reardon et al. (2008) (scale of 1 to 5). In terms of a threshold for minimum number of growth responses, we followed the methods of Corona et al. (2012) and Martin and Germain (2017) using a double threshold analysis. This includes a minimum number of samples per path and a minimum percentage of trees exhibiting a growth disturbance of all trees alive in that given year. This allows for a more robust threshold that accounts for path specific scale and a regional context. Different thresholds were implemented for each avalanche path due to the varying number of samples per path. To generate event chronologies and create return periods (non-spatial) for each path and for the entire study site, we utilized the *R* package slideRun, an extension of the burnR library for forest fire history data (Malevich et al., 2018). Return intervals were fit to a Weibull distribution, useful in analyzing time to “failure”. A Kolmogorov-Smirnov test was used to assess the fit of the theoretical distribution.

For the initial climate-avalanche analyses, we examined average snow water equivalent (SWE) and snow depth anomalies of avalanche years using long term (1922-2018) snowpack data from six National Resource Conservation Service SNOTEL and snow courses in the region (NRCS, 2018). We also used maximum and minimum temperature data from the Kalispell Glacier Airport (901 m) and applied an environmental lapse rate of 6.5° C/1 km resulting in derived temperatures for the mean elevation of the avalanche path starting zones (2083 m). We chose this method rather than simply using automated weather stations located at higher elevations and closer to the study site due to the available long term record (1896–2018). Other nearby station records only extend back to the 1980s.

3. RESULTS AND DISCUSSION

A total of 403 samples from the six avalanche paths in GNP resulted in 1308 identified growth disturbances (GDs) from 10 different tree species. Over 90% of the growth disturbances were observed in *Pseudotsuga menziesii* (Douglas fir) and *Abies lasciocarpa* (subalpine fir). Using the double threshold for determining avalanche years following Corona et al. (2012) (i.e. maximum of 7% and 7 samples for paths with a sample size greater than 51) resulted in 51 classified avalanche years from 1777-2017 for all six paths. When we implemented a more stringent threshold of 10% and 10 samples for all trees exhibiting GDs in any given year only 35 avalanche years were identified (Figure 1). When, following Reardon et al. (2008) we included only Class 1 (clear impact scar associated with obvious reaction wood or growth suppression) and Class 2 (clear scar, but no reaction wood or suppression of growth, or, obvious reaction wood/suppression of growth that occurs abruptly after complacent or ‘‘normal’’ growth and that lasts for approximately 3 years) GDs, the number of avalanche years decreased to 15. Class 1 and 2 GDs constituted over 45% of the GDs recorded. For this paper, we opted to include all classes in the analysis to avoid losing any signals. Manipulating the threshold and stratifying analysis based on the class of GD clearly affects the resultant number of avalanche years. Further work will include a sensitivity analysis and comparison to the historical observational record to quantify the most robust threshold proportion and absolute sample size.

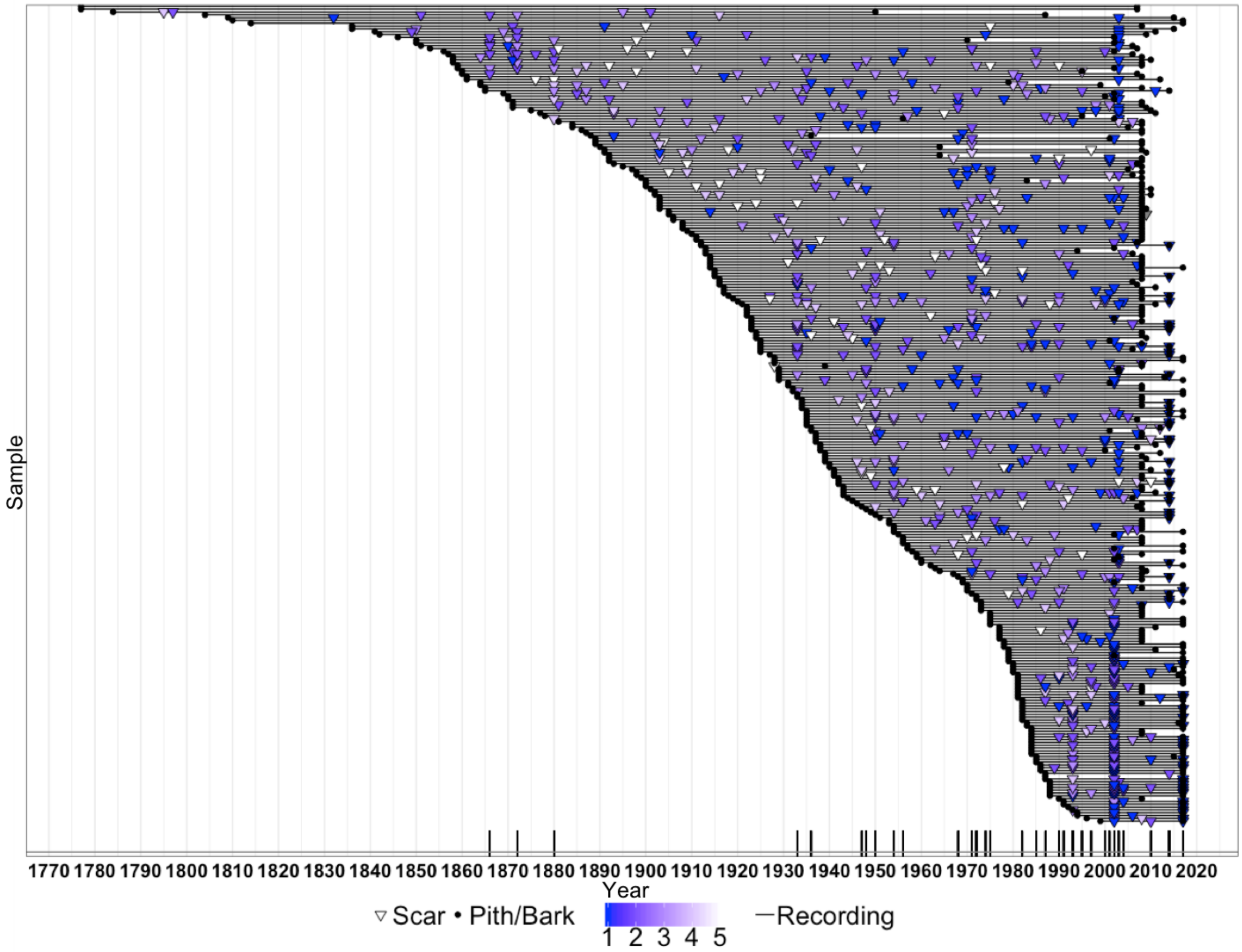

Figure 1: Avalanche chronology demographic plot from all paths in GNP highlighting the avalanche years identified by our analysis. The purple gradient triangles represent an avalanche signal in the tree ring record at any given year (along the x-axis) for each sample (along the y-axis) in this path. The black circles designate the pith (center of the tree) for each sample, and the black triangle indicates the last recording year: thus, the shaded area represents the lifespan of each tree. The vertical black lines along the x-axis represent any year with at least 7% of all trees alive at that year exhibiting a GD and 7 samples exhibiting a GD.

In classifying large magnitude, regional avalanche events, we opted to remove the avalanche path “Shed 10-7” from the initial analysis. Shed 10-7 was sampled in 2006 with an emphasis on spatial return frequencies (Reardon et al., 2008); accordingly the authors collected more samples in the higher elevations of the path in order to capture high frequency, but small magnitude slide events. These samples illustrate the importance of sampling strategy. These data will eventually be included, but filtered for samples lower in the path. Removal of Shed 10-7 resulted in 27 classified avalanche years for the five GNP avalanche paths using the 7% and 7 sample threshold. The average large magnitude slide return period was approximately 5 years over the 1933-2017 common interval. This suggests that within the major transportation corridors of GNP, a large magnitude avalanche (size 3 or greater) is likely to occur every 5 years in at least one of the five avalanche paths (Figure 2). However, when the paths are combined after first applying a specific threshold for each individual path (as per Corona et al. 2012), the mean interval is 8 years (“All Paths (path composite)” in Figure 2) with 18 avalanche years.

Preliminary results using Mann-Whitney U test comparing regional snowpack (SWE and snow depth) suggest that avalanche years occur, on average, during winters with greater SWE and snow depth (p=0.009 and p=0.005 (α = 0.05), respectively) (Figure 3). Despite this significant difference, there are clearly years (*n* = 9) with large avalanches that occur during years with below normal SWE. This likely because the temporal scale of the avalanche process is less than a year. In other words, a series of weather events may lead to large avalanches even during a season with below normal SWE. Differences between mean winter maximum and minimum temperatures were not significantly different (p > 0.05) between avalanche and non-avalanche years. Further work will include a suite of climate and meteorological variables and multivariate analyses.

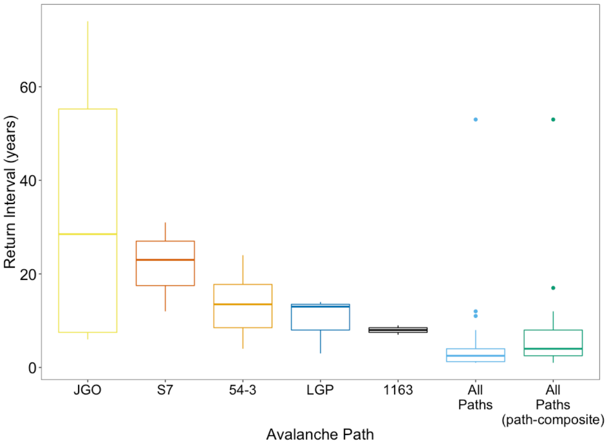

Figure 2: Return intervals for each of the five paths in this analysis (excluding Shed 10-7) as well as all the paths combined as one dataset using a 7% and 7 sample minimum (labeled “All Paths”) and all paths combined after first applying thresholds for each path based on the sample size rather than all paths as a region with a bulk sample size (labeled “All Paths (path composite)”).

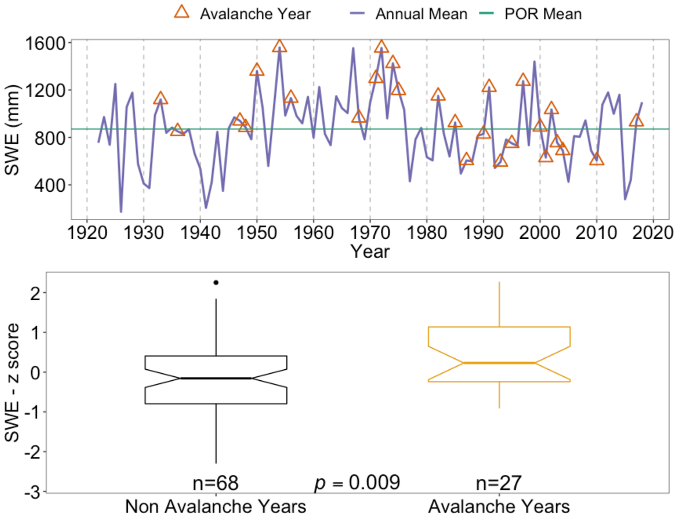

Figure 3: Regional May 1 SWE time series (1922-2018) from NRCS snow course and SNOTEL stations with avalanche year values depicted as red triangles. The period of record (POR) mean for SWE is designated as a green horizontal line. Bottom Boxplot – normalized z scores for avalanche (black) and non-avalanche (yellow) years, illustrating the significant difference between avalanche and non-avalanche years. The results are largely the same for snow depth (not shown).

4. CONCLUSION

This study attempts to estimate the frequency of large magnitude avalanches in the U.S.

Northern Rockies using tree-ring data, and identify any obvious relationships to specific seasonal weather or climate variables. In doing so we collected 617 cross sections and 56 cores from 12 different avalanche paths. Preliminary results from five paths within GNP reveal 1308 growth disturbances over 27 major avalanche years. The estimated avalanche return frequency for large magnitude slides within GNP was shown to occur on average every 5 years, with a range of 1 to 53 years for any given path. These avalanche years generally coincide with winters characterized by high regional snowpack anomalies, though major slide events also occur in low snowpack years. Further work includes sensitivity analysis on the site and regional avalanche year classification thresholds for trees exhibiting GDs, completing and including data from the six additional sites collected as part of regional analysis, a more comprehensive climate/weather and avalanche year analysis, and validation with available historical records from John F. Stevens Canyon.

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