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Landslide Hazards within the Spruce Pine 7.5-Minute Quadrangle: An Evaluation of Structural Controls on Bedrock Deterioration

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Abstract

Landslides are a persistent threat to mountainous communities and a frequent occurrence here in western North Carolina (WNC) due to steep slopes and heavy rainfall. The orientation of weaknesses in the rocks, such as foliations and fractures, can also contribute to landslide frequency. Thus, structural patterns and geomorphological processes need to be understood in order to mitigate these natural hazards. Recent field and geophysical research has suggested that Cenozoic uplift of the southern Appalachian mountains resulted in networks of fracture systems across WNC, called lineaments, that can increase the risk of landslide hazards. Slope failure assessments have been completed in many surrounding counties by the North Carolina Geological Survey (NCGS), with examples of slope failure attributed to lineament fractures. One of the lineaments, the Laurel Creek Lineament, is exposed through the town of Spruce Pine, NC. Fractures associated with this lineament are abundant throughout the Spruce Pine 7.5-minute quadrangle and dominantly strike toward 260°. The target of this study was to examine concentrations of landslides in the Spruce Pine quadrangle and evaluate the role of lineament fractures in the occurrences of these landslides. 63 landslides were identified in the field and from 1-m resolution LiDAR elevation models with ArcGIS software. The aspect of landslide directionality was compared to the orientation of fractures and foliations. Landslide aspects ranged from 010° to 340°, with higher frequencies parallel to the joint fabric. ~25% of the landslides occurred on east or west facing slopes with aspects parallel to the joints. Another 43% of landslides occurred at aspects that could indicate block failure along foliations or wedge failure between the foliations and joint fractures. These data indicate that lineament fractures are an important structural control on slope stability in this quadrangle.

1. Introduction

Established within the topography of the east coast are the Appalachian mountains, in which the bedrock fabric traditionally strikes northeast-to-southwest. However, the southern regions of this mountain range exhibit a series of fractures, known as lineaments, that crosscut the country rock. These lineaments are abundant in the southern reaches of the Blue Ridge, specifically in WNC, where the USGS has been mapping them since 1970 (Fig. 1). The area of this study encompasses the Laurel Creek lineament, in which lineament fractures strike east-west through the Spruce Pine-7.5 minute quadrangle. These fractures create a scenario where bedrock is broken down more easily and can enhance the effects of weathering processes. The weathered bedrock has potential to weaken slope stability and strengthen that of landslide risk. Therefore, susceptible bedrock can be linked to increased landslide hazards due to steep terrain coupled with heavy precipitation.

The trend of these fractures within the lineament do not align with the geologic history of the supercontinent Pangea, which was formed between 450 and 325 Ma. As the North American and African continental plates collided and helped shape Pangea, the Appalachian mountains were uplifted and created a series of foliations and faults that strike northeast-southwest. The assembly of the southern Appalachians were threefold and consisted of different orogenic events. The Taconic (~450 Ma) was the first major mountain building event that thrusted and folded the Tugaloo terrane along with the Ashe Metamorphic Suite, and caused heavy ductile deformation due to high-grade levels of metamorphism. The second orogenic event known as the Acadian (~410 Ma) would further thrust and fold the already accreted terranes of the Taconic. This would again promote uplift of the southern Appalachians and increase anatectic melting that lead to formations of igneous plutons in WNC[1]. Pangea would finally be completed with the beginnings of the Alleghanian (~325 Ma) as it would overprint the topography westward and uplift the Appalachians one last time[2]. However, studies regarding recent volcanism and increased asthenospheric buoyancy weakening the lithospheric mantle suggest that the Alleghanian was not the last orogen of the southern Appalachians[3].

1.1. Cenozoic Lineaments

Recent geophysical research has suggested that the many lineaments mapped throughout WNC are a result of Cenozoic (~25 Ma) uplift rather than the initial formation of Pangea, and they are likely still seismically active[4]. The evidence of these lineaments support topographic rejuvenation in response to delamination of the lithospheric mantle, without an active plate boundary[5]. Isostatic adjustments of the lithospheric root have caused these lineaments to form oblique to the regional bedrock fabric throughout WNC, and elongate eastward toward the piedmont[6]. Hill's research focused on the Boone fault in Watauga county which displays south-side-up motion. This suggests that the lineament fractures must be younger in age than the Pangea history. Similarly, many data points collected for this study concerning the Laurel Creek lineament exhibit parallel fracturing and offset in bedrock with north-side-up motion. These findings further support that the Appalachian mountains were not uplifted in a single uniform event, and Cenozoic rejuvenation is becoming a plausible explanation.

The Laurel Creek lineament has yet to have been extensively mapped, but by understanding the prevalence of post-orogenic faulting within this region tighter constraints can be imposed upon structural discontinuities within the bedrock. Although the lineament sits in alignment with a now passive margin, uplift of the northern block has increased frequencies and density of parallel fractures[7]. This abundance of fractures will indefinitely weaken the foundational strata all along the east-west trend of this lineament. Furthermore, topographic imbalances along the lineament can be traced by the chronicity and aspects of landslides that are occurring relative to the fractures and foliation throughout the quadrangle. By evaluating the surrounding country rock in detail, a clearer interpretation of Cenozoic resurgence is possible.

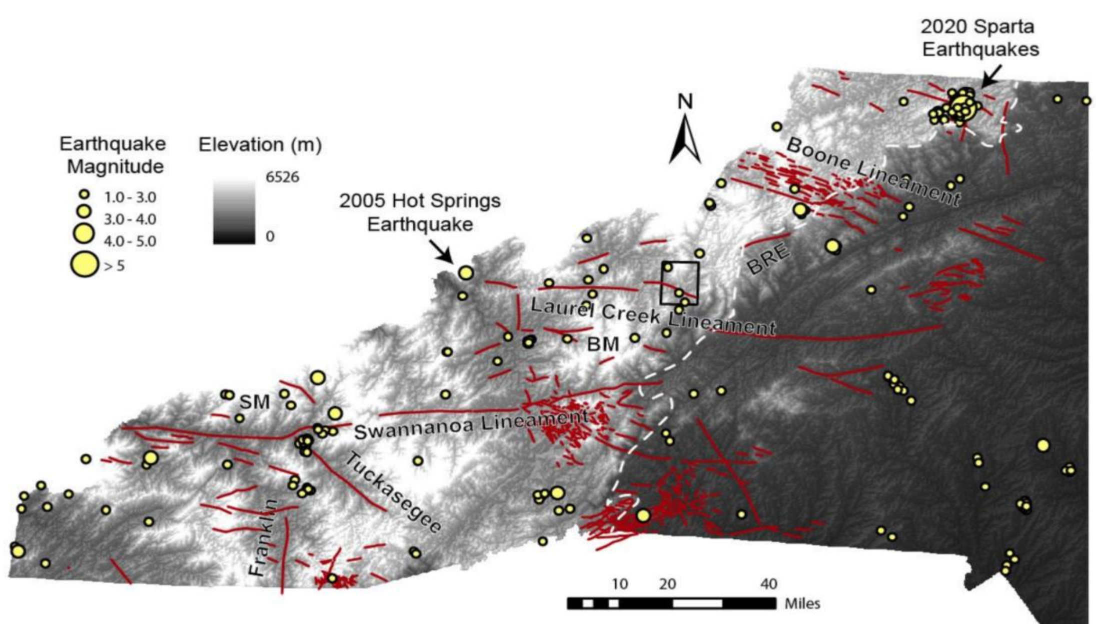

Figure 1. Fractures and lineaments in western North Carolina (red) with earthquakes from USGS. The black rectangle shows the location of the Spruce Pine 7.5-minute quadrangle for this study[13].

1.2. Slope Stability in the Southern Appalachians

The east-west striking joints of the lineament perpetuate further deterioration of bedrock, which leads to slope instability and further concern for landslide hazards. Many of the landslides in WNC are caused by severe weather that triggers debris flow on steep hillsides. Extended periods of heavy rainfall is the most prominent reason for a slide to occur. There are several key factors of slope instability that can determine the overall magnitude and frequency of landslides in the event of heavy precipitation. Hydrologic components such as rainfall infiltration, saturated soils, and pore water pressure can increase the risk of shallow landslides[8]. Over time, these natural processes will accelerate erosion rates and lead to hillside creep. Hales et al., (2012) researched erosion rates related to landslides in the Coweeta basin, otherwise known as the Nantahala Mountains Escarpment, which is to the west of Spruce Pine. They created models of the topography using ArcGIS, used radiocarbon analyses on the colluvial deposits, and calculated volumetric infilling rates near the bases of the catchments[9]. Their findings supported that hillside creep is a product of weathered bedrock and loose soils, which could eventually lead to a major landslide.

There are aspects of geologic structure that will allow for landslides to transpire more easily. Cattanach et al. (2009) analyzed rock slope stability along sectors of the Blue Ridge Parkway to better determine prominent features of bedrock that could lead to planar or wedge failure[10]. They targeted areas along the parkway where there had been known block failures along roadcuts, and collections of large boulders near the bases of steep hillsides. Data was gathered through field mapping and geohazard analyses of jointing and foliation present in the bedrock. Using modeling software such as ArcGIS, RockPack III, and Markland's Test of dip vectors they were able to quantify the slopes at the greatest risk of failure. Bedrock that exemplified steeply dipping foliation and jointing with friction angles greater than 30° were marked as high priority hazards. In analyzing these predetermined friction angles in relation to planar weaknesses along exposed bedrock and intersecting fractures, they found many areas were at risk of failure.

1.3. Scope of this project

Lineament fractures have caused slope failures in many other surrounding counties in WNC. In evaluating the Laurel Creek lineament, it is important to understand what role these fractures have in landslide occurrences. The region of Spruce Pine has previously been mapped by the NCGS, but the points are dated and seemingly confined to the downtown region of the city, where 6 landslides are documented[11]. Landslides are a prevalent natural disaster in this area and it is important to understand their relationship to geologic processes. In making a connection between the Laurel Creek lineament and landslide occurrences there is potential to enhance mitigation tactics. Whether the lineament has a significant control on landslide distribution will be explored in this research, and expand upon the structural and kinematic reasons for which they develop in this quadrangle.

2. Methods

This research consisted of field mapping and images from LiDAR of landslides throughout the 7.5-minute quadrangle along the Laurel Creek lineament in Spruce Pine, NC. Fracture and foliation data was collected from exposed rock outcrops along roadsides and on parts of private property as access was granted. Palmer (2022) mapped the orientation of fractures, foliations, and rock type throughout the quadrangle and these data were used to help determine locations of landslides that were documented in field books and the software FieldMove. known landslide locations from the NCGS database were included. 1-m resolution LiDAR elevation data was used to create a slope and hill shade layer in ArcGIS, to better view surface geomorphology for identifying additional landslide deposits that were not observed in the field. The aspect feature was applied to aid in identifying landslide direction. Contour lines were included to help visualize the elevation in the topography and better show spatial relief. A slope interval feature of 30° or greater was included to target areas that are more susceptible to slope instability. Dominant trends in joint and foliation data were then assessed and compiled into Excel for further kinematic analysis. The aspect azimuth of these landslide data were compared to average joint and foliation strike of the lineament. The frequency of angles between joint and foliation strike was used to determine if there were any linear patterns. Constraints were placed upon the angles in which failure of a slope side would be likely to occur. Stereonets plotted with poles to joints and foliation were generated to show relationships between the strikes and density within the quadrangle.

3. Results

63 landslides were identified in the Spruce Pine 7.5-minute quadrangle throughout the duration of this research (Fig. 2). The landslide aspects ranged from 15° to 350° with the highest concentration sloping to the south-east. Block failures along the joints on north or south facing slopes were found to occur toward 350° or 170°. Failure on east or west facing slopes occur toward 80° or 260° with ~25% of the sample parallel to joint fabric. Slopes facing >43° or <223° could have block failure parallel to foliation and/or wedge failure associated with intersecting fractures. The direction of slope in the existing topography is uniformly distributed. However, landslides had the propensity to form on southeast dipping slopes in relation to foliation within the data set (Fig. 3A and B). Landslide initiation varied throughout the study area, however there were correlations within the distribution. The north-west corner of the quadrangle shows a large cluster of activity, as 18 landslides were identified. Landslide activity is also occurring in developed and trafficked areas such as along highway 19 and in the town of Spruce Pine.

Orientations of fracture and foliation data within the study have been gathered from Palmer (2022) in order to understand the relationship between lineament fractures and landslide activity. In the stereonet, poles to joints and foliation are shown in color to give a representation of density within the quadrangle. Joint data (n=258) are represented within the rose diagram and show a wide variety of directions (Fig. 4). The mean of the joint strikes are 260.5°/80.5° which suggests a dominant east-west trend that aligns with the Laurel Creek lineament. Foliation data were also mapped and provided in a stereonet with (n=499) and a dominant orientation of 049°/11° with dip direction towards 133° (Fig. 5).The highest frequency of landslide activity (n=15) occurred at aspects that were parallel to joint fabric. In the Beaver Creek area of Spruce Pine, NC lineament fractures are the origination of a landslide, which has moved due east and is parallel to strike (Fig. 6A and B). The direction of slope in the existing topography is uniformly distributed. However, landslides (~28%) have shown the propensity to form on southeast dipping slopes in relation to foliation within the data set (Fig. 7A and B). Hillside creep further exposes bedrock (Fig. 8).

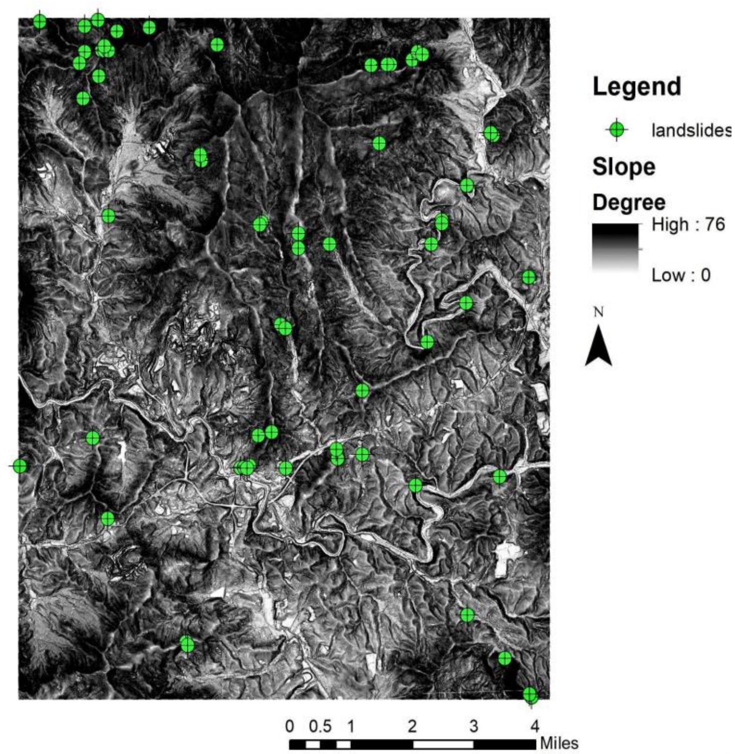

Figure 2. Slope map displaying locations of landslides within the quadrangle.

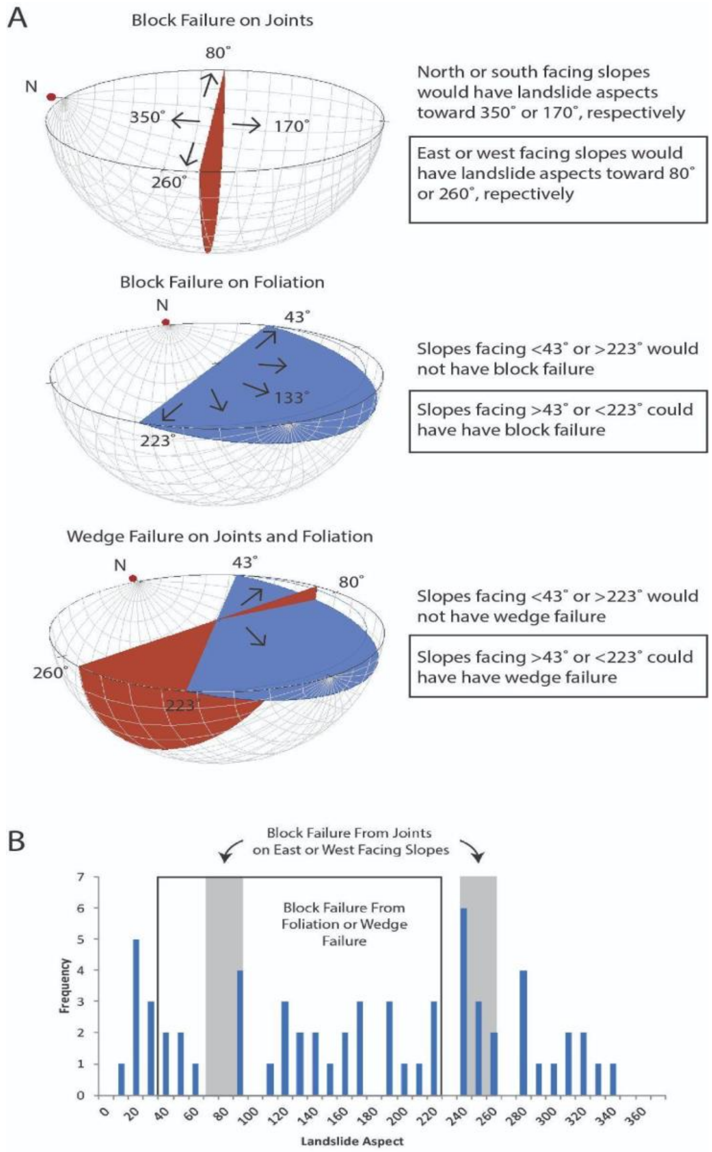

Figure 3: (A) Types of failures associated with landslide aspects. (B) Frequencies of landslide occurrences documented from this research.

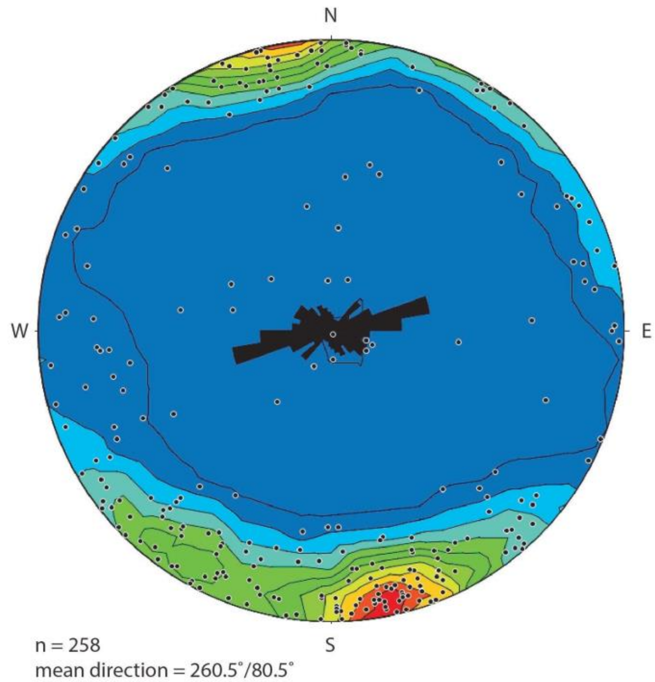

Figure 4. Orientations of faults and joints plotted as poles on a stereonet, red with highest densities and blue with lowest densities. A maximum density of 350° and 170° shows a dominant joint orientation of 080° and 260°. The black bars are a rose diagram of the joint strikes, also aligning with this trend.

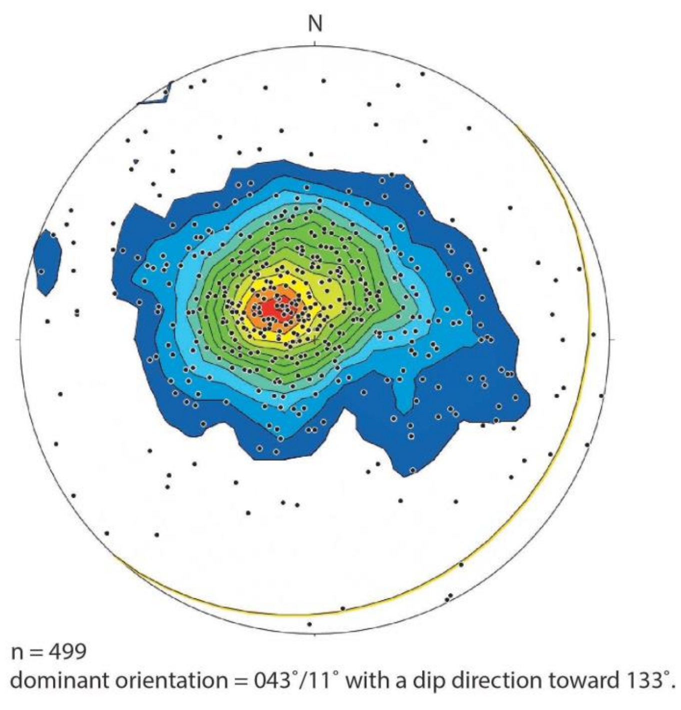

Figure 5. Orientation of foliation plotted as poles on a stereonet. The red shows where the points are densely concentrated, and the best-fit plane to that orientation is the yellow curved line.

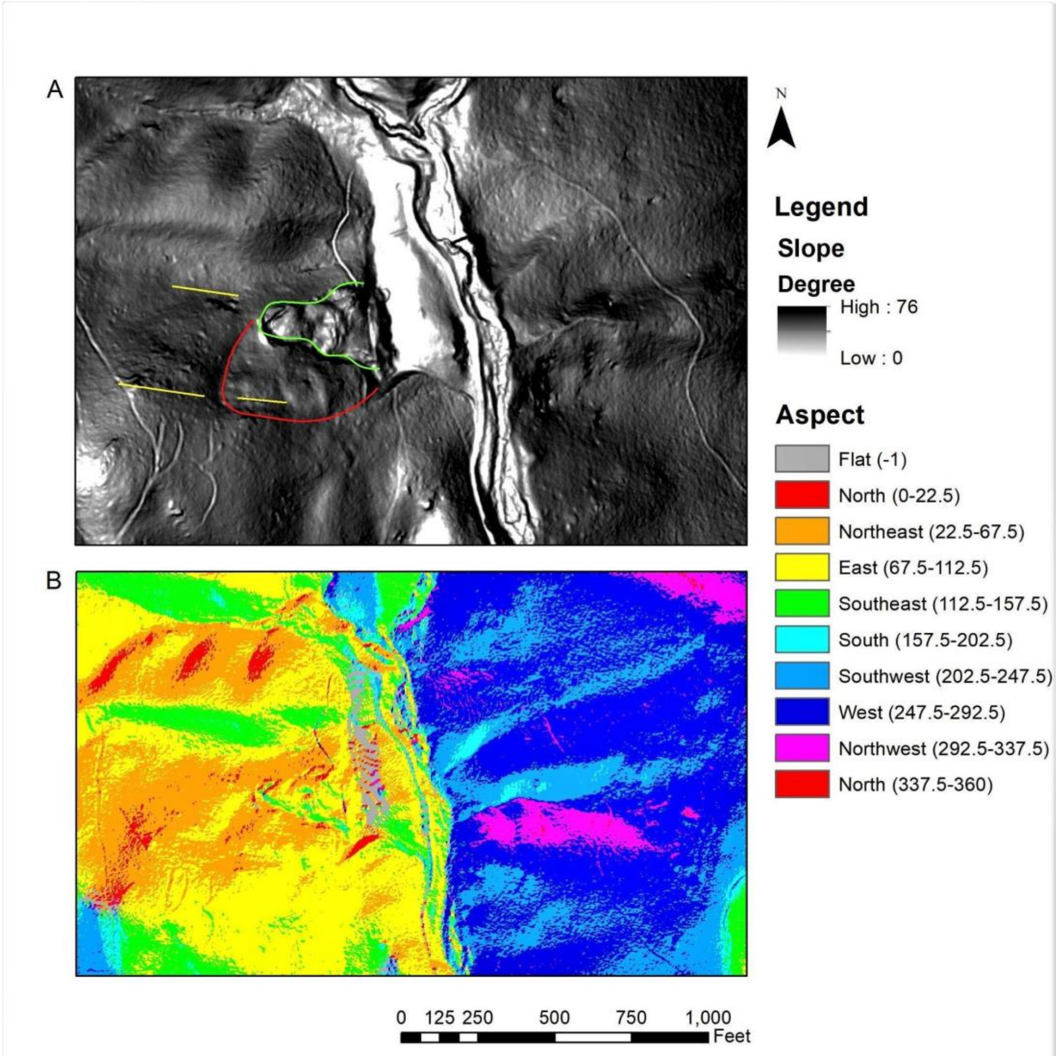

Figure 6: (A) Image from LiDAR showing a landslide in the Beaver Creek area of Spruce Pine. The yellow lines denote fracturing parallel to the Laurel Creek Lineament. The red outline signifies where the landslide had originated, and the green outline represents the newly formed head scarp and toe. (B) Image showing landslide aspect and how color can better exemplify the directionality of slopesides.

 

Figure 7: (A) Fractured and exposed bedrock becomes colluvial debris flow parallel to the Laurel Creek lineament. (B) Saprolite deposition influenced by hillside creep along the Laurel Creek lineament.

Figure 8. Toppled trees and bedrock breakdown associated with the effects of landslide mechanics.

4. Discussion

Landslides are effectively occurring within the Spruce Pine 7.5-minute quadrangle due to fractured bedrock and weathering in tandem with steep hillsides. The distribution of landslides mapped spread throughout the entirety of the quadrangle, but there are noticeable trends that suggest patterns within the topography. The largest cluster of landslide activity was noted to be in the northwest corner of the quadrangle where 18 landslides (~29%) were documented. This region of the study area exhibits higher elevations and some of the steepest slopes within the entire quadrangle which can be referred to in Figure 2. Due to the elevation and steep slopes in this northwest region, landslides are more likely to initiate because of hillside creep and fractures within the bedrock. However, the aspects of landslides are also developing in alignment with the east-to-west trend of the lineament. The topography that parallels the lineament is not as steep, as this is near major developments such as the town of Spruce Pine and highway 19. Higher densities of fractures mapped were nearest to the lineament, and jointing that corresponds to the fabric is a major factor in landslide initiation as seen in Figure 7. These fractures inevitably increase the risk of slope susceptibility and can help explain the patterns in landslide direction.

The Laurel Creek lineament appears to have a slight control on the development and occurrence of landslides within the quadrangle. Of the 63 landslides that were documented there is variability with how they are likely to form. North or south facing slopes will have landslide aspects towards 350° or 170°, while east or west facing slopes would have aspects towards 80° or 260° which can be referred to in Figure 8A. These aspects of azimuth are derived from the truest values in degrees of either north, east, south, and west. There are three distinct parameters of these landslides that have been observed in the quadrangle; block failure on joints, block failure on foliation, or wedge failure along the joints and foliation. Based on the calculations regarding the aspect azimuth of block failure along jointing the highest frequency of landslides occurred between 240° and 260°, which is parallel to the lineament fabric and occurred as a result of lineament fractures. 11 mapped landslides fit within this criteria and have initiated on hillsides that either sloped to the east or west. Block failure along foliation was attributed to southeast facing slopes and occurs most frequently between 43° and 220°. However, the majority of landslides (~43%) occurred as a result of block failure or by intersections of fractures that create the framework for wedge failure. These landslide scenarios are most likely to occur between 40° and 220° with aspects from the northeast to southwest.

The Spruce Pine 7.5-minute quadrangle encapsulates the perfect environment for these natural disasters to occur; areas of high relief, significant amounts of annual precipitation, and bedrock morphology that exhibits structural discontinuities throughout the region. All of these factors create shear stresses within the composition of steep mountainous terrain and contribute to colluvial debris flows[12]. Over time the extensive weathering of bedrock fabric will lead to increased amounts of landslides, so further research will be warranted. In the acknowledgement of these data the observed landslides exhibit a trend related to the geomechanical formation of the southern region of the Appalachian mountains. As a result of Cenozoic uplift these lineament fractures have created a scenario where bedrock has moved north-side-up[7]. The geomechanics of this north-side-up movement has elevated the topography to the north of the lineament and increased the likelihood of weathering, hillside creep, and bedrock block and wedge failures. Hence, landslides will have a greater propensity to occur in this region of the quadrangle. Although the majority of these landslides were found to correlate with foliation strike, lineament fracturing is prevalent within the study area and has an effective influence in forming landslides. Data regarding landslide frequency at elevations parallel to the joint fabric shows that the Laurel Creek Lineament does increase the overall risk of landslides in this quadrangle, especially to the north of the lineament.

5. Conclusion

This study has assessed the kinematic and structural relationships between bedrock deterioration and landslide risk within the Spruce Pine 7.5-minute quadrangle. Prudent analysis of landslides by identification in the field and from 1-m resolution LiDAR elevation models with ArcGIS software has aided the research. The study supports that landslide initiation can occur from a plethora of environmental instances such as weathering, amounts of annual precipitation, and hillside creep. Specification of geophysical analysis has further instituted that structural discontinuities affect aspects of landslide frequencies. Block failure, wedge failure, and colluvial debris from shallow landslides are present within the quadrangle. Jointing in bedrock parallel to the Laurel Creek lineament is causing block failures on east and west facing slopes. These failures are leading to further slope instability and increasing the risk of landslide susceptibility in this region.

6. Acknowledgements

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