Hickory Nut Gorge: A Natural Laboratory to Advance Our Understanding of Progressive Rock Failure

PRF 2022
Progressive Failure of Brittle Rocks
Geological Society of America
Penrose Conference Field Trip
June 22, 2022

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Cover Photos: Top. Hickory Nut Falls in Chimney Rock State Park. **Bottom.** Rockfall deposits from the November 14, 2021 rockfall-debris slide in Chimney Rock State Park

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June 22, 2022

Richard M. Wooten[1], David M. Korte[2], Jesse S. Hill[2], Bart L. Cattanach[2], Jennifer B. Bauer[3], Philip Prince[3], Cheryl Waters-Tormey[4], Corey M. Scheip[5]

[1]Richard M. Wooten, North Carolina Geological Survey (Ret.), Richard.M.Wooten@gmail.com
[2]David M. Korte, North Carolina Geological Survey, David.Korte@ncdenr.gov
[2]Jesse S. Hill, North Carolina Geological Survey, jesse.hill.geology@gmail.com
[2]Bart L. Cattanach, North Carolina Geological Survey, Bart.Cattanach@ncdenr.gov
[3]Jennifer B. Bauer, Appalachian Landslide Consultants, PLLC, Jennifer@appalachianlandslide.com
[3]Philip S. Prince, Appalachian Landslide Consultants, PLLC, Philip@appalachianlandslide.com
[4]Cheryl Waters-Tormey, Western Carolina University, cherylwt@email.wcu.edu
[5]Corey M. Scheip, BGC Engineering, cmscheip@gmail.com

Guidebook Editor – Conference Co-leader
Martha Cary (Missy) Eppes, University of North Carolina - Charlotte

Abstract

The one-day field trip will examine a variety of mass wasting features in Hickory Nut Gorge in Rutherford County, western North Carolina. We will see the spectacular but challenging terrain of Chimney Rock State Park that poses hazards from rockfalls, rockslides, and debris slides and flows. Hickory Nut Gorge is an area of concentrated prehistorical and historical mass wasting, analogous to other post-orogenic, brittle cross-structures that control reentrants incised into the Blue Ridge Escarpment in North Carolina. The gorge has experienced over a century of damaging mass wasting events, notably those in 1916, 1996, 2013, 2014 and 2018.

We will focus on rock slope movements with varied transport rates such as rapid-catastrophic failures, slow-moving incremental failures, and complexes with multiple failure mechanisms and timings. Field trip leaders will present work on the recently completed landslide hazard mapping for Rutherford County, research on the controls on mass wasting, and lessons learned from responses to landslides.

Hickory Nut Gorge is an excellent natural laboratory to advance our understanding of the connections between progressive rock failure (PRF), bedrock structures, geomorphology, landscape evolution, environmental conditions, and mass wasting in order to improve public safety. Our field trip will demonstrate how PRF needs to be considered in a landscape containing orogenic and post-orogenic bedrock structures that influence the landscape from the outcrop to regional scale. We will consider the significance of PRF processes in reducing shear strength, and how they interact with inherited brittle and ductile bedrock discontinuities to affect the stability of rock masses.

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Introduction

Field Trip Overview

The one-day field trip will examine a variety of mass wasting features in Hickory Nut Gorge, a structurally controlled, erosional landform incised into the Blue Ridge Escarpment in Rutherford County, western North Carolina. We will see the spectacular but challenging terrain of Chimney Rock State Park that poses hazards from rockfalls, rockslides and debris flows. Examples of these landslide events within the gorge, notably in 1916, 1996, 2012, 2013, 2014 and 2018, are well documented. The North Carolina Geological Survey (NCGS) and their contractor Appalachian Landslide Consultants, PLLC (ALC) completed the landslide hazard mapping for Rutherford County in 2022. Field trip leaders will present work by the NCGS, ALC, Western Carolina University, North Carolina State University, on landslide hazard mapping and research on the controls on mass wasting.

Hickory Nut Gorge is an excellent natural laboratory to advance our understanding of the connections between PRF, bedrock structures, landscape evolution, geomorphology, and mass wasting in order to improve public safety. Critically, the field trip will demonstrate how PRF needs to be considered in a landscape with a long legacy of fracture-generating processes. For example, we will consider the significance of PRF processes in reducing cohesional strength, and how this interacts with inherited fracture sets and brittle vs. ductile bedrock structures to affect the stability of rock masses. To what extent do fluctuations in ambient environmental conditions control PRF, and how and when do these processes cause hazardous failures? Are these distinguishable from those resulting from high-magnitude (seismic and meteorological) events? How can different causal mechanisms of rockfalls be prioritized and addressed in hazard management strategies? These questions will be considered during the field trip, contextualising the work presented throughout the conference and demonstrating the significance, and challenges, of understanding the role that PRF plays in landform and landscape evolution.

Field Trip Main Take-aways.

- Examine the various mass wasting features in Hickory Nut Gorge, concentrating on rock slope failures, in the context of recently completed landslide hazard mapping for Rutherford County.
- Hickory Nut Gorge is an area of concentrated mass wasting activity analogous to other post-orogenic brittle cross-structures that control reentrants incised into the Blue Ridge Escarpment in western North Carolina.
- Rock slope failure types in Hickory Nut Gorge include rockslides, rockfalls, and topples, that were/are emplaced by various transport rates such as rapid-catastrophic failures; slow-moving incremental failures; complex failures (multiple failure mechanisms).

- Ductile and brittle bedrock discontinuities interact to influence rock slope failures and crack propagation:
  - Ductile bedrock discontinuities: foliation, gnessic layering, and protomylonitic fabrics.
  - Brittle bedrock discontinuities: tectonic fracture (joint) sets, and stress relief (exfoliation) fractures.

The Main Outstanding Questions.

- What are the mechanisms behind the large rock slope failures evidenced by extensive block fields?
- Are there age clusters that indicate co-seismic and/or climate-driven processes?
- What are the implications for public safety?
- What is the origin of the topographic benches found in numerous places along the Blue Ridge Escarpment?

Field Trip Itinerary Overview – June 22, 2022

Depart Flat Rock Conference Center 7:30 a.m.

Stop 1*:* 8:15-9:00 a.m. Scenic overview of Hickory Nut Gorge from the Town of Lake Lure Municipal Parking Lot.

- Overview of local bedrock geology and tectonics – Bart Cattanach
- Overview of geomorphic features and evolution the Blue Ridge Escarpment, topography and stream capture – Philip Prince

Stop 2*:* 9:15-11:15 a.m. (buses depart at 11:30 a.m.) Rumbling Bald rock climbing and bouldering access area, north side of Hickory Nut Gorge.

- Snacks and water, pit stop
- Hiking tour of debris deposits, block fields and cliff source areas (~2.4 km round trip).

Stop 3: 12:00-5:00 p.m. Chimney Rock State Park, south side of Hickory Nut Gorge.

- Lunch and pit stop; take shuttle busses to upper parking lot.
- Overview of historical mass wasting features; and bedrock structural framework
- Walking tour to examine salient features of the Henderson Gneiss, detached exfoliation slabs, overhangs, ductile and brittle rock fabrics.
- Hike along Hickory Nut Falls Trail to examine the 2014 rock fall, and large exfoliation faces and detached blocks on the way to Hickory Nut Falls (~2.2 km round trip).
- Depart Chimney Rock State Park for dinner at the Lake Lure Community Center. *Dinner provided by* ***Psylotech****.*

Depart Lake Lure Community Center for Flat Rock 8:30 p.m.

Bedrock Geological Overview

The 2022 Penrose Progressive Rock Failure Conference field trip takes place along the Blue Ridge Escarpment, the rugged transition zone between Blue Ridge and Piedmont physiographic provinces of the Southern Appalachian Mountains (Figure 1). Underlying bedrock is located entirely within the Tugaloo terrane of Hatcher (2002), an expansive body of highly deformed and metamorphosed sediments, volcanic rocks, and intrusions (Figures 1,2). The Tugaloo terrane in North Carolina averages 60 kilometers in width, is bisected by numerous faults, and currently resides within a stack of accreted terranes on the eastern edge of North America.

The Tugaloo terrane is one of five terranes in western North Carolina accreted to Mesoproterozoic continental crust and associated cover sequences of the southern Appalachian Mountains (Figure 3).

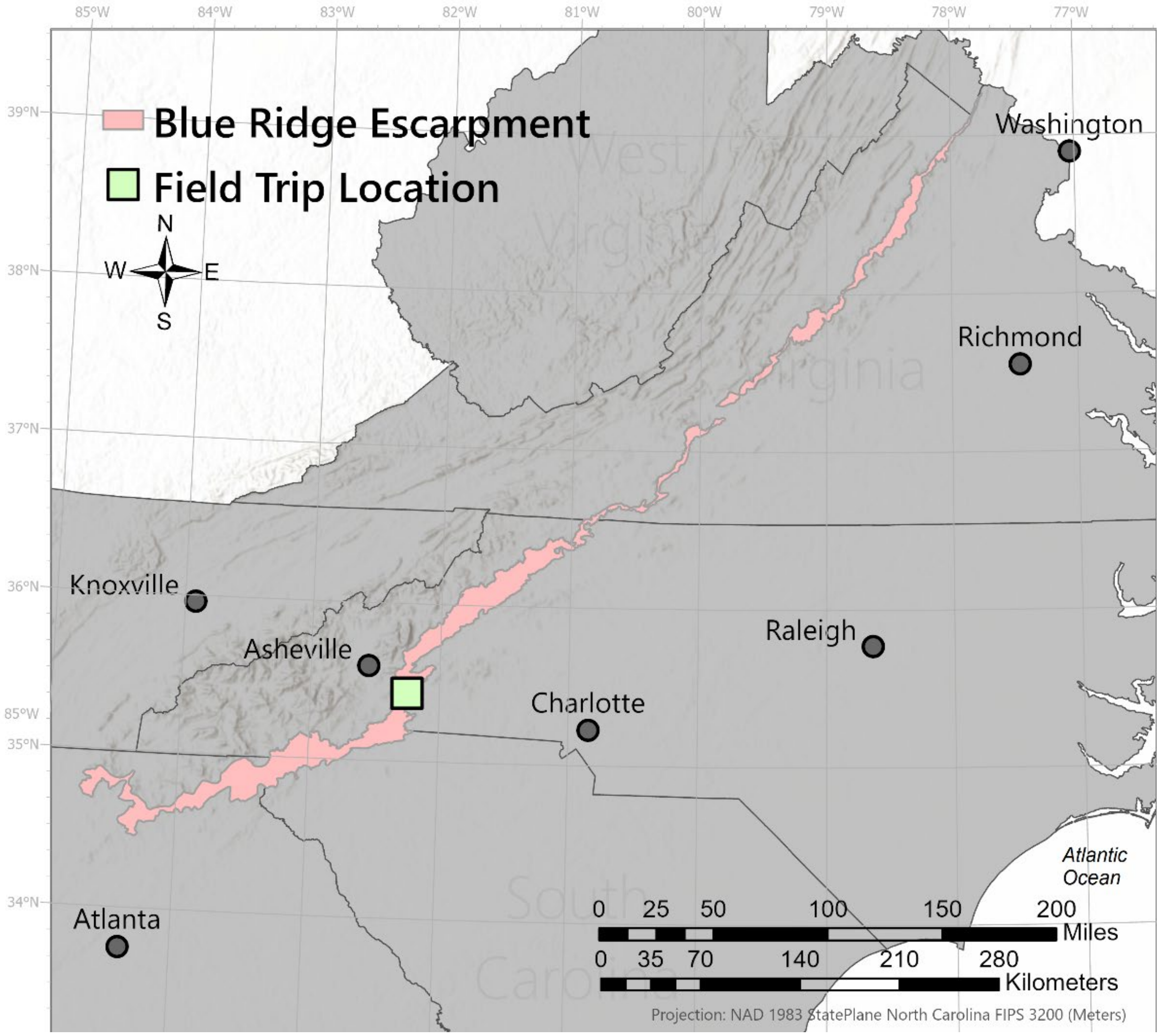


Figure 1. Location map of the field trip area showing the Blue Ridge Escarpment of the southern Appalachian Mountains. Figure by Yates McConnell, NCGS.

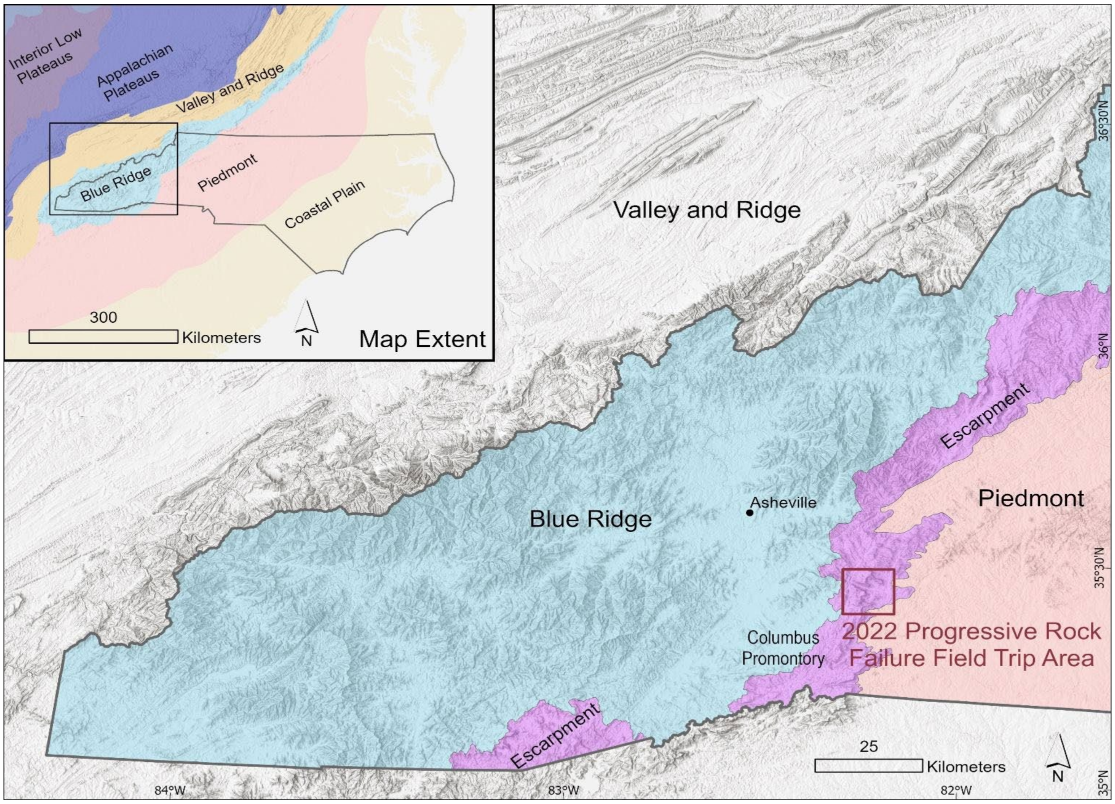


Figure 2. Physiographic Provinces of western North Carolina.

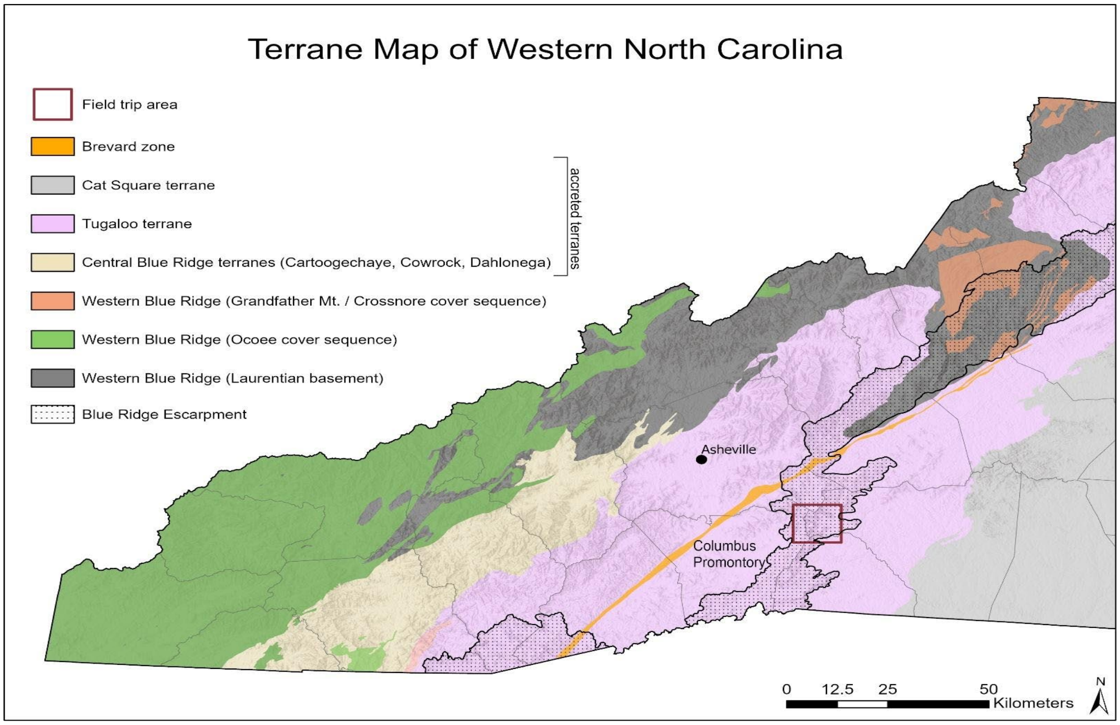
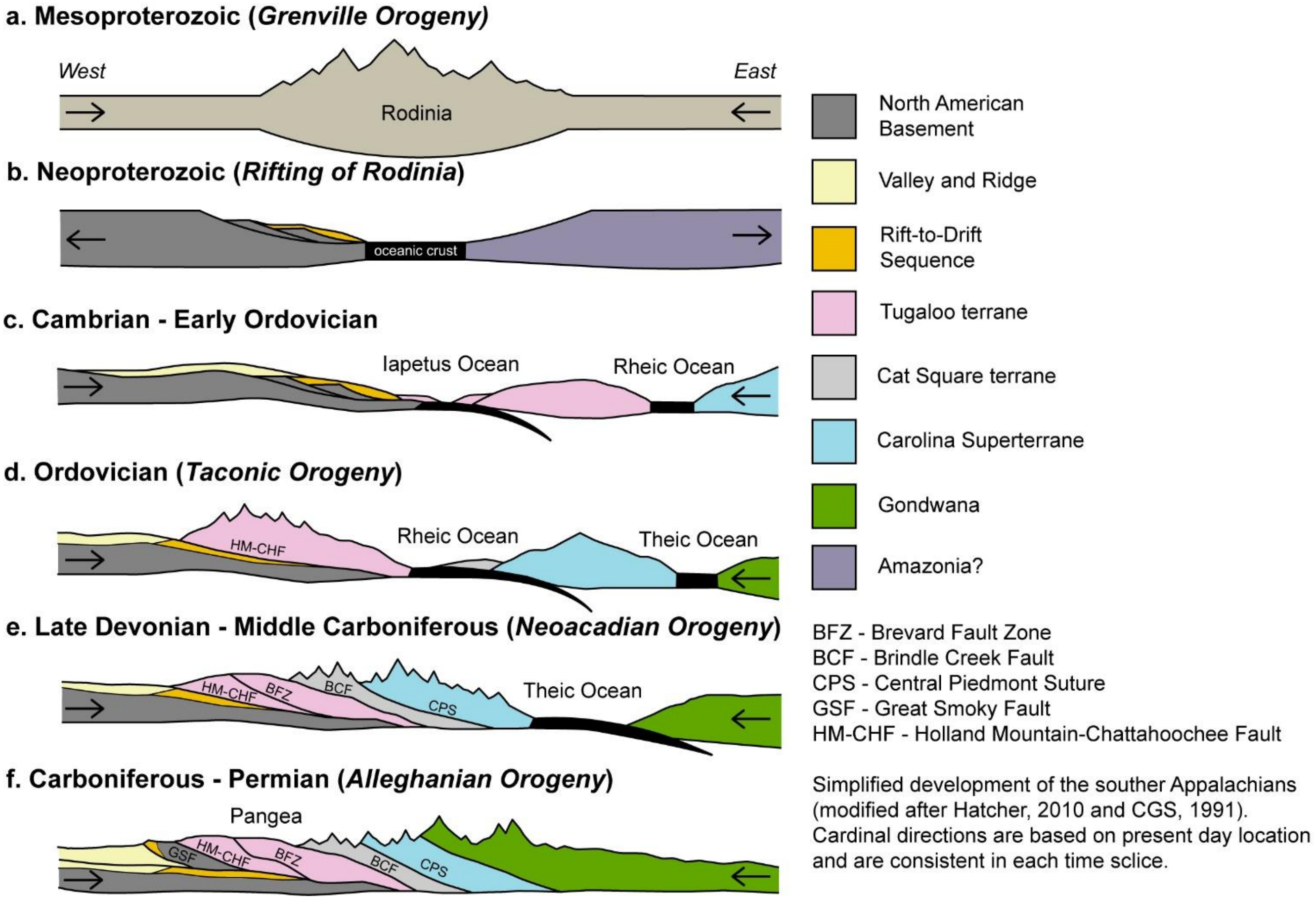


Figure 3. Terrane Map of western North Carolina (NCGS).

The primary components of these terranes are Neoproterozoic to Early Paleozoic sedimentary and volcanic rocks deposited primarily on oceanic or, locally, continental crust. These terranes were joined with ancient North America during three separate Paleozoic orogenic pulses: Taconic (460-440 Ma), NeoAcadian-Acadian (395-345 Ma), and Alleghanian (335-265 Ma). These orogenic events variably deformed, metamorphosed, faulted, and injected numerous plutonic bodies into the accreted terranes. Mesozoic extension and Cenozoic topographic rejuvenation altered the terranes to produce the landforms and features observed at the surface today.

The Mesoproterozoic gneisses

The oldest rocks in North Carolina are found within the western Blue Ridge province and are often referred to as “basement gneisses”. They are Mesoproterozoic in age and have undergone greenschist to granulite facies metamorphism. These gneisses are the product of multiple Mesoproterozoic collisional events during the Grenville Orogenic cycle (1350-1000 Ma) that culminated with the construction of the supercontinent Rodinia (Figure 3a) (Bartholomew and Lewis, 1984; Tollo et al., 2004).



BFZ - Brevard Fault Zone
BCF - Brindle Creek Fault
CPS - Central Piedmont Suture
GSF - Great Smoky Fault
HM-CHF - Holland Mountain-Chattahoochee Fault

Simplified development of the souther Appalachians (modified after Hatcher, 2010 and CGS, 1991). Cardinal directions are based on present day location and are consistent in each time sclice.

Figure 4. Simplified tectonic models of the southern Appalachian Mountains through time.

First rifting

There is a long hiatus in the geologic record of western North Carolina between the end of the Grenville Orogeny and the middle Neoproterozoic. The record picks up again when failed rifting of Rodinia approximately 750 million years ago created continental rift basins where volcanic and siliciclastic rocks were deposited. Bimodal igneous bodies associated with the rifting intruded both the surrounding Mesoproterozoic basement gneisses and rift basin deposits. These distinctive failed rift deposits and igneous bodies comprise the Crossnore Complex that underlies the region around Grandfather Mountain, NC. (Bryant and Reed, 1970; Rankin et al., 1973; Bartholomew and Lewis, 1984) (Figure 3).

Successful rifting of Rodinia approximately 565 Mya created continental basins on the newly-formed Laurentian margin as well as the new Iapetus Ocean basin (Figure 3b) (Thomas, 1977; Aleinikoff et al., 1995). Large amounts of sediments were deposited in these basins. Siliciclastic rocks deposited on top of Mesoproterozoic basement gneisses within continental basins are a key component of the current Western Blue Ridge province (Figure 3).

Offshore of the Laurentian margin, mixed siliciclastic and mafic volcanic rocks were deposited on new oceanic crust (Figures 4c, 5). These deposits are the primary components of the Central Blue Ridge and Eastern Blue Ridge/Western Piedmont terranes, including the Tugaloo terrane.

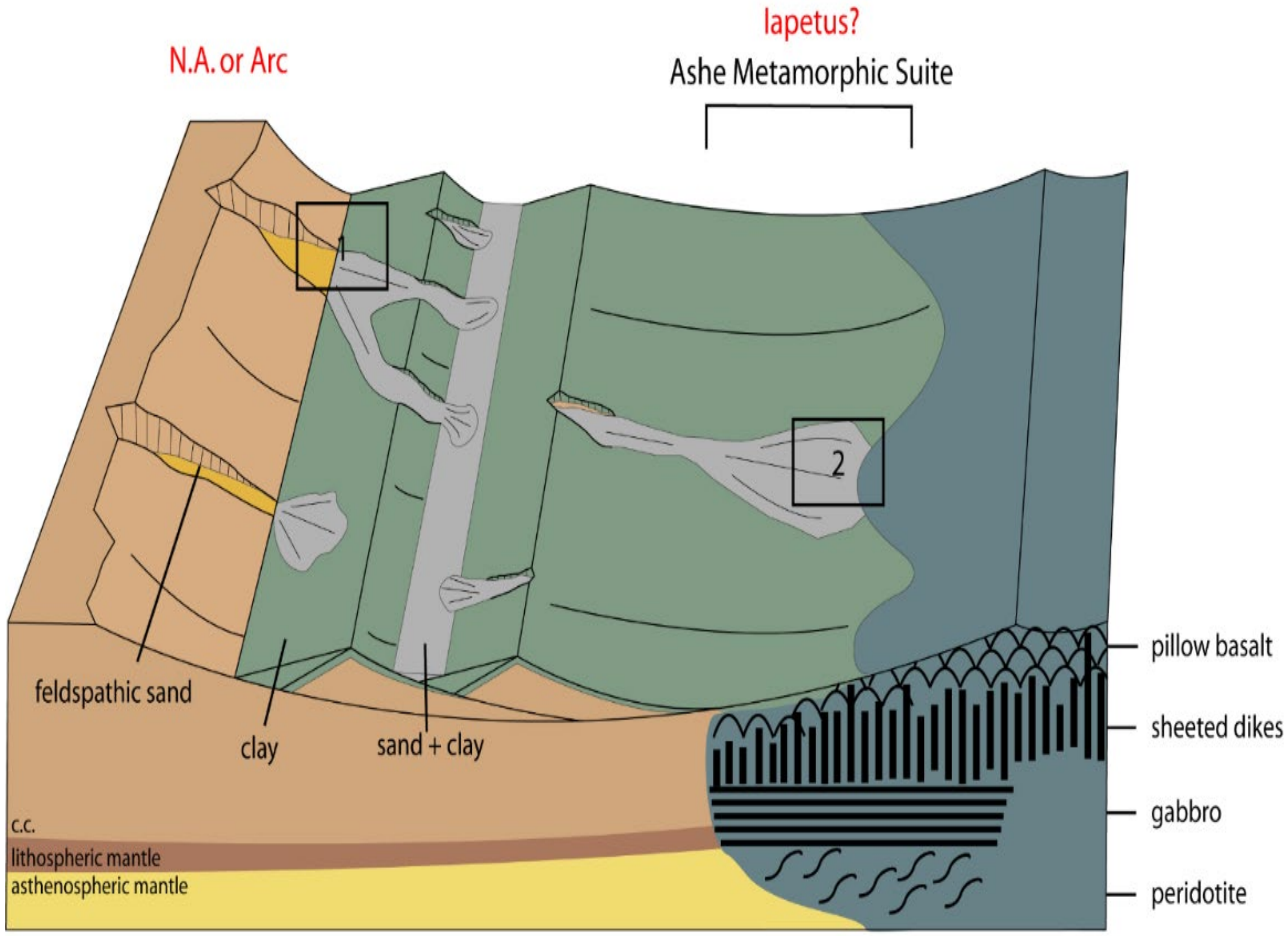


Figure 5. Depositional setting of Neoproterozoic-Cambrian rocks in continental basins (Box 1) and Neoproterozoic to Ordovician rocks in the Iapetus ocean basin (Box 2).

Active rifting along the Laurentian eastern margin (present geography) transitioned to a passive drift stage in the early Cambrian (Hatcher, 2006).

Paleozoic Mountain Building

The Taconic Orogeny, first of three Paleozoic orogenic events affecting the area, began in the Early Ordovician Period (Figure 3d). Sedimentary rocks and some underlying oceanic crust of the Central Blue Ridge and Tugaloo terranes were metamorphosed and accreted to ancient North America. This event produced upper amphibolite to granulite facies metamorphism and several large plutonic bodies. The largest of these is the granodioritic Henderson Gneiss that makes up the walls of Hickory Nut Gorge, the site of the Progressive Rock Failure Conference field trip.

The Neoacadian Orogeny affected these rocks beginning in the Silurian Period as the Perigondwanan-affinity Carolina Superterrane docked with eastern North America (Figure 3e). This collision produced regional deformation and upper amphibolite to granulite facies metamorphism. It formed the dominant gently dipping NE-SW trending foliation and folding preserved in the rocks of Hickory Nut Gorge as well as several large thrust sheets within the Tugaloo terrane. Hickory Nut Gorge is possibly the best place to view the internal stratigraphy of the Tugaloo terrane (Back Cover Map). The Henderson Gneiss makes up the Tumblebug thrust sheet, the structurally lowest package in Hickory Nut Gorge (Davis, 1993; Davis and Yanigahara, 1993). Many of the surrounding mountains (Sugarloaf, Rumbling Bald, Shumont) are capped by metasediments and metavolcanics of the Poor Mountain Formation that was thrust over the Henderson Gneiss along the Sugarloaf fault and survive as erosional klippes.

Paleozoic mountain building culminated in the Permian Period with the Alleghanian Orogeny, in which Gondwana collided with Laurentia to help form Pangea (Figure 3f). This event served to transport rocks of the Piedmont and Blue Ridge over 350 kilometers northwestward over platform sedimentary rocks of North America (Hatcher et al., 2007).

The northeast-trending Brevard fault zone separates the Tugaloo terrane into western and eastern portions (Figure 2). It is a zone of strongly deformed rocks active during both the Neoacadian and Alleghanian orogenies and is one of the major structural features in the southern Appalachian Orogen. Brevard zone assemblages include mylonite, phyllite, graphitic schist, metasandstone, and marble. Interestingly, peak metamorphic conditions northwest of the Brevard zone in NC were reached during Taconic orogenesis (Moecher et al., 2011) while those southeast of the Brevard zone were reached during Neoacadian orogenesis (Hatcher, 2010). High temperature, ductile oblique and dextral strike-slip motion took place along the Brevard zone during Neoacadian orogenesis. The Brevard zone was reactivated during Alleghanian orogenesis by high temperature strike-slip motion and late reverse brittle motion along the narrow Rosman fault at the northwestern edge of the zone.

Second Rifting

Rifting of Pangea to form the current North American and African continents produced numerous basins in central and eastern North Carolina beginning in the Triassic Period. Mesozoic rifting also produced mafic magmatism in North Carolina (Ragland, 1991). Diabase dikes are distributed over a wide area with the western-most exposure found to date being just a few kilometers southeast of the field trip locale, with many more being found in the central part of North Carolina. The rifting also created systematic joint sets oriented NW-SE that are subparallel to many of the diabase dikes (Figure 6). There are also prominent lineaments that cross-cut regional Paleozoic fabrics. Immediately south of the field trip area, Garihan and Ranson (1993) identified a series of ENE-WSW brittle fractures and joints interpreted to be related to Mesozoic extension. To the north, a localized E-W trending joint set is prominent within two of the major E-W trending lineaments that are attributed to post orogenic doming of the southern Appalachian Mountains (Hill and Stewart, 2012). To the south, in Polk County, there are also E-W-striking, lineament parallel fracture sets that are likely Cenozoic in age, and certainly post-orogenic (Wooten et al., 2022).

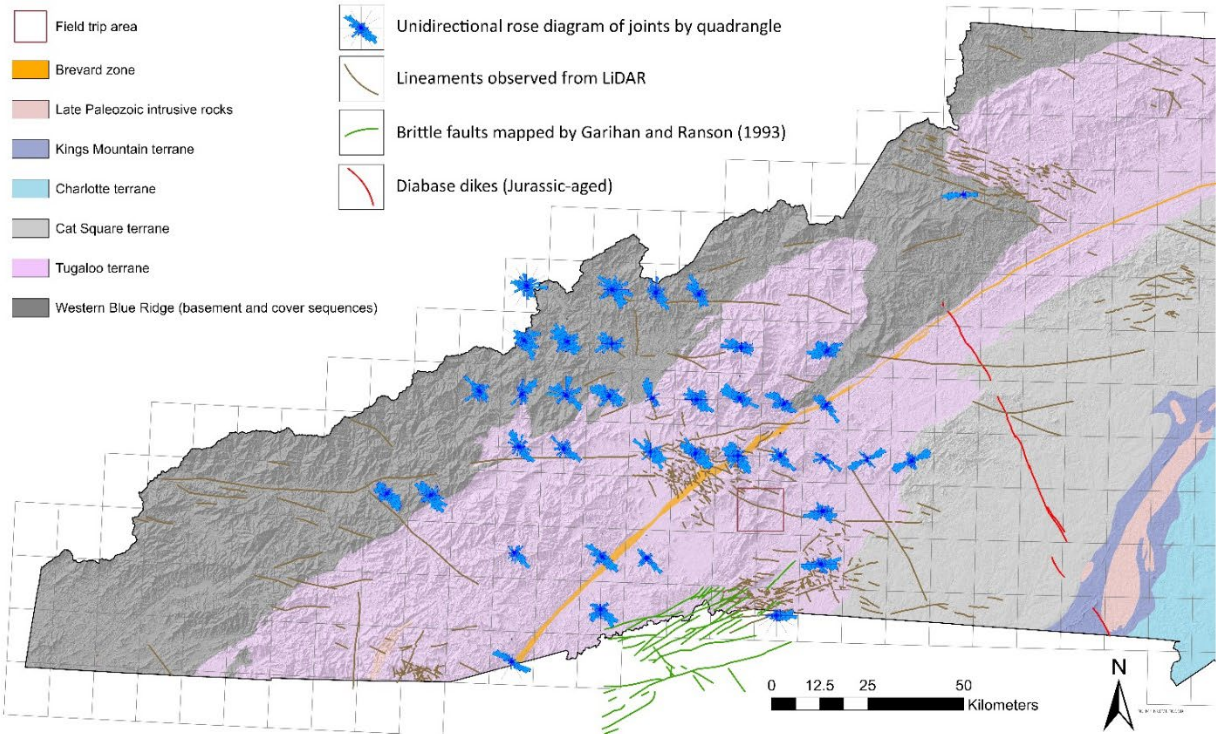


Figure 6. Select post-Paleozoic features in western North Carolina.

The Mesozoic Era also likely saw the formation of the Blue Ridge escarpment. Several hypotheses have been proposed for the origin of the feature. One interpretation is that it formed in response to asymmetrical rift-flank uplift on the western margin of the Triassic basins and has migrated westward during the Cenozoic in response to erosion along high energy streams flowing eastward to the Atlantic Ocean (Spotilla et al., 2004). Regardless of its origin, the landform is a significant geologic feature. High relief, steep slopes, and the dissected nature of the escarpment, make it susceptible to many types of mass wasting. Regional and local scale orographic forcing of rainfall along the BRE also contributes to a high frequency of debris flows. This effect is evidenced by the generally greater rainfall totals along the BRE as compared to the surrounding regions for the major debris flow producing tropical cyclones of July 15-6, 1916 (Scott 1972) and August 10-17, 1940 (US Geological Survey, 1949).

Ongoing research in North Carolina reveals a pattern of recurring landslide events within structurally controlled topographic reentrants into the BRE (Bauer et al., 2019; Gillon et al. 2009; Hill, 2018; Hill and Stewart, 2018; Wooten et al., 2019a, Wooten et al, 2022).

Another intriguing element of the region is evidence for Cenozoic topographic rejuvenation. Although the mechanism for such uplift is unclear, the presence of retreating knickpoints in the landscape, increased Miocene sedimentation in the Atlantic and Gulf of Mexico basins, and regional drainage patterns suggest that modern topographic relief in the area increased substantially during the Cenozoic Era (Hack, 1982; Gallen et al., 2013; Liu, 2014; Hill, 2018).

Hickory Nut Gorge

Hickory Nut Gorge is a WNW-trending trench lineament that transects the Columbus Promontory of the Blue Ridge Escarpment (Figure 7). WNW-ESE trending topographic lineaments and associated subparallel fracture (joint) sets have been related to post-orogenic, possibly Cenozoic, brittle cross-faulting in the Mills Gap fault zone ~18 km to the WNW (Figure 6) near Asheville (Cattanach et al., 2014, Wooten et al., 2010). The WNW-ESE-trending Mills Gap fault zone and associated topographic lineaments project into the Hickory Nut Gorge area. One objective of an ongoing research collaboration between Western Carolina University and the NCGS is to better understand the controls these brittle cross-structures and earlier ductile bedrock structures have on rock slope failures and debris flows in Hickory Nut Gorge.

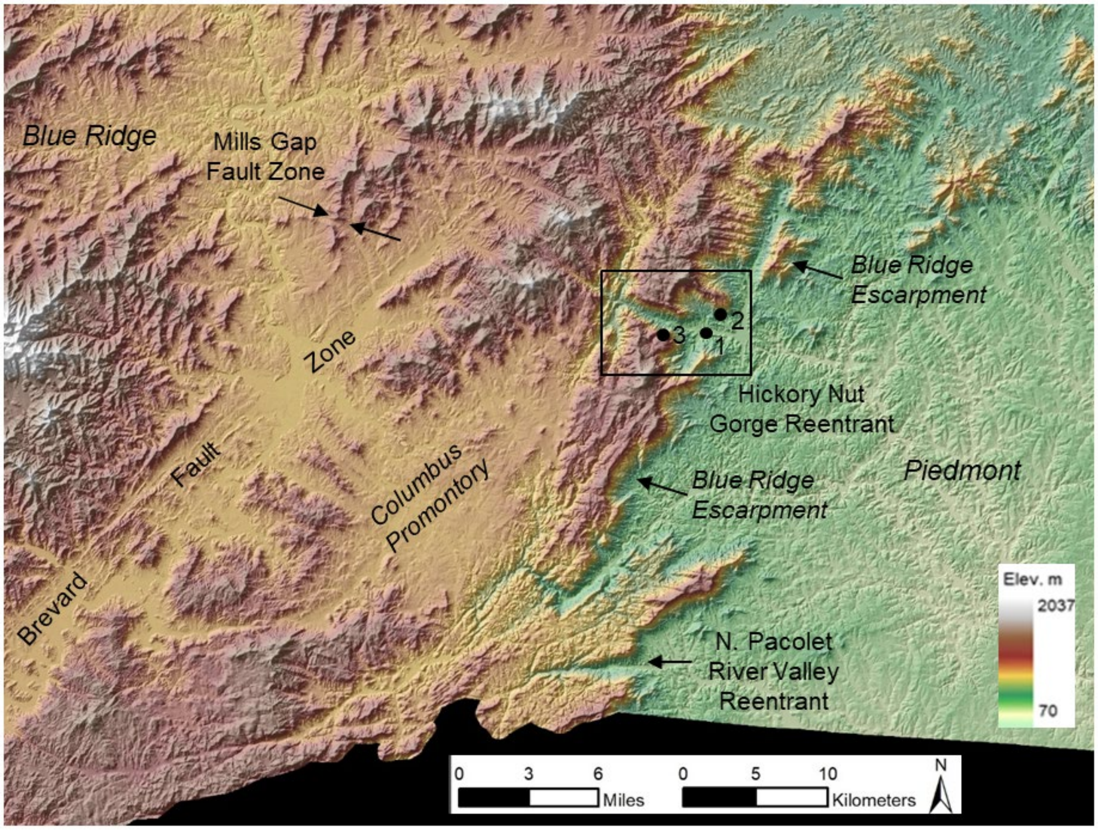


Figure 7. Relief map color coded by elevation of the Columbus Promontory area of the Blue Ridge Escarpment showing the numbered stop locations in the field trip area in Hickory Nut Gorge and other relevant features. Map base is a 6m pixel resolution lidar digital elevation model.

Brittle, post-orogenic cross structures associated with slope instability have been identified elsewhere in western North Carolina. Gillon et al. (2009) mapped a zone of rock slope instability in Watauga County, ~100 km northeast of Hickory Nut Gorge, where Paleozoic ductile faults are overprinted by high angle ESE-WNW fractures and brittle faults. This zone aligns with the Deep Gap reentrant into the Blue Ridge Escarpment, a location where nearly 600 of the >2,000 landslides and debris flows triggered by an August 1940 tropical cyclone are concentrated (Witt and Wooten, 2018; Wooten et al. 2008). Hill (2018) later mapped this zone as the Cenozoic Boone fault, a seismically active, high-angle ESE-striking fault zone that traces directly in line with the Deep Gap reentrant (Hill and Stewart, 2018). Wooten et al, (2022) identified a zone of concentrated landslide activity within the fracture controlled, E-W trending North Pacolet River Valley in Polk County, ~25 km south-southwest of Hickory Nut Gorge (Figure 7).

Some WNW-ESE brittle cross-structures are also linked to seismicity in the region. Reinbold and Johnson (1987) describe shaking events near Rumbling Bald Mountain in Hickory Nut Gorge that suggest seismically induced rockfall, and Soplata (2016) postulates a coseismic origin for massive rockfall deposits mapped in detail in that area of Hickory Nut Gorge. Along the WNW lineament swarm trend from Hickory Nut Gorge, the Mills Gap fault zone is in the general epicentral area of the 1916 M 5.2 Skyland earthquake (Stover and Coffman, 1993; Bechtel, et al., 2006). The seismically active, ESE-trending lineament that contains the Boone fault that traces direction in line with the Deep Gap reentrant in Watauga County (Hill, 2018) also houses the estimated epicenter of the magnitude 5.0 earthquake in Wilkes County (Stover and Coffman, 1993; Bechtel, et al., 2006). The recently identified and mapped ESE-striking Little River Fault in Allegheny County, North Carolina produced ground rupture from the Mw 5.1 Sparta earthquake (Hill, et al., 2020, Figueiredo, P.F., et al., 2022)

Hickory Nut Gorge which includes Chimney Rock State Park, and the Village of Chimney Rock, has a long record of historical landslide events documented in the NCGS landslide geodatabase including those in 1916, 1994, 1996, 2008, 2012, 2013, and 2018. Extensive rock boulder and block footslope deposits show that steep gorge walls have been prone to Quaternary debris flows and debris slides, and rock falls (Soplata, 2016; Wooten et al., 2017). Cliffs in the Gorge walls formed along the WNW-ESE fracture set common in the area. Massive blocks of Henderson Gneiss detach along these and other fracture surfaces, contributing large boulders to the hillslope and valley deposits below. Numerous debris flows have also deposited block- and boulder-sized debris into the Rocky Broad River and its tributaries (Figure 8).

Geomorphological Overview

Distinctly cruciform Hickory Nut Gorge is the result of structurally-controlled incision into the margin of the Blue Ridge Upland by the Rocky Broad River, a tributary of the Broad-Santee River system (Figures 8, 9). Comparison to other Blue Ridge Escarpment reentrants suggests development of Hickory Nut Gorge resulted from capture of the Rocky Broad River from the elevated, Gulf of Mexico-draining French Broad River system by a headwardly eroding tributary of the lower elevation, Atlantic-draining Broad River (Figure 9) (Prince et al., 2010). Connection of the elevated Rocky Broad headwaters to a near-field Atlantic base level ~300 m below its pre-capture valley would have initiated a pulse of rapid incision in the integrated drainage network. This incision pulse would have been characterized by knickzones migrating upstream from the capture point and rapid entrenchment of the capturing stream within the Escarpment zone due to significantly increased discharge over its steep gradient. Despite the shift in drainage basin, channel elevations, and surrounding topography, the planform geometry of the modern drainage network is interpreted to inherit significant elements of the pre-capture geometry. Pre-capture geometry, in turn, likely promoted capture due to the intersecting orientations of drainage-controlling lineaments. Timing of the inferred capture event, along with the pace of post-capture channel adjustment and gorge development, are unknown.

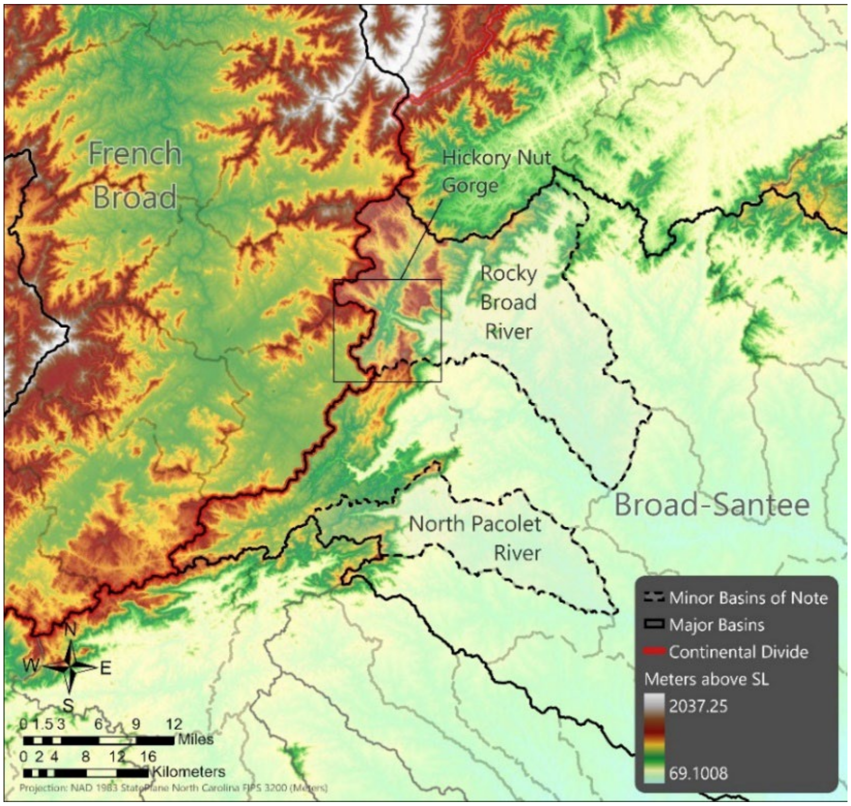


Figure 8. Map showing the geomorphological setting of the field trip area with respect to the Eastern Continental Divide, and major and minor river basins. Map base is a lidar digital elevation model color coded by elevation. Figure by Yates McConnell, NCGS.

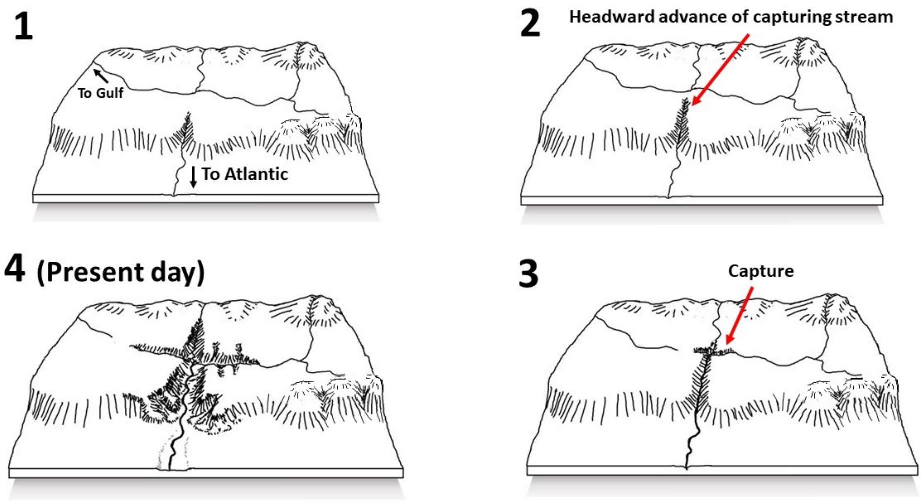


Figure 9. Conceptual model of Hickory Nut Gorge development following capture of the ancestral, Gulf of Mexico-draining Rocky Broad River. **1**. Headward erosion of an Atlantic-draining Broad River erodes into the Blue Ridge Escarpment, utilizing a topographic lineament. **2**. Headward advance of the Atlantic headwater approaches the Gulf-draining ancestral Rocky Broad River. **3**. Capture occurs when the Atlantic headwater erodes into and intersects the ancestral Rocky Broad, diverting it off the steep Blue Ridge Escarpment to the Piedmont, ~300 m below. Rapid incision begins. **4**. The present-day gorge system reflects ongoing incision and retreat of gorge walls as upland topography within the captured basin is consumed and eroded to Piedmont elevations. Note inheritance of pre-capture drainage pattern in the modern gorge due to strong structural control of river networks.

Today, the Hickory Nut Gorge-Rocky Broad River landscape remains in a state of transient adjustment following the inferred capture event. Knickzones continue to propagate upstream through the Rocky Broad channel network, which maintains unincised, “relict” headwaters reaches which are yet to adjust to the new Atlantic base level. Incised areas, most notably Hickory Nut Gorge, host over steepened slopes where frequent mass wasting events supply sediment to the energized fluvial network. These dynamic slopes reflect ongoing adjustment of the Rocky Broad drainage area towards an elevation and topography consistent with the rest of the Atlantic-draining Piedmont landscape. Mass wasting events can thus be regarded as an expression of locally accelerated “consumption” of elevated Blue Ridge topography following the Rocky Broad capture event.

A regionally significant aspect of the stream capture interpretation is that gorge development does not require focused topographic uplift or movement on an active fault structure. Potential energy to drive Rocky Broad incision existed due to the elevation difference between the Blue Ridge Upland and Piedmont; headward stream erosion along the existing steep boundary between the two landscapes accessed this potential energy through capture events (Prince et al., 2010). Capture events here and elsewhere along the Escarpment were (and are) promoted by the orthogonal intersection of drainage-controlling lineaments, which allow minor headward erosion by low-order Atlantic streams to capture large, Escarpment-parallel Upland streams. Intermittent capture events are thus able to produce localized landscapes (*e.g.*, Hickory Nut Gorge) which evolve under atypically extreme boundary conditions not seen throughout the area.

Field Trip Stops

Stop 1: Hickory Nut Gorge Scenic Overview. Arrive 8:15 a.m. Depart: 9:00 a.m.

Location: Town of Lake Lure Municipal Lot off U.S. 64/Alt. 74 Lat. 35.435203° Long.-82.229817°

Purpose: Scenic overview of Hickory Nut Gorge

Field Trip Leaders: Bart Cattanach – North Carolina Geological Survey; Philip Prince – Appalachian Landslide Consultants.

- Overview of local bedrock geology and tectonics – Bart Cattanach
- Overview of geomorphic features and evolution the Blue Ridge Escarpment, topography, and stream capture – Philip Prince

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Stop 2: **Rumbling Bald** Arrive: 9:15 a.m. Depart: 11:15 a.m.

Location: Rumbling Bald rock climbing and bouldering access area, north side of Hickory Nut Gorge.

Leaders: David M. Korte, Bart L. Cattanach, Jesse S. Hill, North Carolina Geological Survey

Purpose:

- Snacks and water, pit stop in the parking area
- Hiking tour of debris deposits, block fields and cliff source areas (~2.4 km round trip).
    - Block origin and timing?
    - Cereal Buttress breakup (~100 m wide)

Introduction

Home to Peregrine falcons and rock climbers alike, Rumbling Bald Mountain (RB) is a WNW-ESE-trending promontory parallel to the Hickory Nut Gorge (HNG) (Figure 2-1). Anecdotal accounts claim it is named for "rumbling" noises that emanated from the mountain after an 1874 earthquake. It is likely the reported sound was caused by large rockfalls (Reinbold and Johnson, 1987; Soplata, 2016). The promontory of RB forms a thin spine along the western part of the ridge, then widens into a rounded peak at 920m. HNG at this location has approximately 600m of relief from the top of RB to the western edge of Lake Lure, approximately 2.5 km to the south. Henderson Gneiss (Ohg) makes up the cliffs that give the HNG its dramatic appearance. Where Henderson Gneiss is the rock type, the mountaintop is rounded into a "Sugarloaf" type shape (e.g., Owen, 2014), as opposed to a sharp peak where it is capped by the Poor Mountain formation garnet-mica schist and quartzite (Opms) (Figures 2-2 and 2-3). This pattern can be found elsewhere near the HNG, where the Ohg forms lower relief mountain peaks above steep exfoliation cliffs. Cereal Buttress is found on the south-facing side of RB, and has evidence for large rockfall events, both historic and prehistoric in age (Figure 2-4).

Geologic background, mass wasting, and the development of Rumbling Bald

To understand the landscape evolution of RB, we list the influential structures at the site in order of genesis. This area is part of the western Inner Piedmont portion of the Tugaloo terrane, which includes metamorphosed sedimentary and igneous rocks. The granodioritic protolith of the Henderson Gneiss intruded Neoproterozoic to Early Ordovician Tallulah Falls metasedimentary rocks at approximately 448 Ma (Moecher et al., 2011). These units were then intruded by a granitic body of the Table Rock Plutonic Suite (SOgg) around 438 Ma (Odom and Russel, 1975). These rocks experienced intense folding, faulting, and metamorphism during Paleozoic orogenesis. The main foliation of the Henderson Gneiss is interpreted to be the result of upper amphibolite facies Acadian-Neoacadian (390-340 Ma) metamorphism during accretion to Laurentia as part of a series of stacked thrust sheets that comprise much of the Columbus Promontory (Davis, 1993; Merschat and others 2018). The rocks at RB and Chimney Rock State Park are all within the Tumblebug thrust sheet, except for the small klippes of the overriding Sugarloaf thrust sheet (Figures 2-2 and 2-3). The shallow dipping Neoacadian-related foliation is the first important outcrop-scale fabric at RB.

Post-Paleozoic orthogonal, sub-vertical joints comprise the second outcrop scale fabric at RB. The timing of formation of these features is poorly constrained but they are expressed mainly as WNW-ESE and NNE-SSW sets (e.g., Garihan et al., 1993; Hill, 2018; Wooten et al., 2022) in the HNG area. These joints strike parallel and perpendicular to the HNG and define the rectilinear drainage networks of the field trip area and parts of Rutherford, Henderson, Polk, and Buncombe counties that contain granitic gneisses.

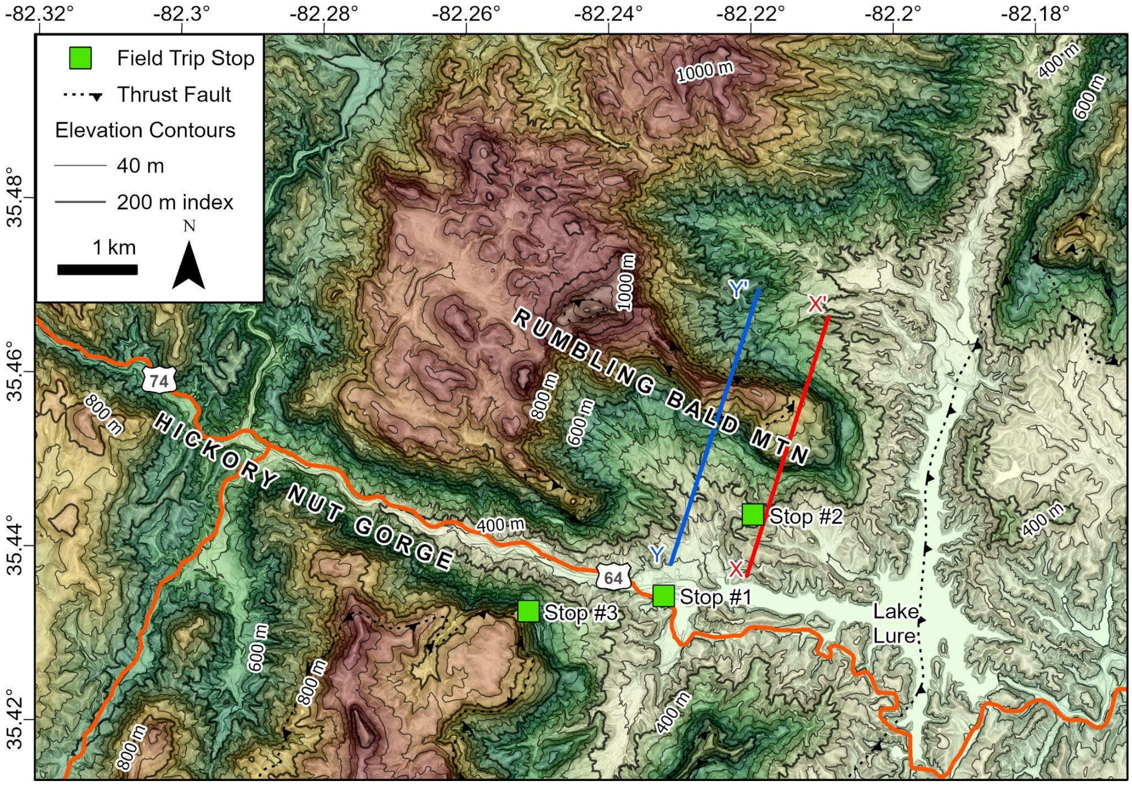

Figure 2-1. Map of field trip area. Note the WNW-ESE and NNE-SSW patterns of the landscape of the Hickory Nut Gorge and Rumbling Bald Mountain. Topographic profile from lines X-X' and Y-Y' shown in Figure 2-2. Thrust fault contact digitized from Davis and Yanigahara, 1993. Teeth are on the hanging wall of the fault.

The youngest major fabric element influencing RB is a set of exfoliation joints. Peeling away like the layers of an onion, these tend to form perpendicular to surface aspect and work to detach large sheets and blocks of bedrock. In places the exfoliation joints are parallel and sub-parallel to the post-orogenic joints and can be difficult to distinguish in outcrop alone.

The metamorphic foliation, thrust faults, post-orogenic joints, and the exfoliation joints combine to drive the geomorphology and mass-wasting of RB and throughout HNG. The exfoliation joints and the regional and local post-orogenic joints combine to form large blocks, often limited in size by intersections with sub-horizontal foliation, leading to overhangs on the cliff face. The upward propagation of exfoliation sheets being limited by intersecting discontinuities occurs in large granitic vertical faces elsewhere in western North Carolina, and very large exposures such as El Capitan in Yosemite National Park (Stock et al., 2012).

Rockfalls account for only 1% (66/5932) of the slope movements cataloged in the North Carolina Geological Survey landslide geodatabase (https://www.landslidesNCGS.org) but the majority of the rockfalls occur in gneisses (Figure 2-5). Importantly, the NCGS landslide database is a work in progress, as we have not performed detailed landslide mapping in many areas that contain steep cliffs of metamorphosed sandstones and other quartz-rich rocks, where large block talus fields sit below steep cliffs. Perhaps the failure mechanisms at RB could apply to other locations with granitic gneisses where rockfall also is a significant process, but more work is needed to understand the varied picture of rockfall hazards in western North Carolina.

The intersecting structures provide a source area for large rockfalls, but it is noteworthy that the talus fields below contain semi-equidimensional blocks rather than large sheets (Figures 2-6 and 2-7). This may indicate that the mass-wasting of the cliff face occurs as blocks and not slabs, or that any large slab that falls breaks into blocks upon impact before disbursing into the talus field below. Although there are fresh-looking sides to some of the boulders in the talus field and parts of the cliff that appear to have failed recently, we have not matched any of the boulders to their source with any level of confidence beyond speculation. The mismatch between foliation in outcrop and in the boulders below indicate that there has been toppling, rolling, and sliding of many of the large blocks (Figure 2-7).

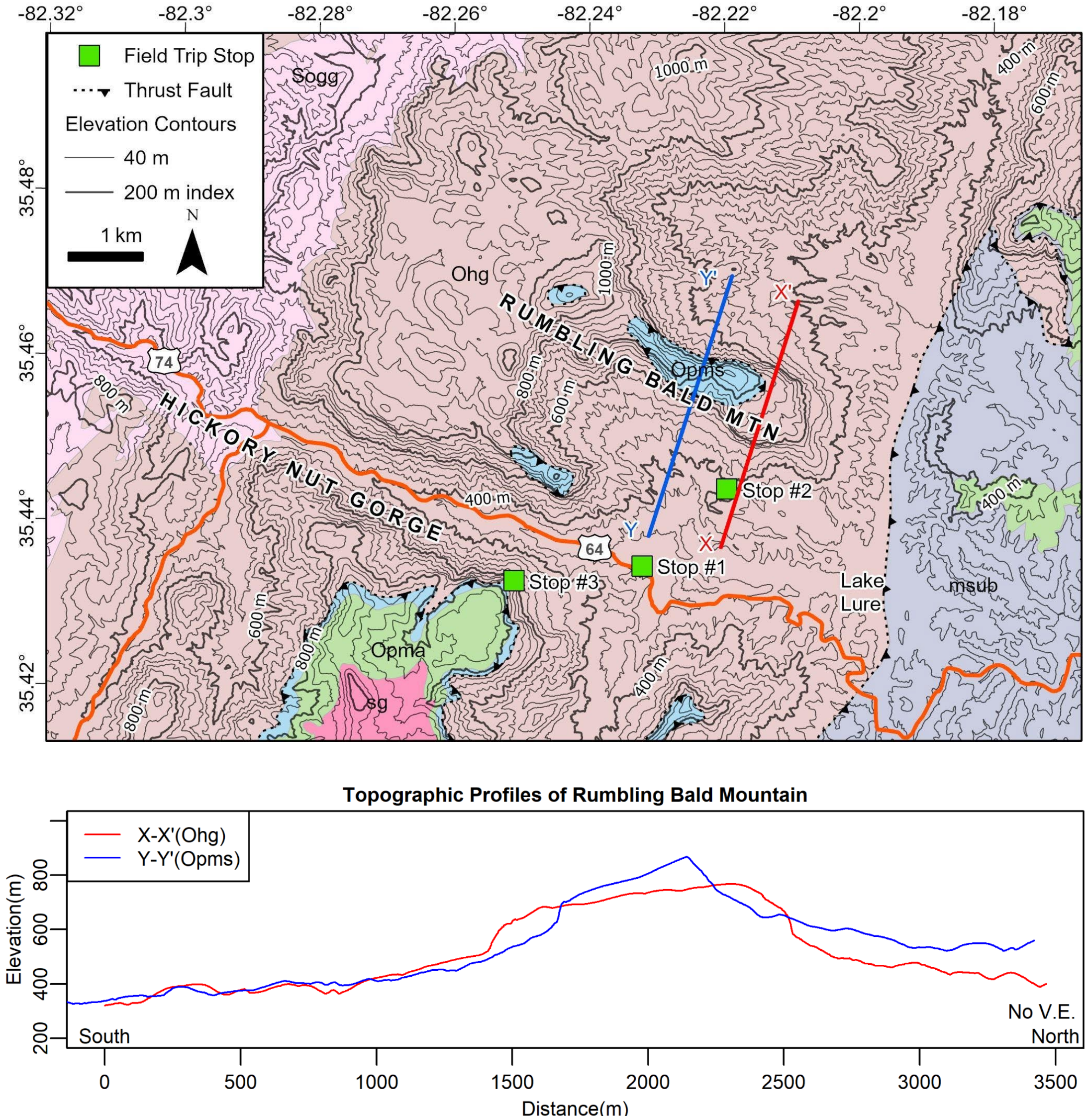

Figure 2-2. Top. Bedrock map of field trip area with same spatial extent as Figure 2-1. Bedrock units and fault contacts digitized from Davis and Yanigahara, 1993. Ohg = Henderson Gneiss; SOgg = granitic gneiss; Opms = Poor Mountain garnet-mica schist and quartzite; Opma = Poor Mtn amphibolite and amphibolite gneiss; Sg = Sugarloaf Gneiss; Msub = Upper Mill Spring migmatitic biotite gneiss. Note the structural klippes formed where the Sugarloaf thrust fault has moved Poor Mountain Fm (Opms) above the Henderson Gneiss (Ohg). **Bottom.** South-to-North topographic profiles across Rumbling Bald Mountain. Note the sugarloaf shape where it crosses the Ohg in contrast to the steep peak where it crosses the Opms unit.

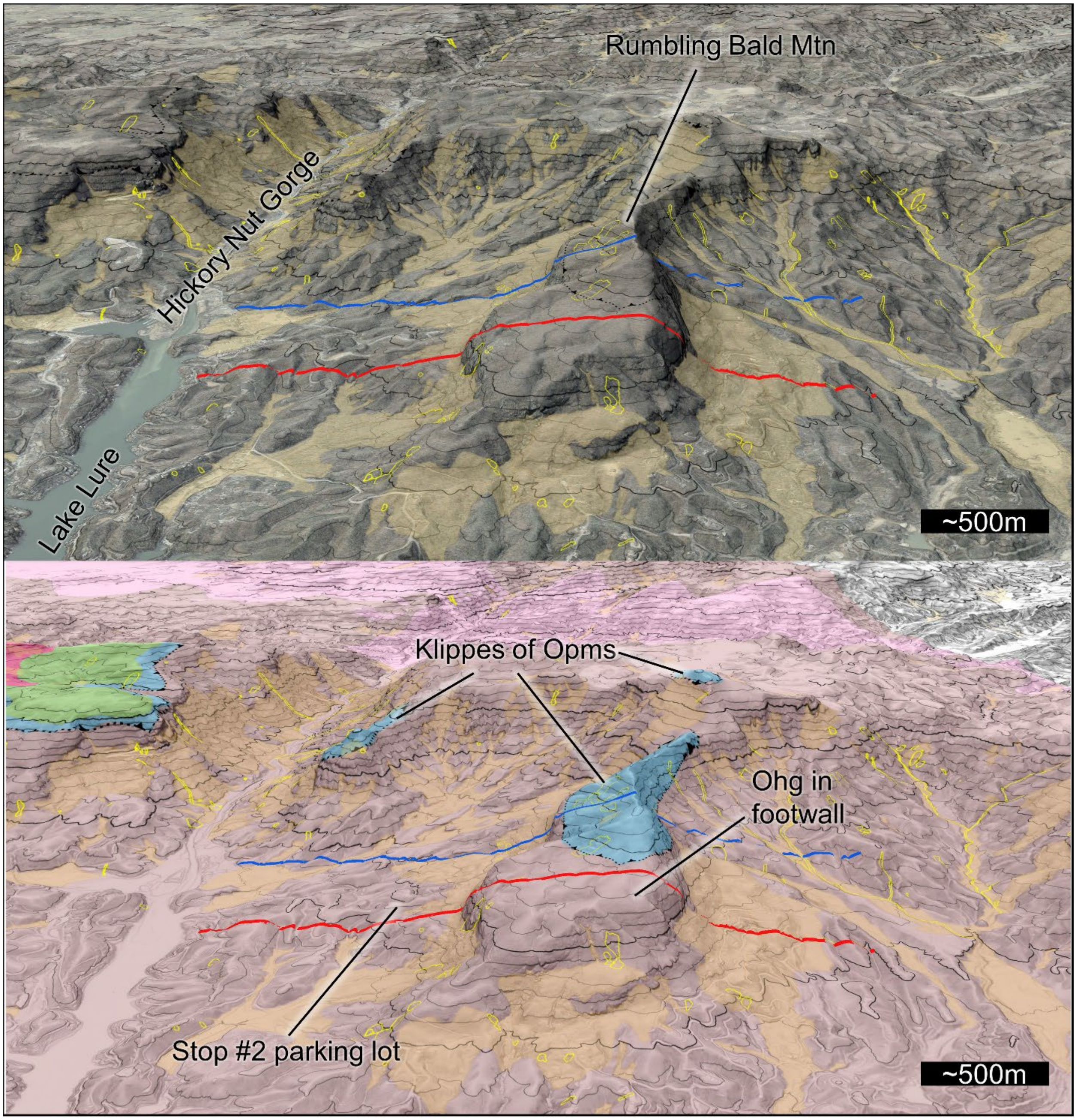

Figure 2-3. Top. 3D view looking WNW up the Hickory Nut Gorge and at Rumbling Bald Mountain. Red and Blue lines are profile lines shown in Figure 2-2. Yellow outlines are landslides and rockfalls, and orange polygons are landslide/rockfall deposits. Topographic contours are at 40m intervals. **Bottom.** Same view as above with the bedrock map draped over the topography. Bedrock units digitized from Davis and Yanigahara, 1993.

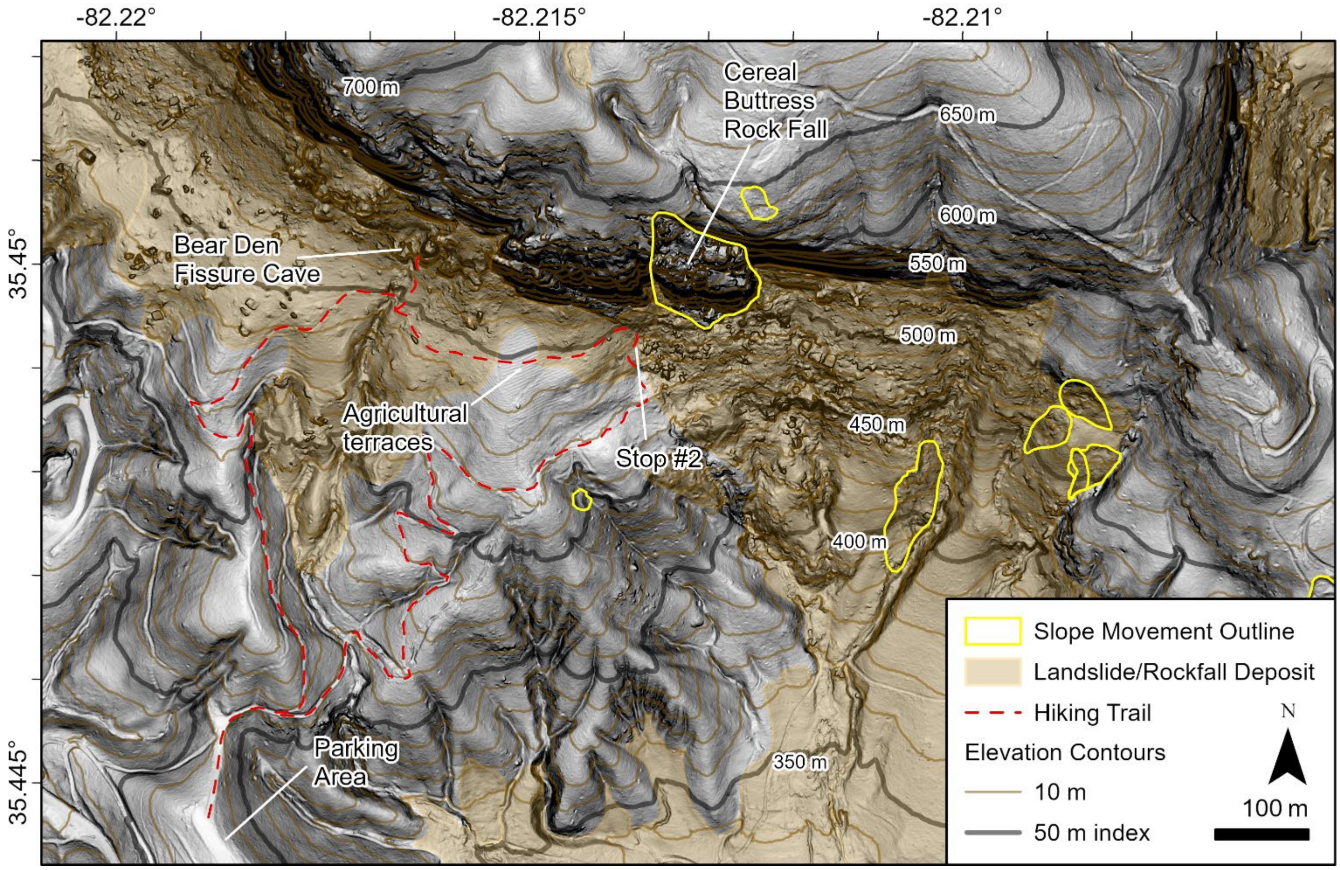

Figure 2-4. Map showing hiking trail used to gain access to the Cereal Buttress and Bear Den fissure cave.

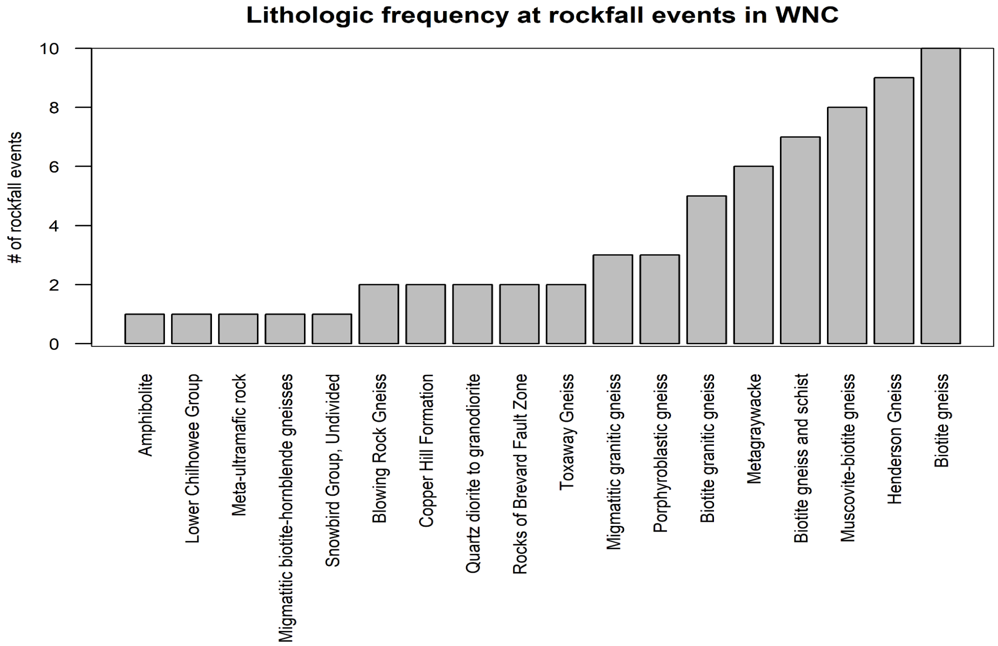

Figure 2-5. Histogram of rock types extracted from the 1:500k statewide bedrock map of North Carolina (NCGS, 1985) at rockfall locations catalogued in the North Carolina Geological Survey landslide geodatabase (n=66) (www.landslidesNCGS.org). Note how the majority of rockfalls occur in gneisses in this dataset.

Cereal Buttress and the progressive failure of Rumbling Bald

Progressive failure at RB can be roughly split into three stages: early, middle, and late (Figure 2-6A). Within WNW-ESE-trending RB, there is a south-facing promontory that exemplifies these stages of progressive failure. Above the hiking trail we will take to get to the site is the earliest stage of this process. Here there is no evidence of large rockfall in the outcrop, nor is there any extensive talus field below. Found immediately to the east, the Cereal Buttress rockslide is a detached block measuring approximately 720,000 m^3 and is one of the major landforms of RB. This constitutes the middle stage of failure. The Cereal Buttress rockslide has a back detachment that aligns with the WNW-ESE fracture set, with lateral detachment surfaces defined by the NNE-SSW set. Although there is no large overhang above the main rockslide, there are overhanging ledges within the main block that are the intersections of joints and foliation. The slide is highly disaggregated and serves as the source area for the large blocks we will see on this field trip. There is a well-developed talus field with many fracture-bounded blocks of varying depositional ages, as evidenced by the different degrees of weathering, rounding, and lichen and other vegetation. Further to the east of the Cereal Buttress slide, the late stage of failure shows a complete removal of material from the cliff face and a large talus field below that can experience a remobilization in the form of debris slides and debris flows (Figure 4). The talus fields around RB grade into large debris fans, some which contain very blocks 10's of meters wide as far down as the HNG.

A similar general progression of failure can be seen moving westward along the south-facing promontory. Along this stretch of RB there is the Bear Den fissure cave (Figures 2-4 and 2-7). Bounded by NNE-SSW joints and formed as spaces between large, toppled blocks held open by other blocks acting as "keystone" wedges, the fissure cave is very different from caves formed from dissolution of carbonate rocks. Holler (2008) describes nearby(?) Rumbling Bald Cave which at that time had 549 m of mapped passageways. Of particular interest is the map of Rumbling Bald cave (Holler, 2008, Figure 1) which shows interconnected linear WNW-ESE and NNE-SSW trending passages that parallel joint populations identified in Hickory Nut Gorge (Stop 3, Figure 3-x). The scale map shows a WNW-ESE passage roughly 190m long and 1-5m wide inside Rumbling Bald Mountain at distances of approximately y 40m to 100m from a series of three NNE-trending cave entrances. If correct, this mapping indicates the presence of areas with internal openings parallel to the cliff face which could represent future detachment surfaces for large scale rock slope failures.

We will have the opportunity to visit the fissure cave named Gneiss Cave at Stop 3. The best-known fissure cave system in Hickory Nut Gorge is Bat Cave. For a discussion of Bat Cave and related rock slope failure processes see the supplemental section in this guidebook, '*Preliminary Geologic Observations and Interpretations: Bat Cave Fissure Cave Network, Hickory Nut Gorge*'.

Further west along the trail we will encounter the west boulder field and views of the cliffs above that are the source areas for the rockfall boulders here (Figure 2-9). Although the most impressive features at RB may be the large cliffs, but the surfaces above the cliffs also play an important geomorphological role. Colluvial hollows develop as debris accumulation zones with great potential energy to carry material over the cliffs and into the debris fields below as debris slides and debris flows. Where RB is capped by the Henderson Gneiss and forms a sugarloaf shape with a low-relief top, there is less stream power than where the Poor Mountain formation is thrust above, and shallow seated debris slides and flows are much less common. However, if the convergent colluvial hollows become sufficiently saturated, these can fail as debris flows that carry material over the steep cliffs and into the talus and debris fields below.

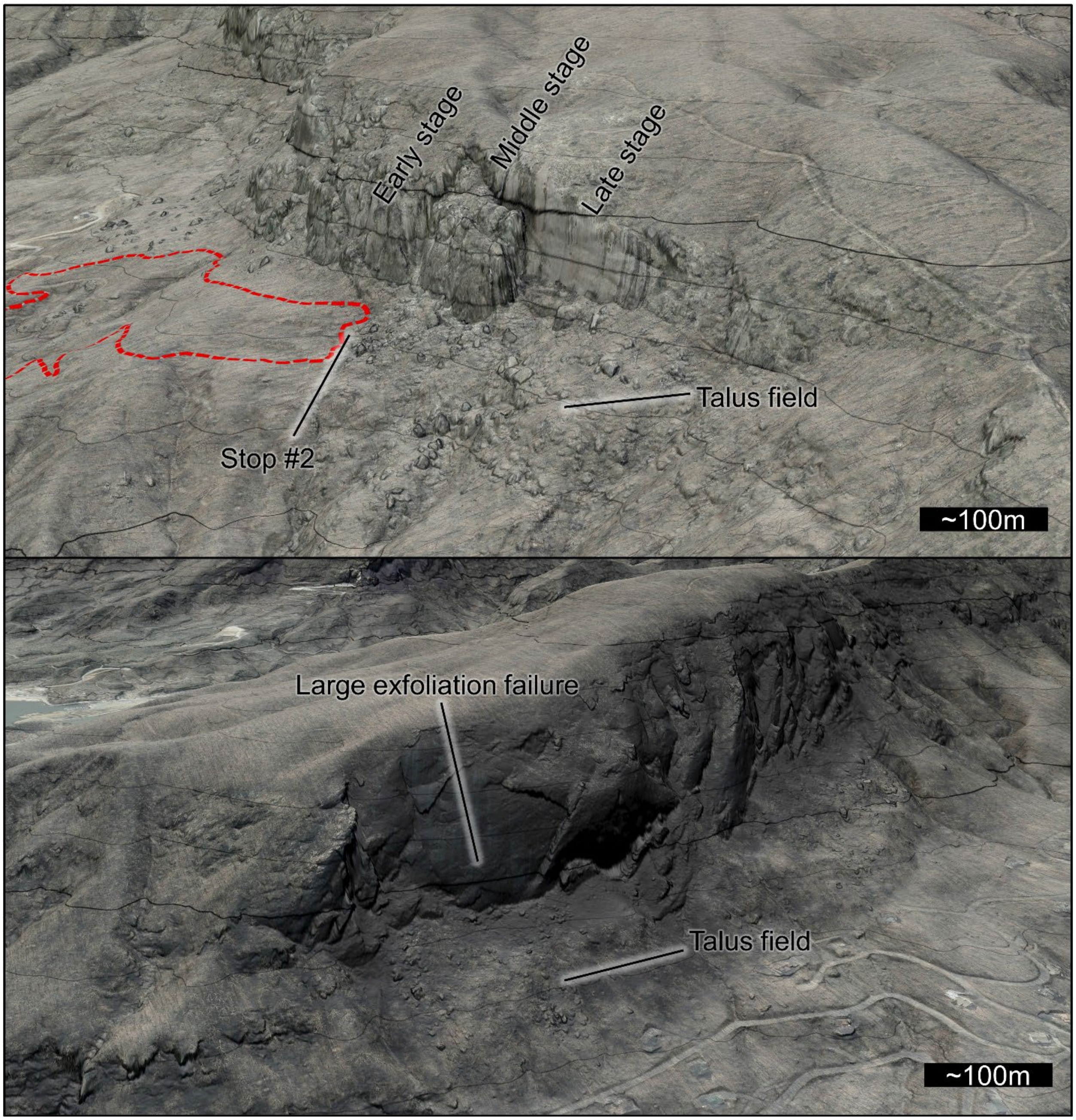

Figure 2-6. Top. 3D view looking NW at the Cereal Buttress rockfall on the south side of Rumbling Bald Mountain. There are three stages of rockfall failure at this location: early, middle, and late. Note the lack of talus below the early stage, the large, detached block in the middle stage, and complete removal of detached material in the late stage. Topographic contours are at 40m intervals. Red dashed line is the hiking trail also shown in Figure 2-4. **Bottom.** 3D view looking SW at the northern side of Rumbling Bald Mountain. Note the large exfoliation face in the center of the frame which is approximately 150m wide at the base.

Figure 2-7. Approximately 5m tall boulder within the talus field below Cereal Buttress at Rumbling Bald Mountain. The difference in foliation within the cliff and within this boulder indicates some amount of toppling and/or rotation. In outcrop, the isoclinal folds in this boulder would be recumbent.

Figure 2-8. Bear Den fissure cave. **Left.** Inside the fissure cave. Quartzo-feldspathic veins cross-cut foliation in the exposed fracture face of the Henderson Gneiss. Wedged and fallen keystone blocks are visible within the opening between the main rock faces. **Center.** Entrance on the south-facing slope Rumbling Bald Mountain. Talus blocks of Henderson Gneiss in the foreground. **Right.** Dissolution weathering on the ESE side of the entrance to Bear Den cave indicates the long exposure time for this cliff face in contrast with unweathered surfaces that would be exposed by relatively recent rockfalls.

Figure 2-9. West boulder field and source area.

Regional Perspective, take home points, and food for (research) thought

Rumbling Bald Mountain is a good example of how multiple structural discontinuities can act in concert to influence the modern landscape in Hickory Nut Gorge and elsewhere in the Columbus Promontory. Along the Blue Ridge Escarpment, where gneisses outcrop as large, near vertical cliffs, there is a potential for rockfall hazards. This hazard is enhanced where the steep face of the Blue Ridge Escarpment is intersected by topographic lineaments, areas known to have high landslide densities, many being influenced by lineament-parallel fractures and faults (Gillon et al., 2009; Hill, 2018; Wooten et al., 2022).

One standing research question lies in the name of Rumbling Bald itself. Is this a seismically active zone, and if so, are the earthquakes big enough to trigger rockfalls? Soplata (2016) postulated that the large rockfalls in HNG could be seismically triggered. Other topographic lineaments in the southern Appalachians are seismically active (Hill, 2018; Figueiredo et al., 2022), but what about the HNG? Further to the north-north-west but along strike of the HNG is the Mills Gap fault zone, where colluvium has been cut by Cenozoic faults, indicating some post-Paleozoic orogenic motion (Wooten et al, 2010), and coincidentally within the epicentral area of the 1916 M 5.2 Skyland earthquake (Stover and Coffman, 1993).

There is a potential for research into understanding how the exfoliation process works at RB, and how it might be affected by thermal cycling and slope aspect. Recent work using remote thermal imaging and terrestrial lidar in the Yosemite Valley has revealed that large exfoliation sheets can be held on by relatively small rock “bridges” connected to the intact cliff (Guerin et al., 2019). Ground-based thermal and lidar analysis may elucidate where the rockfalls hazards are greatest in HNG. Does surface aspect and difference in sunlight exposure lead to varying levels of thermal expansion and geomorphic asymmetry of RB and HNG? How does exfoliation propagation change with the influence of near vertical fractures?

Preliminary Geologic Observations and Interpretations: Bat Cave Fissure Cave Network, Hickory Nut Gorge

Richard M. Wooten[1], Jesse S. Hill[2], David M. Korte[3], Corey M. Scheip[4], Thomas J. Douglas[1]

[1]Richard M. Wooten, North Carolina Geological Survey (Ret.), Richard.M.Wooten@gmail.com
[2]Jesse S. Hill, North Carolina Geological Survey, jesse.hill.geology@gmail.com
[3]David M. Korte, North Carolina Geological Survey, David.Korte@ncdenr.gov
[4]Corey M. Scheip, BGC Engineering, cmscheip@gmail.com
[1]Thomas J. Douglas, North Carolina Geological Survey (Ret.), tjd2000@msn.com

Introduction

Located on the southwest slopes of Hickory Nut Gorge approximately 2.7 km northwest of Chimney Rock State Park, Bat Cave is perhaps the best-known fissure cave in western North Carolina (Figure BC-1). Bat Cave is the namesake for the nearby Town of Bat Cave in Henderson County. Several colorful legends surrounding Bat Cave predate the emergence of the Gotham City superhero in 1939. These legends include Revolutionary War era British prospectors who hid gold in the cave; a Civil War era hiding place for the Underground Railroad and Confederate soldiers escaping from the Union Army; and, lest we forget, covert moonshine activity (Hendersonville Best, 2022).

Other fissure caves produced by slope movement process such a sliding and rockfall in nearby western North Carolina include Talus Tunnel, Sliding Rock, and Rumbling Bald Caves in Rutherford County; and, Devil's Kitchen Cave and Little Warrior Mountain Cave in Henderson and Polk Counties respectively (Holler, 1981; Holler 2009; Holler et al., 2020). The Bear Den Cave (Stop 2) and Gneiss Cave (Stop 3) visited on this field trip are other examples. With over 2km of surveyed passages the Bat Cave complex is thought to be the world's longest augen gneiss cave network (Holler et al., 2020). Features of the Bat Cave network include Big Bat Cave, Little Bat Cave, and the Blowhole. The main chamber, known as Big Bat Cave, is reported to be more than 90m (~300 ft) long and approximately 26m (~85 ft) high (Blue Ridge National Heritage Area, 2022).

The North Carolina Nature Conservancy established the 0.75 km (186-acre) Bat Cave Preserve in 2009 to protect the cave's residents, including the rare Indiana Bat (Myotis sodalist). The U.S. Fish and Wildlife Service Endangered Species Act recognizes the Indiana Bat as endangered. Access to the Bat Cave network, therefore, is restricted to help prevent the spread of the White Nose Syndrome, a fungal disease that affects bats and has resulted in widespread extinctions (Galloway, 2022).

Methods

The North Carolina Nature Conservancy provided guided access to Bat Cave to NCGS geologists, Tommy Douglas, Jesse Hill, David Korte, Corey Scheip, and Rick Wooten on April 27, 2021. We made reconnaissance level field observations and collected bedrock and slope feature data using GPS-enabled field computers. Lidar-derived digital elevation models and topographic data aided in field mapping and interpreting landforms related to the Bat Cave area shown in Figures BC-1, BC-2, and BC-3. Selected field photographs are included in Figure BC-4.

Observations and Interpretations

Observed landforms and slope features are consistent with the Bat Cave fissure network originating as a rockslide within the Henderson Gneiss. Secondary areas of rockfall have also occurred as evidenced by detached rock blocks on the right (south) flank of the displaced mass (Figures BC-1 and 2), as well as within fissure openings (Figure BC-4). A distinct transverse depression resulting from down-dropped blocks below a main scarp cuts across a rocky interfluve near the 600m elevation contour (Figure BC-1). Vertical displacement within the 'graben-like' depression is on the order of 21m as estimated from the topographic profile (Figure BC-2). The topographic profile also reveals a pattern of stepped topography that extends ~180 downslope to an over-steepened zone interpreted as the toe bulge of the rockslide. In this interpretation, the composite rockslide-rockfall comprises an area of ~3.7 ha, with a maximum length of ~180 m, a maximum width of ~215 m, and a maximum thickness (normal to slope) of ~60m. Total NE-directed translational displacement of the Bat Cave rockslide is not known but is estimated to be on the order of 10s of meters. Along the rough-textured right (south) flank, a component of SE-directed movement is evident related to the falling, toppling, or sliding rock blocks that have accumulated in the stream channel.

Bedrock structure appears to control salient features of the rockslide. The trends of linear segments of the of the transverse depression, as well as the observed fissure (fracture) openings in Little and Big Bat Caves (Figure BC-4) are generally consistent with the steeply dipping NE- and NW-striking fractures measured in outcrop on the north side of Bat Cave (Figure BC-1). Similar trends are visible in what are interpreted as a series of stepped blocks within the slide mass (Figure BC-3). The horizontal displacement between the fracture surfaces is on the order of 4-5m near the floor level at the opening of Big Bat Cave (Figure BC-4A). A translational basal sliding surface is interpreted to be sub-parallel to the foliation in the Henderson Gneiss, the apparent dip of which is approximately 16 degrees as shown in the conceptual cross section in Figure BC-2. Some back-tilting of slide blocks was noted (Figure BC-4) indicating a subordinate component of rotational movement.

Interestingly, the NE- and NW-striking fracture trends observed here are oblique to the overall WNW trend of Hickory Nut Gorge and related fracture sets. Stepped kinematic indicators observed on a vein filling exposed on the fracture face of a displaced block at the Big Bat Cave entrance reveal a left-lateral component of the inferred oblique displacement (Figures BC-1 and BC-4B).

Based on the quartzo-feldspathic and mica mineralization present on the fracture face, we interpret the shear movement to be tectonic in origin, and pre-date slide movement. It is possible that accessible fissure (fracture) networks extend beyond the mapped extent of the Bat Cave rockslide, especially upslope of the main scarp. Much more work is needed to understand the origins, ages and structural implications of the fracture networks related to Bat Cave.

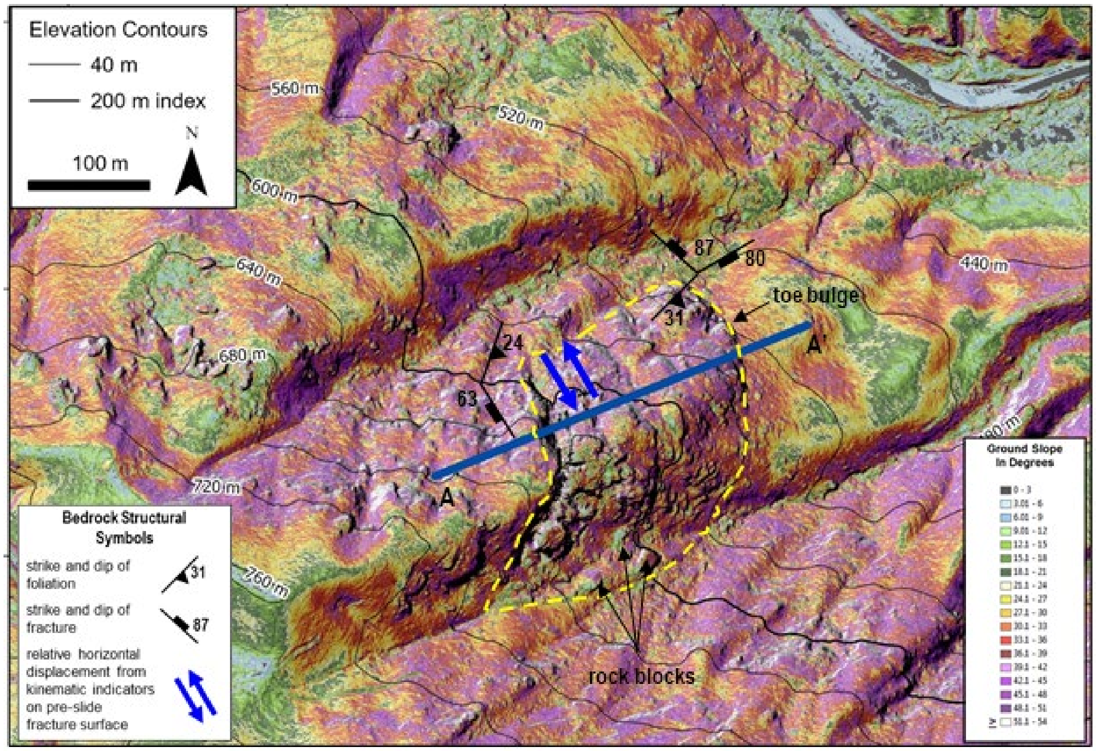

Figure BC-1. Map showing the approximate extent (yellow dashed line) of the Bat Cave rockslide that includes the Bat Cave fissure cave network. A-A' = location of cross section line in Figure BC-2. Blue arrows show the approximate horizontal displacement along pre-slide shear fractures (mode 2) estimated from stepped kinematic indicators on the fracture face (see Figure BC-4). Map base is a shaded relief and slope map derived from a 0.5m pixel resolution lidar DEM. Topographic contour interval = 20m.

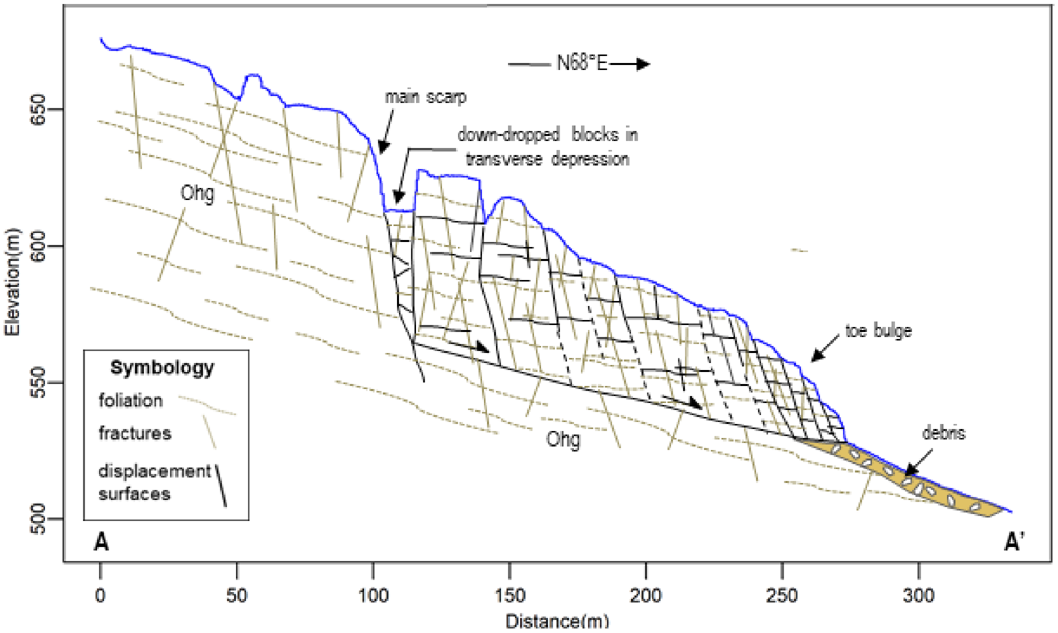

Figure BC-2. Interpretive schematic geologic cross section A-A' through the Bat Cave rockslide. Ohg = Henderson Gneiss from Davis and Yanagihara (1993). Foliation and fracture orientations are based on nearby field measurements (see Figure BC-1). Locations and orientations of displacement surfaces are interpretive. Topographic profile derived from a 0.5m pixel resolution lidar DEM.

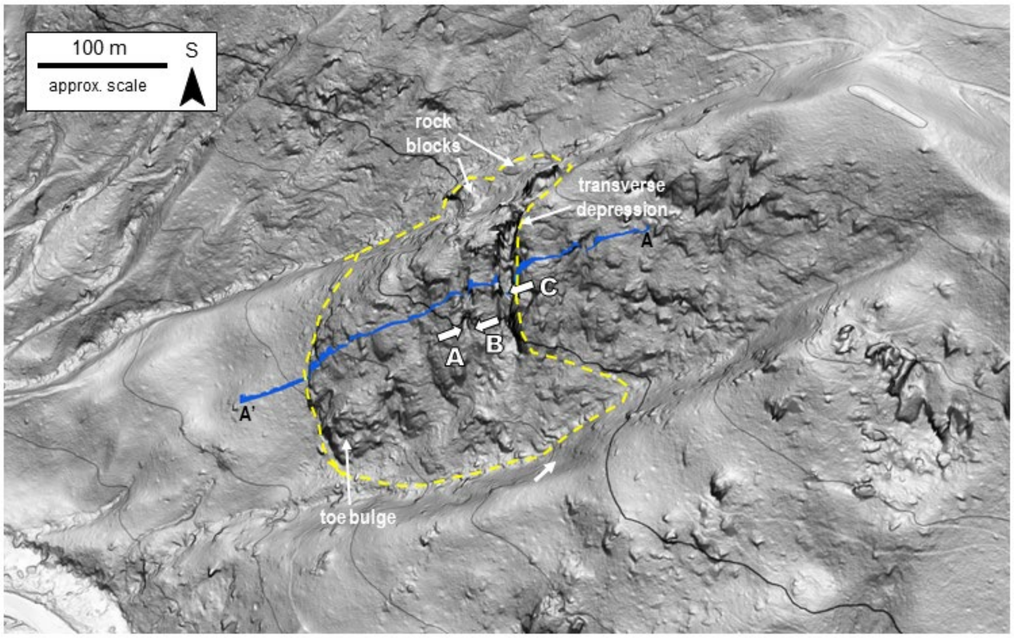

Figure BC-3. Oblique 3-D view of the inferred extent of the Bat Cave rockslide (yellow dashed line). Lettered locations refer to the locations of photographs in Figure BC-4. A-A' = cross section line in Figure BC-1. Image derived from a 0.5m pixel resolution lidar DEM. **Note:** South points up – opposite from Figure BC-1.

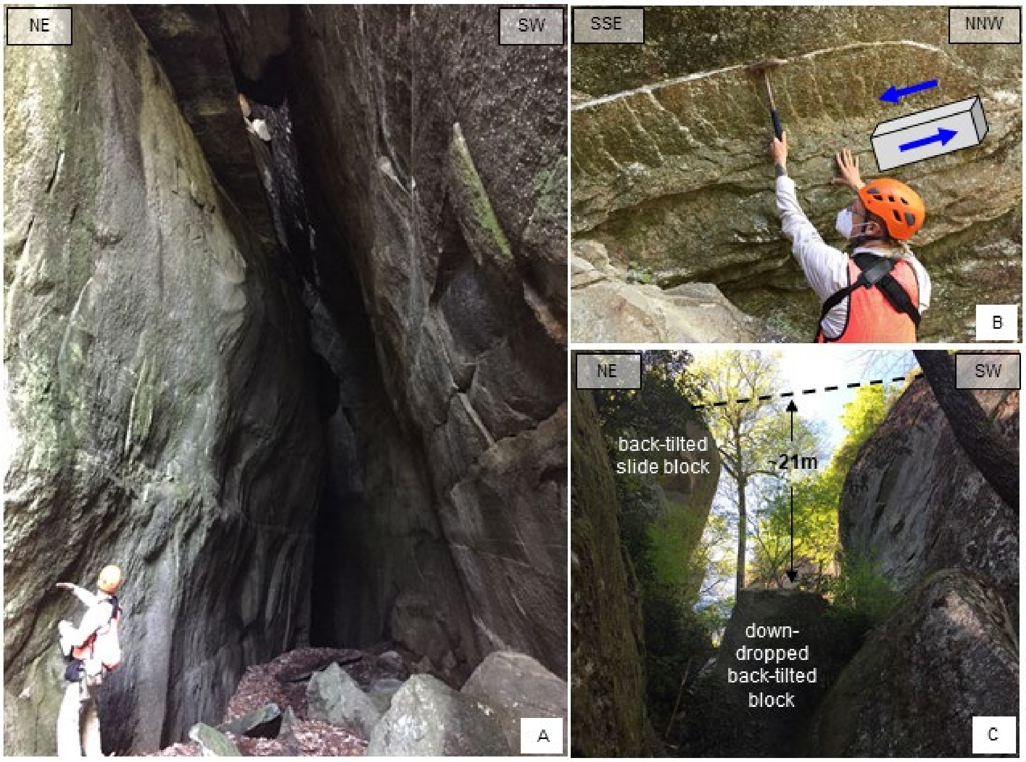

Figure BC-4. Photographs of features of the Bat Cave fissure cave network in the rockslide. **A.** Entrance to Big Bat Cave where wedged and fallen keystone blocks are visible within the opening. **B.** Stepped, kinematic indicators on a fracture surface of a displaced block in the SW side on Big Bat cave. Arrows show the inferred displacement direction of the fracture surface relative to the opposing block (block diagram inset) no longer in contact with the fracture surface. **C.** View of displacement of the down-dropped block in the transverse depression at the main slide scarp. Refer to Figure BC-3 for locations of lettered photographs. April 27, 2021, NCGS photo

Potential Hazards

Other than the report of a rockfall at the entrance of Big Bat Cave during the winter of 1986 when a 60-ton block fell from the ceiling (Holler, 2009) there are no known reports of other rockfalls or sliding movements at Bat Cave. An obvious rockfall hazard exists within the fissure openings as evidenced by the boulders that have accumulated on the entrance floors (Figure BC-4). Falling and toppling of rock blocks from the disjointed slide mass remains a potential hazard, particularly along the disrupted south flank (Figure BC-1). Overall, the rockslide appears to be in a dormant, quasi-stable state with respect to sliding. Ongoing, but undetected, incremental sub-meter scale displacements within the rockslide mass are certainly possible as the landform continues to evolve. Many questions remain about triggering mechanisms for initial and subsequent movements of the rockslide that could be precursors to future activity.

Acknowledgements

Access to Bat Cave granted by the N.C. Nature Conservancy is gratefully acknowledged. Brian Parr, of the Nature Conservancy, skillfully led an informative field excursion to the Bat Cave fissure cave network on April 27, 2021.

Stop 3: Chimney Rock State Park

Field Trip Leaders: Rick Wooten, Cheryl Waters-Tormey, Bart Cattanach, David Korte, Jennifer Bauer, Philip Prince

Location: Chimney Rock, NC. (Longitude -82.250294W, Latitude 35.432733N)

Purpose: Examine the Henderson Gneiss and landslide hazards in the Chimney Rock area of Hickory Nut Gorge. Enjoy the scenery and the Chimney Rock State Park experience.

Itinerary

11:45 a.m. Buses arrive at main parking lot. Take shuttle buses to the pavilion.

12:00-1:00 p.m. Have lunch at the pavilion, then ride buses to the upper parking lot.

Note: Shuttle buses will be available near the Pavilion to take those interested to the upper parking lot to see the tunnel to the elevator (max. capacity 8 people), visit the Skyline Lounge and gift shop, the Sky Walk, and see the view atop the Chimney before 1:30.

1:30 p.m. Gather at the Outcroppings Trail - Gneiss Cave platform area: geological framework overview.

2:15 – 4:00 p.m. Hike the trail to Hickory Nut Falls: View and discuss fracture set interactions, landslide events, the WCU monitoring station, 2012 rockslide, and rock slope features at Hickory Nut Falls.

4:00 p.m. Depart Hickory Nut Falls, return to upper parking lot, ride shuttle buses to the lower parking lot.

5:00 p.m. Depart lower parking lot for the Lake Lure Community Center

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Geological Framework

(gather at the platform near the Gneiss Cave)

Bedrock lithology and ductile deformation fabric have the potential to influence the intensity and internal geometry of fracture networks. Bedrock in the eastern HNG is comprised of the Henderson Gneiss and Poor Mountain regional map units (Figure 3-1). In this area, the Henderson Gneiss is dominated by mylonitic gneiss. Foliation is defined by recrystallized wings of cm-scale feldspar porphyroclasts, grain shape preferred orientation of finer grained quartz and biotite, and cm- m-scale layers/lenses of polycrystalline coarser-grained felsic domains. The stretching lineation is defined by aligned porphyroclasts, elongated quartz, elongated felsic lenses, and locally, tight cm- to m-scale fold axes. Where observed, shear sense is top to the SW. The relative development of lineation versus foliation varies, but in the field area around stop 3, lineation-dominated zones are less common. Several lithological components of the Poor Mountain map unit lie structurally above the Henderson Gneiss (Figure 3-1 and Figure 3-2). These are (1) fine-grained, mafic amphibolite gneiss typically exhibiting a cm-scale straight compositional foliation with lineation defined by aligned hornblende; (2) fine-grained felsic gneiss in which foliation and lineation are defined by grain shape fabric of biotite, feldspar, and quartz; (3) medium-grained muscovite foliated schist; and, volumetrically minor, (4) fine grained biotite-hornblende gneiss enclosing 1-100 cm scale lenses of coarser grained felsic domains. Subparallel grain shape fabrics, compositional foliation, and outcrop patterns, suggest that these units define a 1-10-m thickness scale compositional foliation.

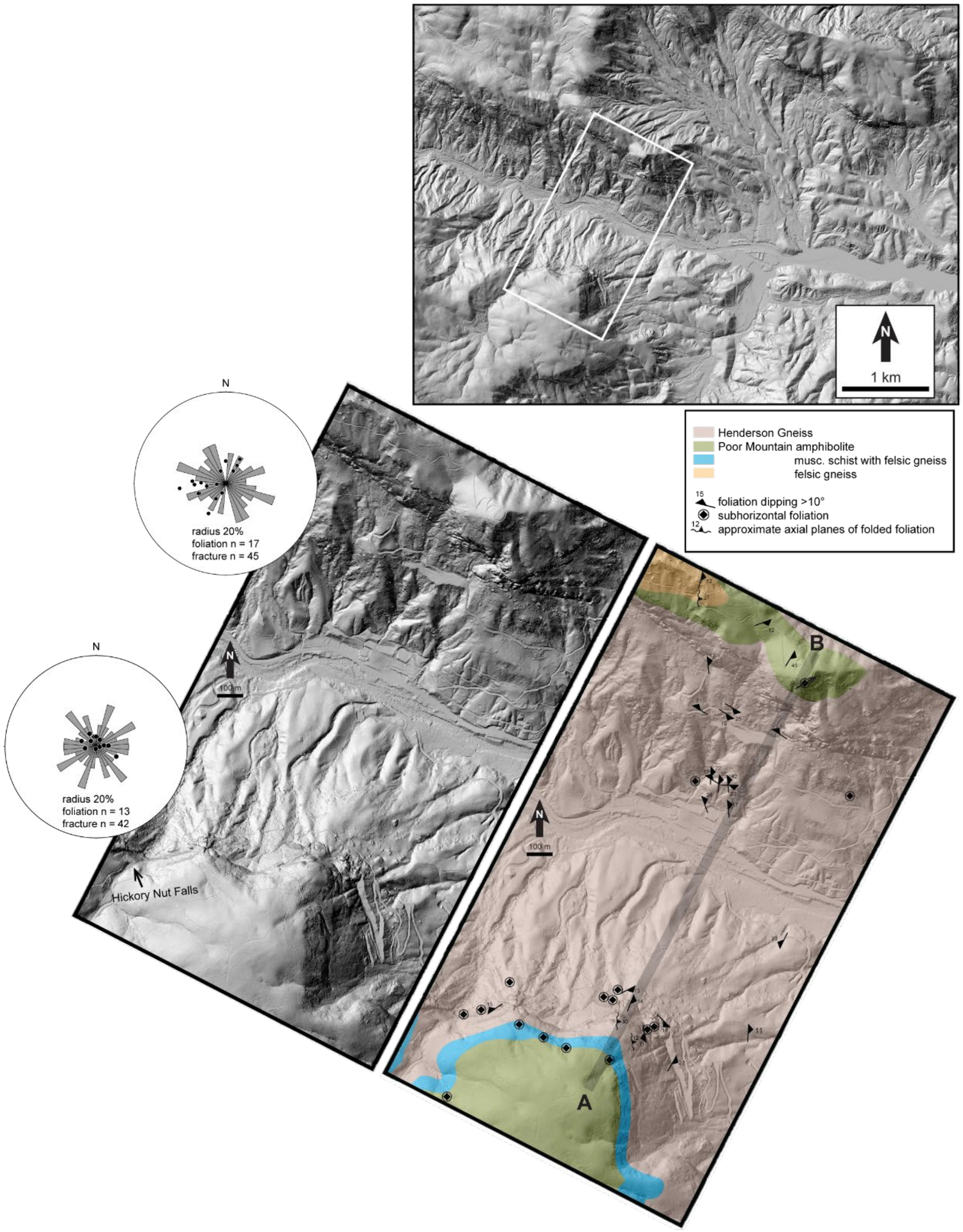

Figure 3-1. **Top.** Lidar DEM overview map of lower HNG. Box indicates Stop 3 map area in (b-c). **Lower Left.** Lidar DEM with rose diagrams of outcrop fracture measurements in the north and south sides of the gorge (see Figure 3-5 profile). **Lower Right.** Bedrock unit distribution and representative foliation orientations (note subdivision of Poor Mountain unit). Profile line A-B shown in Figure 3-5).

The nature of the Henderson Gneiss – Poor Mountain map unit contact also has the potential to influence fracture network patterns. Regionally, the contact is interpreted as a discrete thrust fault (Davis and Yanagihara, 1993)). Ongoing work in the lower HNG area suggests a second working hypothesis for the contact proposed by the WCU working group. For example, mineral assemblages defining penetrative ductile deformation fabrics suggest similar metamorphic facies in both map units. Further, the contact does not record significant ductile strain localization zone (i.e., a mylonitic thrust shear zone associated with the strongest foliation intensities and/or consistent rotation of older fabrics approaching the contact). Rather, kinematically-consistent fabric domains, shear sense indicators, and stretching lineations occur throughout both units (D&Y, 1993; ongoing work). These observations suggest that (at least locally) the contact is transposed, along with the contacts between internal lithological domains within each map unit, and m- to grain-scale ductile deformation fabrics within those domains. Domains within the Henderson Gneiss dominated by migmatic textures (e.g., in the Rumbling Bald area) may be lower strain lenses within the penetrative ductile deformation fabric.

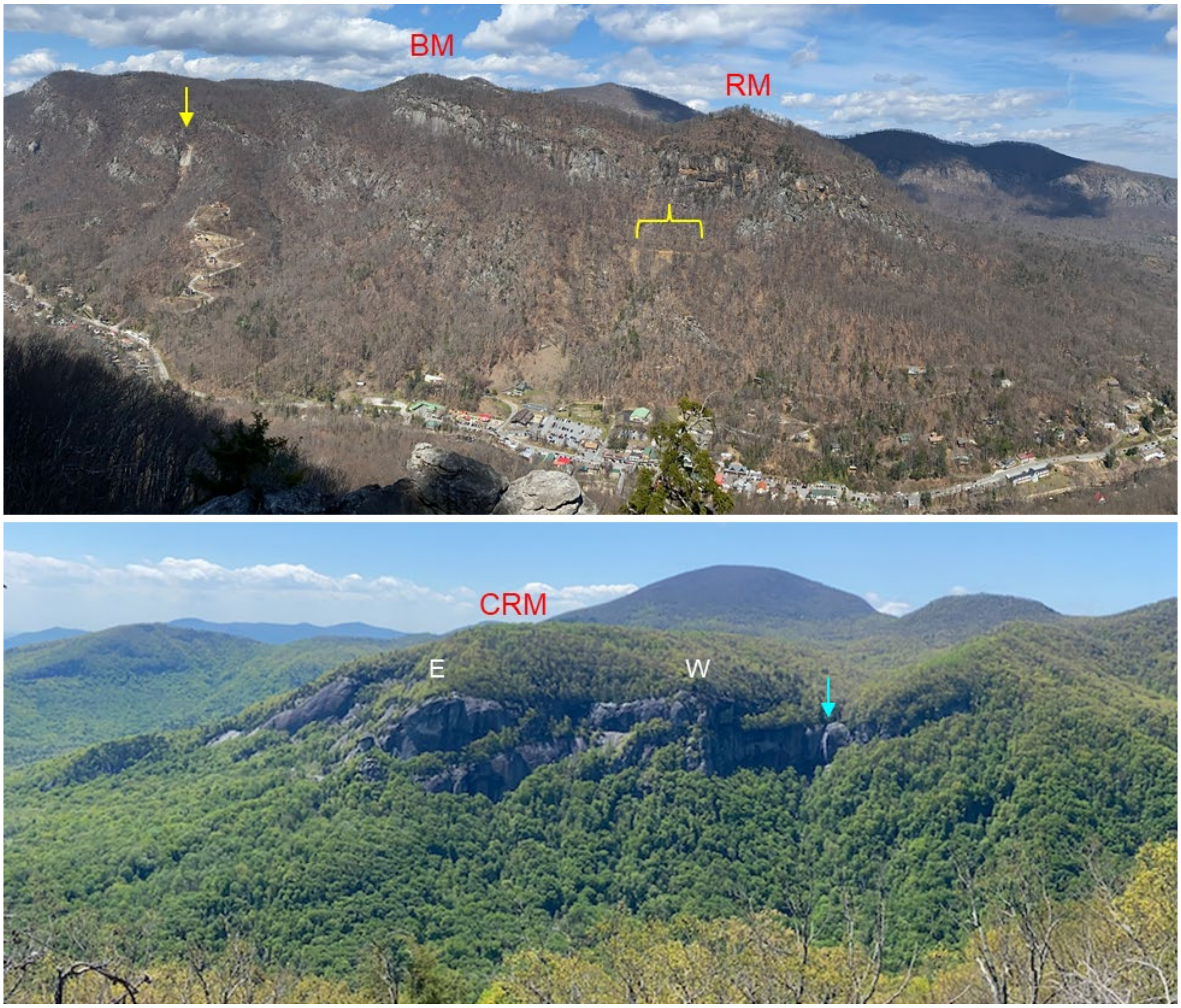

Figure 3-2. **Top.** View looking N across HNG from pulpit rock in CRSP to Round Mountain (RM) and Bald Mountain (BM) ridgeline (Rumbling Bald ridgeling in background). Yellow arrow indicates 2018 debris flow; yellow bracket indicates source area for debris flows at ‘Silver City’ property. **Bottom**. View looking SE across HNG of Chimney Rock Mountain (CRM) from Bald Mountain. Eastern E and western (W) promontories; Hickory Nut Falls (blue arrow).

Fracture Network Overview

Ongoing mapping of fracture set orientations and morphologies suggests the WNW, NW, N, and NE orientation sets observed elsewhere in the region all occur in the eastern HNG. The apparent intensity of foliation-parallel fractures in Henderson Gneiss is higher where compositional domains are straighter and more closely spaced Fig. 3-18 Left). Foliation-parallel fractures are typically well developed in the Poor Mountain units except within felsic gneiss domains. In outcrop, at least 2-3 orientation sets define the m-scale fracture network. Schematic diagrams in Figures 3-3 and 3-4 are examples of how fracture sets interact to form 10m-scale features in the eastern promontory. Note foliation-parallel fracture sets forming overhanging ledges in the top right-hand example of Figure 3-4.

Most fractures are interpreted as extensional (joint) fractures. Curved N to NW fracture surfaces in the eastern (Figure 3-4 center and left) and western promontories (Figure 3-4 top middle) Left) are interpreted as exfoliation (lateral? shallow stress relief) fracture propagation.
Secondary fractures (i.e., low angle Riedel-type) are occasionally observed along NE- and WNW-striking fractures in the Henderson Gneiss (Figure 3-4 left center). NE- and WNW-striking fractures in the Poor Mountain mafic and felsic gneisses occasionally exhibit 0.5 mm-thick dark-colored cores, suggestive of cataclasis. These latter observations may indicate a shear component.
The dominant fracture sets are steep (most >75°) and formed in bedrock with gently inclined to horizontal ductile rock fabric. Anisotropy due to this fabric, and overall lithological “stiffness”, may have played a role in fracture size and spacing, and therefore the geomorphology across this part of the gorge. In particular, vertical fracture height seems to be inversely related to the degree of compositional domain alignment.

Within the Henderson Gneiss, vertical fracture height seems to be truncated where the gneiss contains more felsic compositional domain alignment (Figure 3-4 left center); Fig. 3-18 Left). Fracture heights are larger in lithotextural zones in between, where (1) porphyroclast abundances and sizes are lower and spacing between the biotite folia is smaller, (2) compositional domains are more spaced, or (3) compositional domains form m-scale folded (sheath fold?) domains.

In contrast to the Henderson Gneiss, the Poor Mountain unit is characterized by 1cm–10 m-scale compositional foliation thicknesses, better developed and penetrative foliation-parallel fractures, and shorter cross-cutting fracture heights. Consequently, large blocks of Poor Mountain lithologies are typically not seen in the block fields.

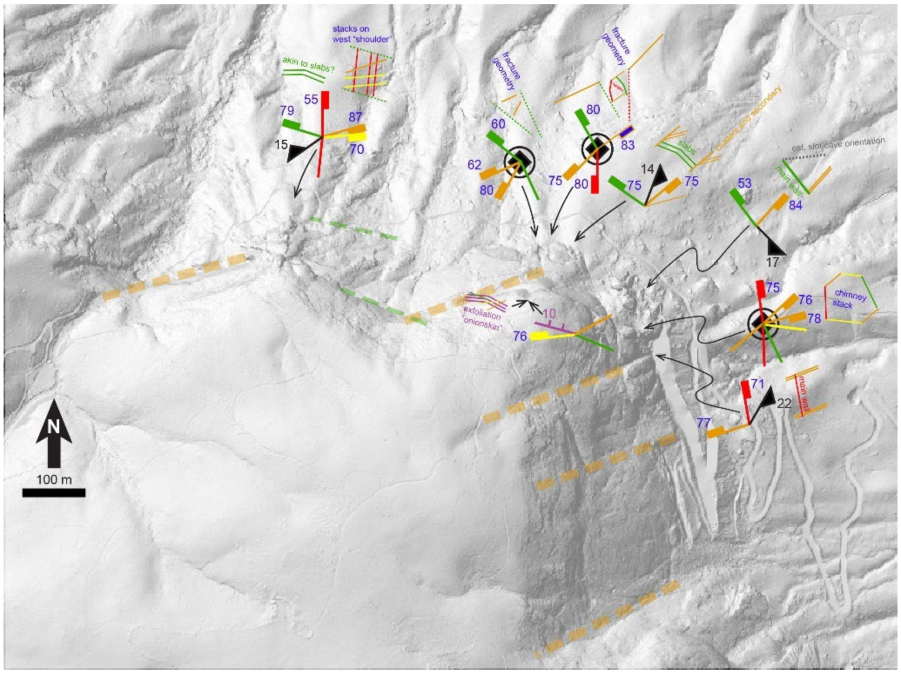

Figure 3-3. Fracture geometry examples in Henderson gneiss on edge of Chimney Rock Mountain (E, eastern promontory; W, western promontory). Foliation (black) as for map in Figure 3-1. Colored strike and dip symbols represent fracture sets (box indicates dip direction). green, NW; red, N; orange, NE; yellow, E; purple "onion skin exfoliation. Strike symbols without ornament indicate subvertical orientation. Schematic map-view diagrams indicate fracture arrangement spatially in map view for each example, color coded with fracture orientation set. Semi-transparent dashed lines indicate possible structural compartments defined by major NE (orange) and NW (green) fractures inferred from lineaments. Outcrop pictures from the NW compartment are in Figure 3-4.

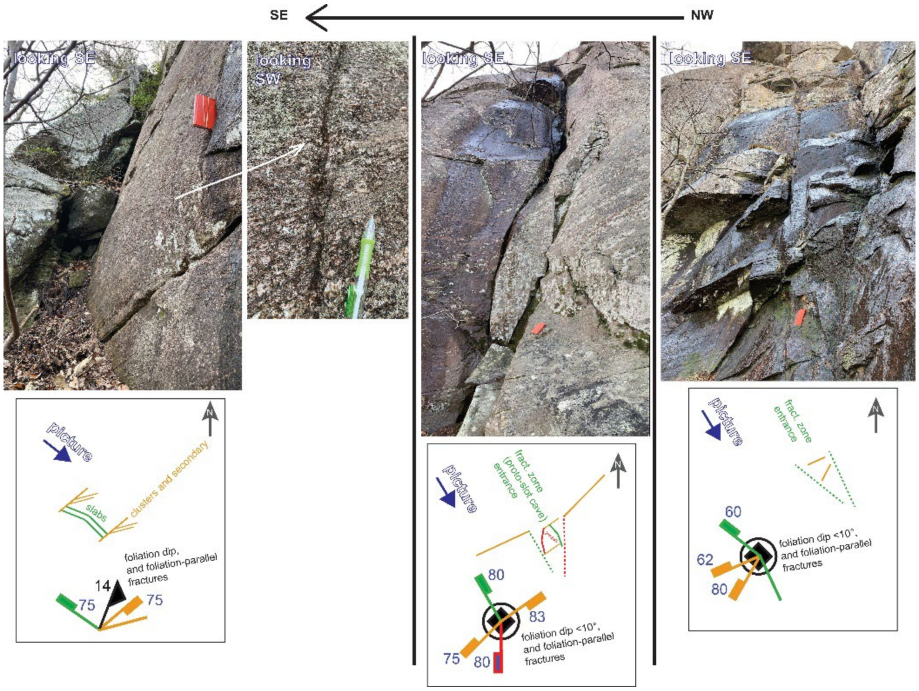

Figure 3-4. Top Row. Outcrop pictures from the base of the eastern promontory (see Figure 3-3 for locations) **Boxes:** foliation and fracture set orientations, and map view geometry from Figure 3-3 at each location. Colors and symbols as for Figure 3-3. **Top Left.** Slabs detached along NW fracture and bounded laterally by NE fractures leaning against the cliff. Closer view shows geometry of secondary fractures slightly oblique to the NE set. **Top Middle.** Curving NW and N fractures within a fractured zone. **Top Right.** Blocks bounded by NE and NW sets, and foliation parallel fractures.

Fracture set variation across and within HNG

At a larger-scale view, slopes formed by taller fractures in the upper Henderson Gneiss are visible across the gorge (Figure 3-2). Although access is limited, the cliff zones occur below, but not adjacent to, the contact with the Poor Mountain unit. For example, at Exclamation Point in CRSP, the Henderson Gneiss just below the contact is tightly folded and the slope is shaped by gently dipping “onionskin” exfoliation fractures. Here, the steep fractures have 10-cm heights in contrast to the cliffs below (Figure 3-3).

Additionally, slopes and lidar “texture” in the Henderson Gneiss on the N (Round Mountain) and S (Chimney Rock Mountain) sides of the lower HNG have contrasting morphologies (e.g., promontories and recesses only on the S side). In contrast, the topographic and lidar “texture” in the overlying Poor Mountain unit is similar on both sides (Figure 3-1). The Henderson Gneiss cliffs, and their morphology differences from north to south, may be partly a result of ductile rock fabric variations discussed above but at the 0.5-km scales.

Outcrop observations and structural measurements along a traverse across the lower HNG from Chimney Rock Mountain (SW) to Round Mountain (NE) are shown in Figure 3-5 to illustrate variation in fracture orientation populations across and within HNG. In the Poor Mountain unit, fracture surfaces are smaller (10 cm^2-scale) and dominated by NW orientations. In the amphibolite and schist, foliation-parallel-fracture sets are also very well developed.

Below (~1300-2300 feet elevation), fracture populations in outcrops are not dominated by NW sets. On the NE side, the steeper cliff zones and outcrops below contain a combination of NW and NE sets. Within the eastern promontory on the SW side (grey-shaded rose diagrams), the main sets are W, NW, or NE, depending on structural level (see also Figure 3-3). NE fractures are more abundant at the base of the promontory, perhaps consistent with the recesses defined by mostly NE-oriented slopes (Figure 3-3). At the lowermost levels, outcrops exhibit a wider range of fracture sets. This structural level is also closest to the center of the gorge, A wider range of fracture sets could partially explain incision forming the gorge.

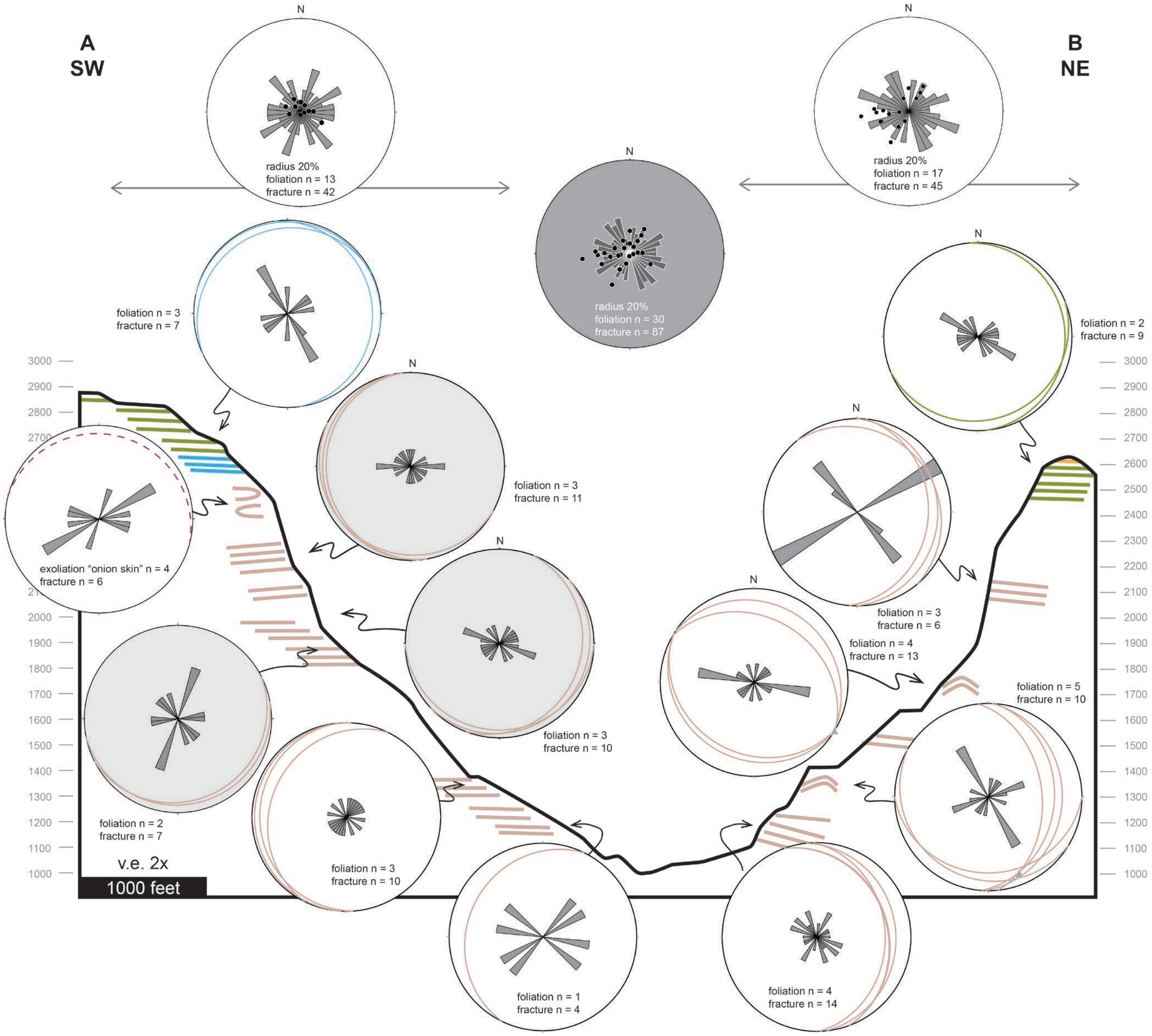

Figure 3-5. Top. Fracture strikes and poles to foliation from the N and S sides of HNG, gray shaded is all data. Below. Outcrop measurements grouped by structural level. Location and bedrock unit colors in Figure 3-1. Trace of foliation apparent dip shown schematically at no. V.E. Light gray shading indicates data from the NW structural compartment of the eastern promontory. Foliation (color by unit) and exfoliation (purple), planes and poles to foliation (black circles, top row) in equal area, lower hemisphere projection. Fracture strikes (most dips (>75°) in rose diagrams bins of 10° and centered on 000; max. petal radius 50% except where otherwise noted.

Past Storms and Associated Debris Flow Events

Geologically, the high relief, steep slopes, and highly dissected nature of the BRE make it susceptible to debris flows (Figure 3-6). Orographic forcing of rainfall along the BRE also contributes to the frequency of debris flows. This effect is evidenced by the generally greater rainfall totals along the BRE as compared to the surrounding regions for the major debris flow producing tropical cyclones of July 15-6, 1916 (Scott 1972) and August 10-17, 1940 (US Geological Survey, 1949).

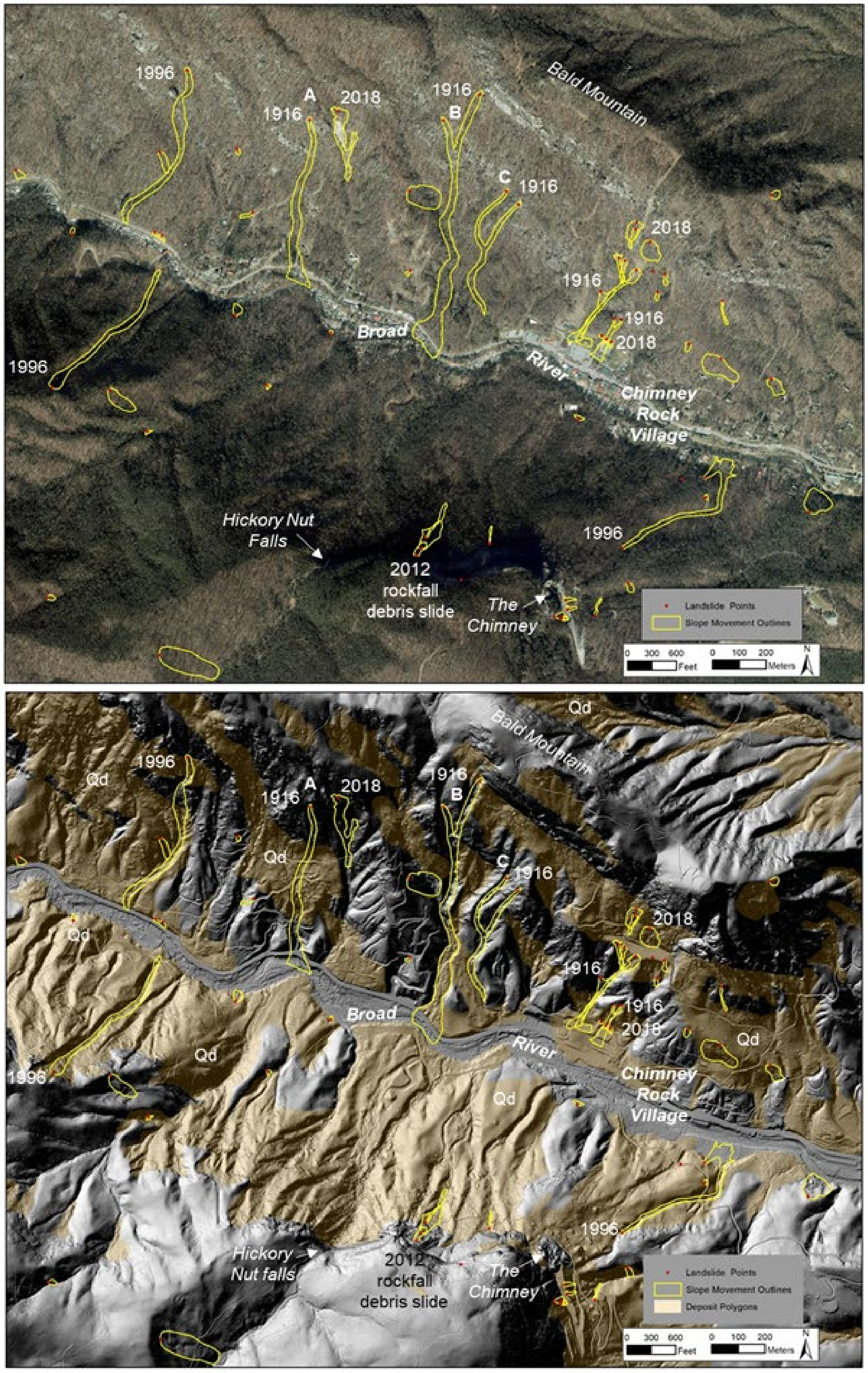

Figure 3-6. Locations of the slope movement features in Hickory Nut Gorge in the vicinity of Chimney Rock State Park and Chimney Rock Village. Year of occurrence is given for selected slope movements. Qd = Quaternary debris deposits. Map base 2019 orthophotography **(top);** shaded relief map derived from 0.5m resolution lidar digital elevation model **(bottom).** Lettered locations for the debris flow tracks from the July 15-16, 1916 storm correspond with those on Figure 3x. Data sources for landslide features: NCGS landslide geodatabase (https://landslidesncgs.org); Soplata, 2016; L. Haydock, personal communication).

The July 15-15, 1916 storm is the storm of record for the French Broad watershed (Witt, 2005) and set the 24-hour rainfall record for western North Carolina of 22.2 inches (~564 mm) at Altapass on the crest of the BRE ~55 km NE from Chimney Rock. Extensive flooding and numerous landsides throughout western North Carolina resulted in at least 50 fatalities, with 18 of those related to landslides. The distribution of the generalized locations of areas in western North Carolina affected by debris flows and other landslides from the July 15-16, 1916 event, generally coincide with the Blue Ridge Escarpment (BRE) and reentrants incised into it (Wooten et al., 2016) including those in the Chimney Rock area shown in Figures 3-7, 3-8, and 3-9)

Figure 3-7. Debris flow tracks from the July 15-16, 1916 storm on the south facing slopes of Hickory Nut Gorge. Lettered locations for the debris flow tracks storm correspond with those on Figure 2. View looking north from the Appian Way, Chimney Rock Park, 1920-1922. William A. Barnhill N. C. Collection – Pack Memorial Library.

The September 4, 1996 rainfall event is of particular interest with respect to the meteorological influence of the Hickory Nut Gorge where an isolated area of high intensity rainfall measuring 317mm (~12.5 in) within a 3-hour period triggered flash flooding (Johnstone and Burrus, 1998), and at least four debris flows and one debris slide (Soplata, 2016; L. Haydock, personal communication). Johnstone and Burrus (1998) posit that Hickory Nut Gorge provided a “V” shaped opening in the BRE that acted to focus upslope flow and intense rainfall resulting from interactions between a low in eastern Tennessee and tropical cyclone Fran that produced heavy rainfall and flooding in the North Carolina Piedmont ~300 km to the east.

Debris Flows and Debris Slides – Alberto, May 28-30, 2018

Rainfall from remnants of subtropical cyclone Alberto triggered six known damaging debris flows and debris slides in the Chimney Rock area of Hickory Nut Gorge, mainly on the south-facing slopes of Bald Mountain. Three debris flows converged into one stream channel (Fig. 3-8 left, Fig. 3-9) and caused property damage to a park in the Village of Chimney Rock (Wooten et al., 2019b). These three debris flows initiated as embankment failures originating in the former Silver City amusement park (Figure 3-9). Immediately to the southeast, other areas of the former Silver City property show signs of subsidence associated with a series of scarps and tension cracks in the embankment material. These features observed in 2018 and 2019 indicate unstable material that could mobilize into future damaging debris flows.

Two debris slides (cut slope failures) damaged the Chimney Rock Volunteer Fire Department (Fig. 3-8 right, Fig. 3-9). The 2018 debris flows and debris slides shown here coincided with areas affected by debris flows triggered by rainfall from the July 15-16, 1916 tropical cyclone (Figures 3-7 and 3-9). Arrows in the upper part of Figure 6 point to 2018 debris slides and a debris flow with source areas in boulder and block debris originating from the WNW-trending cliff lines upslope. In these areas debris from past rocks slope failures accumulated of hillslope benches, and subsequently activated in response to rainfall from Alberto.

Figure 3-8. Left: View looking upslope (north) along the path of the debris flow (embankment failure) that damaged a Village of Chimney Rock park. 2019 NCGS photo. Location A – Figure 3-9. **Right**: Damage to the Chimney Rock Volunteer Fire Department (CRVFD) by a May 30, 2018 debris slide (cut slope failure) triggered by subtropical depression Alberto. View looking northwest. 2018/05/30 CRVFD photo. Location B – Figure 3-9.

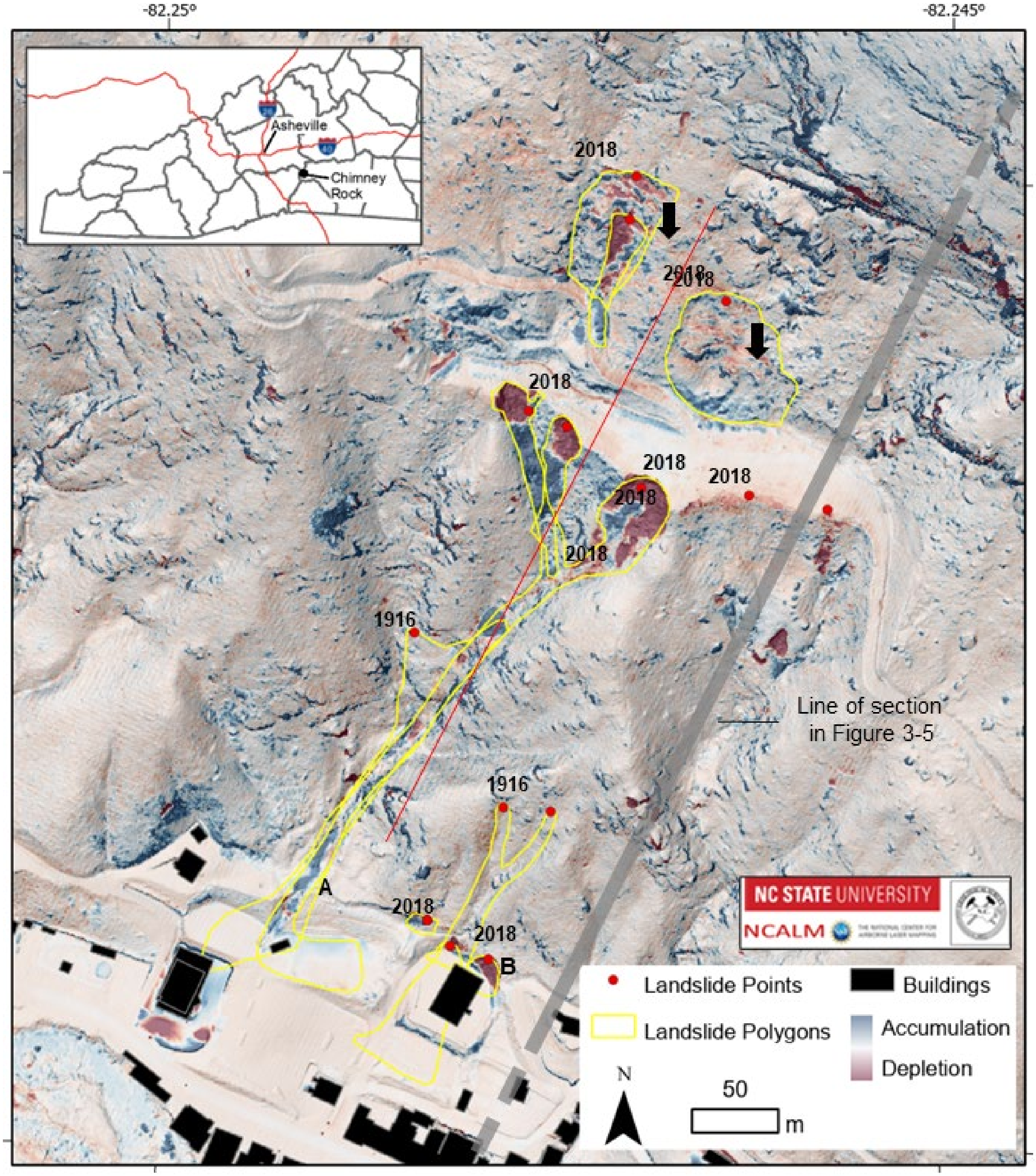

Figure 3-9. 2017-2020 lidar comparison map showing locations of debris flows, and debris slides triggered by rainfall from Alberto during May 28-31, 2018 in the same areas that were affected by debris flows from the July15-16, 1916 tropical cyclone. Arrows in upper map point to 2018 debris slides and a debris flow with source areas in the boulder debris that originating from the WNW-trending cliff lines upslope. Location A corresponds to the debris flow track in Figure 3-x left. Location B corresponds to the debris slides that affected the Chimney Rock Volunteer Fire Department in Figure 3-x right. Landslide data sources: NCGS landslide geodatabase (https://landslidesncgs.org); Soplata, 2016. Lidar base map adapted from Scheip, 2021.

November 14, 2012 Rockfall – Debris Slide: Chimney Rock State Park

During the night of November 14, 2012 a major rock fall occurred in Chimney Rock State Park in Hickory Nut Falls Gorge (Figures 3-10 through 3-17). A 1,400-2,000-ton rock slab dislodged from an overhanging outcrop ledge about 340 feet in elevation above the trail to Hickory Nut Falls (Wooten et al., 2019b). The rock slab detached from an overhang on the cliff face where an exfoliation joint intersects foliation planes in the Henderson Gneiss (Figures 3-10, 3-11, 3-12). The block fell and shattered into boulders when it impacted a rock slope immediately below the overhang. A portion of the boulder debris severely damaged a 210-foot-long section of trail and destroyed a section of a steel girder footbridge (Figure 3-16). Some of the boulder debris impacted a colluvial deposit upslope of the trail triggering a debris slide resulting in approximately 3,000 yd^3 of unstable material remaining on the slope above the trail (Figures 3-13 and 3-14). Fortunately, the rock fall occurred after park hours, as the trail to Hickory Nut Falls (Fig. 3-11) is a popular in the Park. The NCGS report on the rock fall event (Wooten et al., 2012) supported the Division of Parks and Recreation's effort to obtain funding to remediate the trail and remove the hazardous material above the trail before it reopened to the public. This rock fall and other NCGS responses to landslide events is summarized in Wooten et al. (2017).

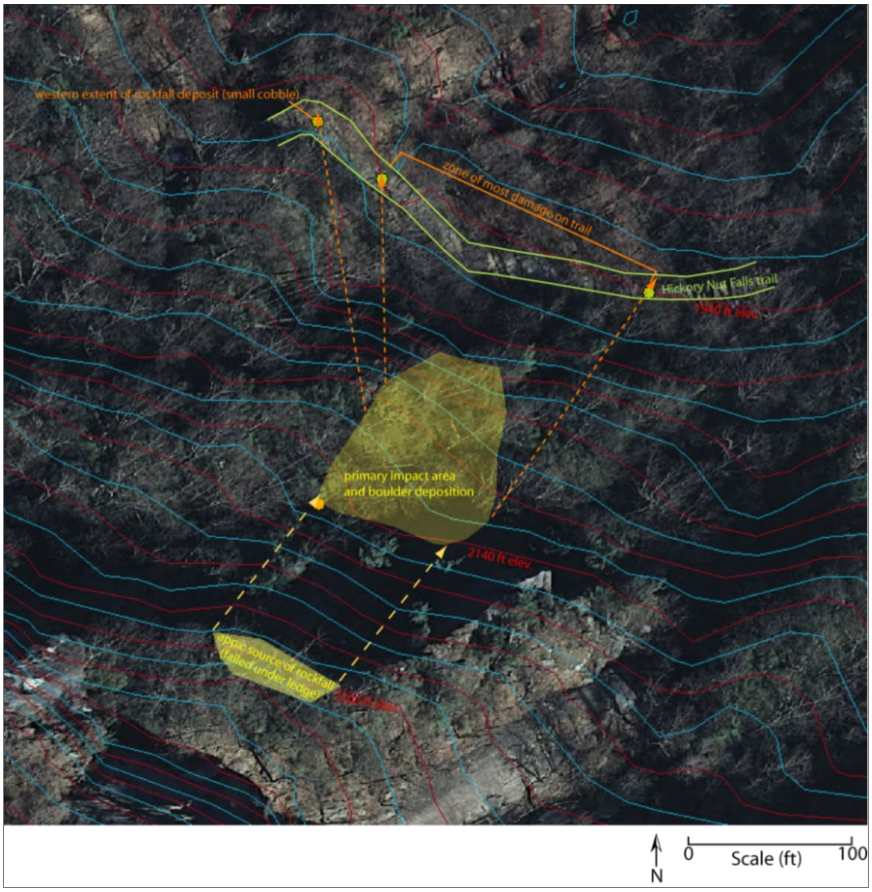

Figure 3-10. Schematic map showing approximate location of the November 14, 2012 rockfall, including the source area, boulder deposit area, and damaged trail area. Map base is a 2012 orthophotography. Topographic contours are derived from the Light Detecting and Ranging (LiDAR) digital elevation model. Contour interval = 20 feet.

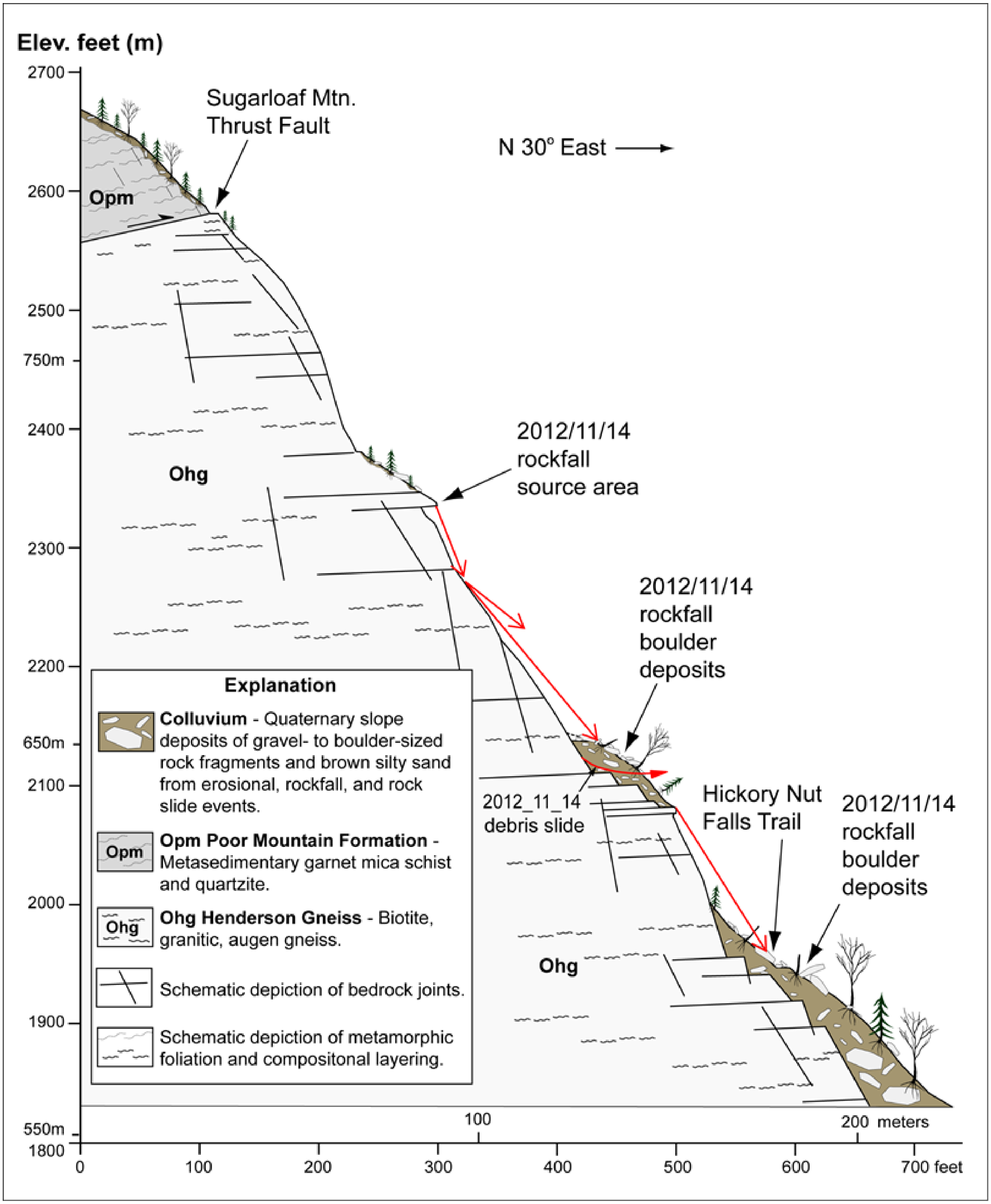

Figure 3-11. Schematic geologic cross section through the area of the November 14, 2012 rockfall showing the rockfall source area, and the rockfall boulder deposit, and unstable debris slide above the Hickory Nut Falls trail. Topographic profile derived from the light detecting and ranging (lidar) digital elevation model (20-ft pixel resolution) with 20-foot topographic contours. Geology adapted from Davis and Yanagihara, 1993.

Figure 3-12. Photograph looking upslope toward the rockfall source area. The rock slab detached from an overhang on the cliff face where an exfoliation joint intersects foliation planes in the Henderson Gneiss. 2012/11/19 NCGS photo.

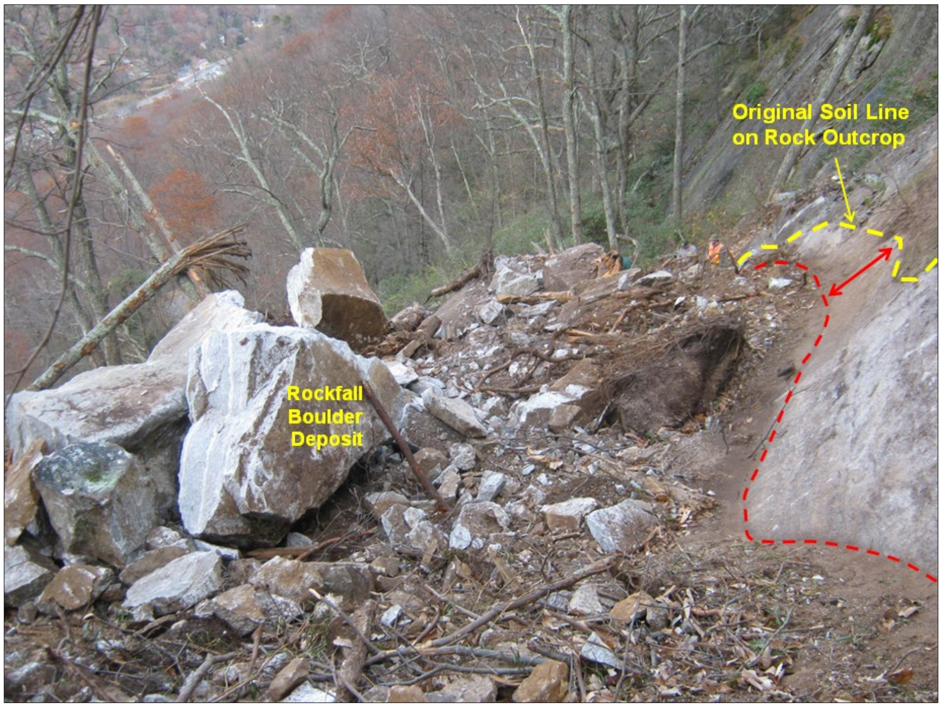

Figure 3-13. Displacement along the scarp of the debris slide developed here along the contact between bedrock and pre-existing rocky colluvium overlain by boulders from the November 14, 2012 rockfall event. The displacement is shown by the distance between the yellow and red dashed lines. 2012/11/19 NCGS photo.

Figure 3-14. Unstable boulder deposit and trees damaged by the November 14, 2012 rockfall event. 2012/11/19 NCGS photo.

Figure 3-16. Left. Severe damage to the footbridge on Hickory Nut Falls trail caused by rockfall and trees downed by the rockfall. 2012/11/19 NCGS photo. **Right.** Arrow points to a rock projectile from the November 14, 2012 rockfall imbedded into a tree below the Hickory Nut Falls trail. The rock fragment is about 2.5-3.0 m above the base of the tree. 2012/11/19 NCGS photo.

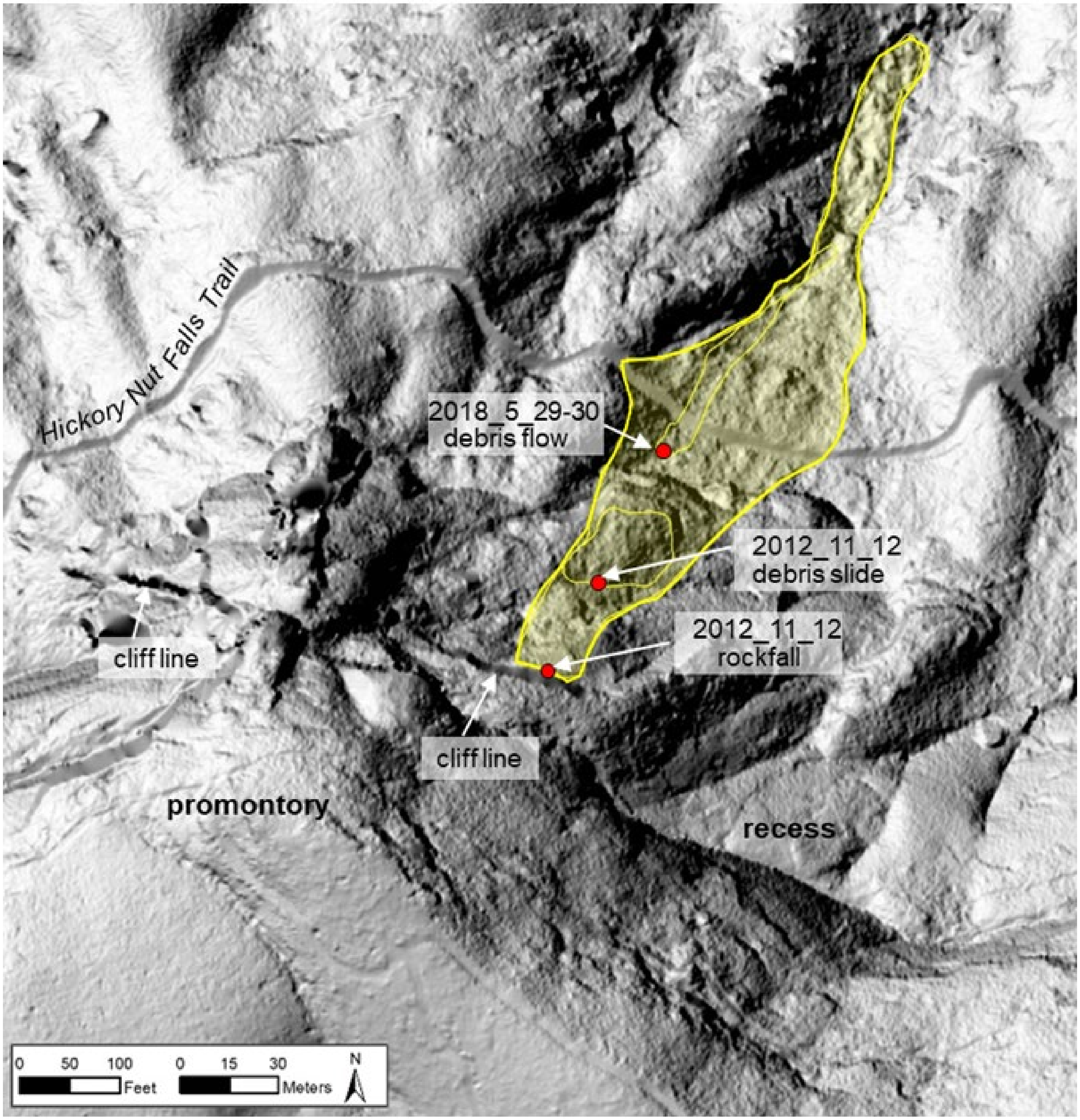

Figure 3-17. Map showing the extent of the November 11, 2012 rock fall – debris slide and a subsequent debris flow triggered by subtropical cyclone Alberto during May 29-30, 2018. The 2012 rock fall occurred along a WNW-trending fracture-controlled cliff line that transects the promontory. Map base is a shaded relief map derived from a 2017 0.5m pixel resolution lidar DEM.

Hickory Nut Falls Viewpoint

Hickory Nut Falls is within a recess along the cliff face. From the Hickory Nut Falls viewpoint on the trail we can see the progressive development of exfoliation fracture networks along the cliff face resulting in the partial detachment of massive sheets of Henderson Gneiss on the on the SE side of the falls (Figure 3-18), and on the NW side of the falls (Figure 3-19). To the SE of the falls meter-scale openings between the sheets and the cliff face are visible. On the near side of this feature the plumose pattern on a NW-striking fracture plane indicates the fracture prorogated toward the NW (approximately normal to and away from the cliff face). Although a subordinate fracture population within the Gorge, similarly oriented NW-striking fracture sets are pervasive throughout the area (Figure. 3-5). Fundamental questions remain as to how the failure will progress at this location. One scenario could involve incrementally slow or rapid buckling or rupture of the toe area that could result in sliding and back-rotational displacement of the rock sheets.

Northwest of the falls a partially detached mega-block of fractured Henderson Gneiss can be seen along the cliff face (Figure 3-19). An exfoliation fracture network is progressing to form a detachment zone for the mega-block. The degradation or loss of toe support would seem to be a critical factor for a catastrophic failure of the mega-block to occur. Given the internal fracturing within the mega-block, falling or toppling of individual blocks is a likely failure scenario.

Figure 3-18. Views of exfoliation fracture network SE of Hickory Nut Falls **Left.** Closely spaced foliation-parallel fractures in Henderson Gneiss. Location at Inset L in center photo. **Center.** Metastable exfoliation sheet detached from the cliff face along a fracture zone network. Insets shows the locations of photos left (L) and right (R). **Right.** Close-up view of fracture network of the detachment zone at inset location shown on photo left. Arrow shows the direction of fracture prorogation toward the NW (approximately normal to and away from the rock face) as inferred from the plumose pattern on the fracture. Location at Inset L in center photo.

Figure 3-19. View of Hickory Nut Falls from the Skyline Trail (currently closed) in Chimney Rock State Park. An exfoliation fracture network is progressing to form a detachment zone for a large block of Henderson Gneiss. View looking west. 2012/11/26 NCGS photo. The tree line just above the cliff face coincides roughly with the trace of the Sugarloaf Mountain thrust fault which places the Poor Mountain formation (Opm) over the Henderson Gneiss (Ohg) (see Fig. 3-5 profile).

Acknowledgments

The cooperation and support shown by the Park Rangers and staff of Chimney Rock State Park over the years is gratefully acknowledged, especially that of Park Superintendent James Ledgerwood and former Ranger Katherine Scheip. Talia Davis of Chimney Rock Park helped immensely in arranging the field trip logistics in the Park. The recollections of LuVerne Haydock and records of her family's history in the Chimney Rock area related to the storms of 1916 and 1996 were especially helpful in understanding and documenting the human side of the story.

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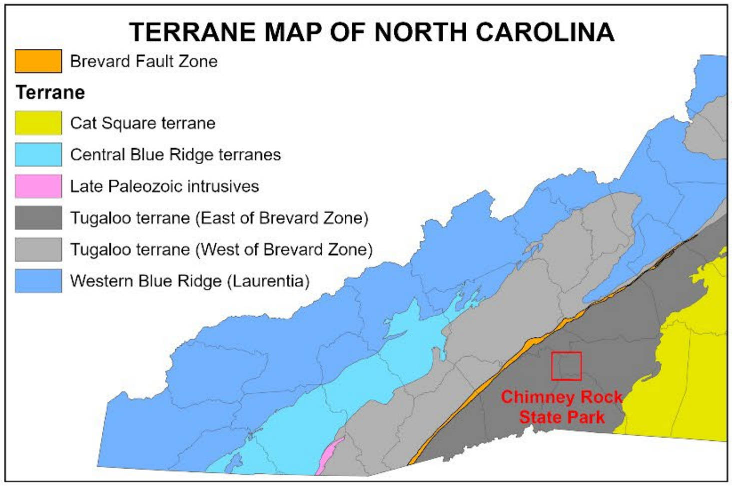
Notes

Notes

Geologic Map of Chimney Rock State Park



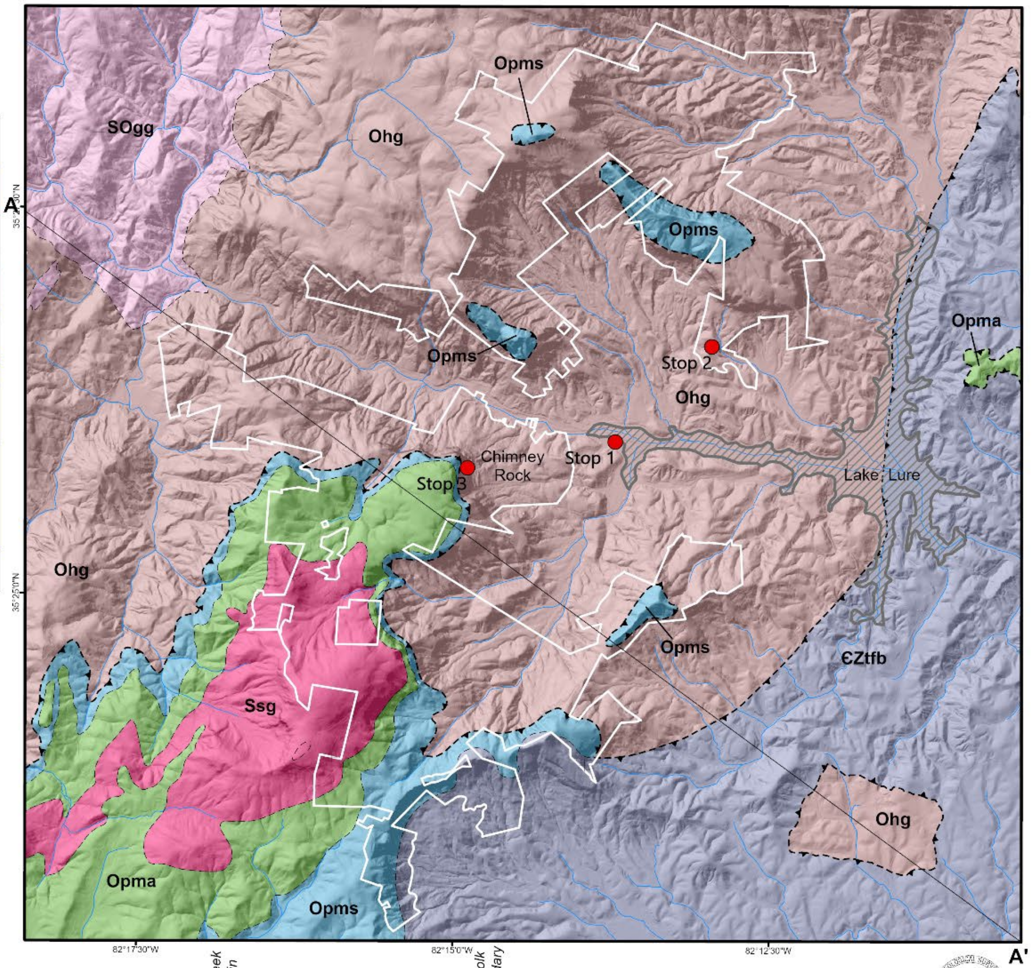
GEOLOGIC UNITS

- **Ssg** Sugarloaf Gneiss
- **Opma** Poor Mountain amphibolite
- **Opms** Poor Mountain felsic gneiss, schist
- **SOgg** granitic gneiss
- **Ohg** Henderson Gneiss
- **ЄZtfb** Tallulah Falls biotite gneiss

GEOLOGIC CONTACTS

- - - - Contact
- - -▾- - Thrust Fault- teeth on upper (tectonically higher) plate
▨ Chimney Rock State Park

Scale 1:50,000
0 0.5 1 Kilometers



CROSS SECTION A-A'