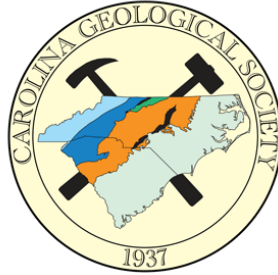


River and Topographic Evolution in Western North Carolina: Evidence from Linville Gorge, Hurricane Helene, and the Laurel Creek Lineament, Spruce Pine, NC

**Field Trip Leaders:
Brad Johnson (Davidson College) and Jackie Langille (UNC-Asheville)**



**Carolina Geological Society Annual Meeting
and Field Trip: November 7-9, 2025**



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On the cover: USGS employees stand at the top of a landslide on private property in the Wilson Creek area during the 2025 Southeastern Friends of the Pleistocene (SEFOP) field trip.

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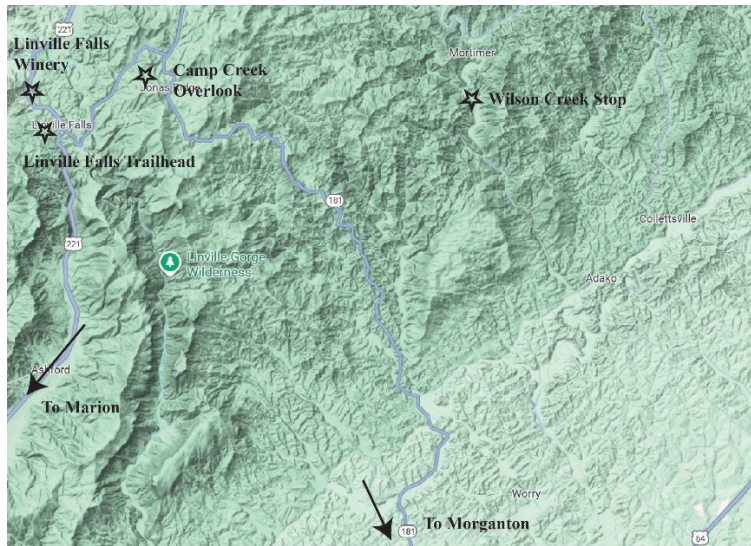
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Tentative Timeline and logistics for Saturday

8:00 AM – Leave Morganton – Please use facilities and fill water bottles before leaving!

9:00 AM – Arrive in Wilson Creek – Guided tour of a variety of sites but also freedom to explore on your own within area defined by field trip leaders. There is one bathroom in the house near the parking spot. The landowner has given us permission to this space; please keep it clean. Take-and-go snacks available. **Please return to buses to depart promptly at 11:30 AM.**

11:30 AM – Depart Wilson Creek

12:15 PM – Arrive at Camp Creek Overlook – 15 minute stop for discussion

1:00 PM – Arrive at Linville Falls Winery for lunch (provided) – Please feel free to make purchases to support this small business, but they are not staffed to serve large groups. Seating available around the property including limited table seating. Bathroom and water bottle refill facilities available. **Please use facilities and fill water bottles before returning to buses to depart promptly at 2:15 PM.**

2:15 PM – Leave the Winery

2:30 PM – Arrive at Linville Falls Trailhead – This is a USFS maintained trail we will follow for ~1.5 miles, out and back. The last 0.5 mile is somewhat steep with 200 feet of elevation gain. There is time to pace yourself, or feel free to stay with the buses. The buses will park near a cabin with a USFS pit toilet behind it. It is usually (but not always) open.

4:30 PM – Leave for Morganton – we'll take US 221 back down the escarpment. Buses will spread out for a very short bathroom stop in the North Cove area, but options are limited, and most gas stations only have one stall.

5:30 PM – Arrive back in Morganton

Background

Our research on the Linville River and the stream capture story that is the focus of this field trip originated as a result of our broader research on the evolution of the Linville River. Specifically, my undergraduate research students researching stream terrace along the Linville River (Olivia Stanley) and Upper Creek (Stine Ornes) prompted my examination of the upper portions of the Linville River during the first summer of COVID (i.e., 2020). After our work on the Linville was published, we received an EDMAP grant from the USGS to map the geomorphology of Wilson Creek (east of Upper Creek and the Linville River). Thus, prior to Hurricane Helene, we were already working on mapping in the area which allowed us to more easily pivot towards post-Helene impacts.

While the Saturday Fieldtrip for CGS will primarily focus on Hurricane Helene in Wilson Creek (morning) and the way that the Linville River captured the uppermost portions of the North Toe River (afternoon), I have also included optional stops at other field sites such that one could examine the broader geomorphology of the field area.

We have licensed the entirety of Johnson (2020) so that the full details for the capture of the Linville River can be provided. That paper will appear later in the document, but we wanted to provide the full context of the – some of it in simpler terms below with new figures.

Field Area

Bedrock Geology

The majority of our day will be spent in or immediately adjacent to the Grandfather Mountain Window (Figures 1 and 2) where younger Paleozoic rocks are eroded off the top of underlying crystalline rock. Specifically, the Linville Falls Fault brings Cambrian metasedimentary rocks, including the Chilhowee Group, up and over Precambrian crystalline rocks (Figure 1). The Linville River often flows along the contact at the Linville Falls Fault and the lower portions are outside the window. To the east of Linville Gorge, erosion has subsequently exposed crystalline rocks including the Grandfather Mountain Formation and the Wilson Creek Gneiss and so Wilson Creek is nearly entirely within the window (see below).

Linville Gorge is defined below Linville Falls where the river drops of the escarpment as a result of basin capture above the escapement. Steep valley walls within the gorge typically comprise quartzites of the Chilhowee highlighting the strength of those units. The Linville River eroded through the Chilhowee along most of its length exposing the underlying softer, crystalline rocks (Grandfather Mountain Formation and Wilson Creek Gneiss) as part of the southwestern most portion of the Grandfather Mountain Window.

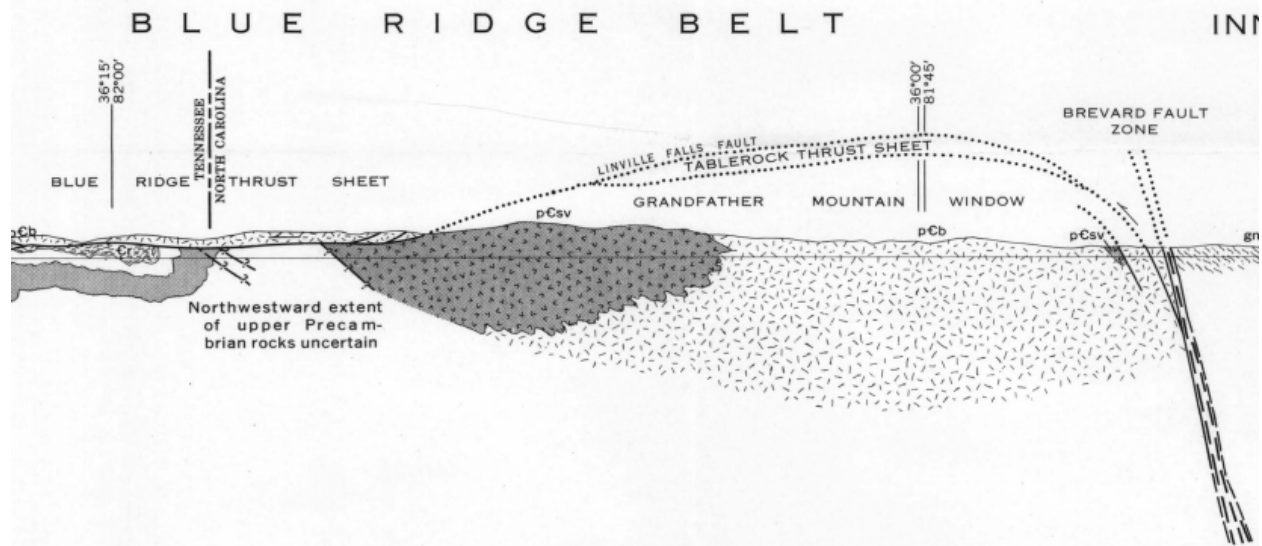


Figure 1 – Modified from Bryant and Reed (1970), this diagram shows the vertical geometry of the Linville Falls Fault and shows how subsequent erosion has exposed crystalline rocks within the Grandfather Mountain Window.

The Wilson Creek drainage basin is entirely within the Grandfather Mountain Window with the majority of the area comprising Wilson Creek Gneiss – which in and of itself is variable. The lowest portions of Wilson Creek flow through a gorge created by the much harder Brown Mountain Granite (Bryant and Reed, 1970). This gorge is a knickpoint and allows for lower gradient streams upstream to store alluvial sediments. The uppermost portion of the field area comprises units of the Grandfather Mountain Formation. There is an upper set of knickpoints that were initially hypothesized to have formed as a result of differential erosion in the Grandfather Mountain Formation but more recent work mapping knickpoint locations indicates that they are more likely the result of earlier stream captures.

Note that a full description of the geomorphology and soil geomorphology of the Blue Ridge is available in the 2022 CGS field trip guide (Johnson, 2022).

Drainage Reorganization

Rivers above the escarpment tend to flow parallel to the Eastern Continental divide while smaller streams along the escarpment face generally flow directly down (Figure 3). Figure 3 specifically shows the differences between the New River drainage above the escarpment and the smaller escarpment face basins. The result is a situation whereby small streams with high potential energy (and relief) have the ability to capture larger drainage basins and pull them over the escarpment face. Figure 4 shows the drainage directions before the capture of the Linville (left) and the resulting Linville River Basin after the capture. Notice how it crosses the orange line which is the Blue Ridge Parkway – which would normally be the Eastern Continental Divide. Note that here the basin crosses the presumed Eastern Continental Divide.

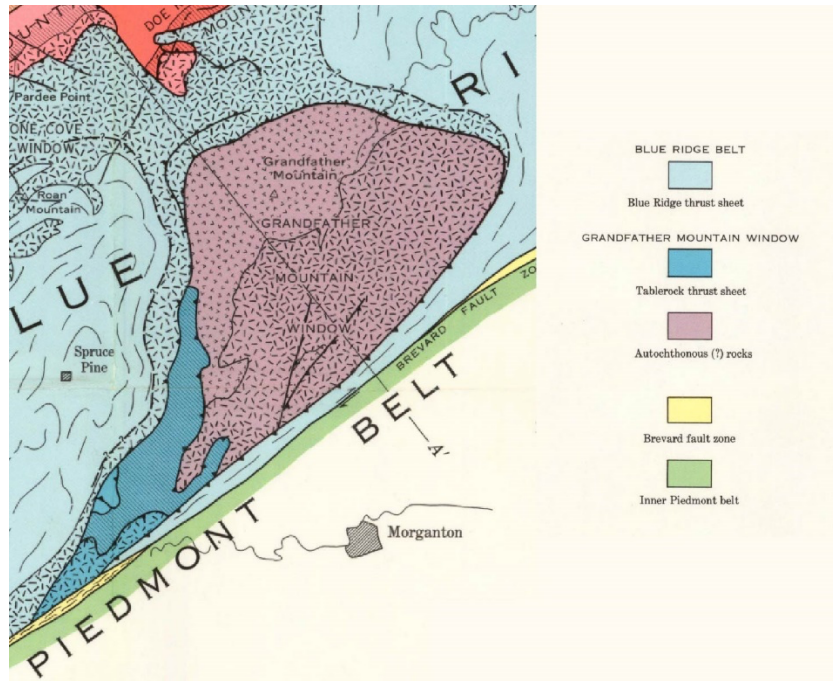


Figure 2 - Modified from Bryant and Reed (1970), this map shows the relationship between the Blue Ridge Thrust Sheet and the underlying crystalline rocks of the Grandfather Mountain Window.

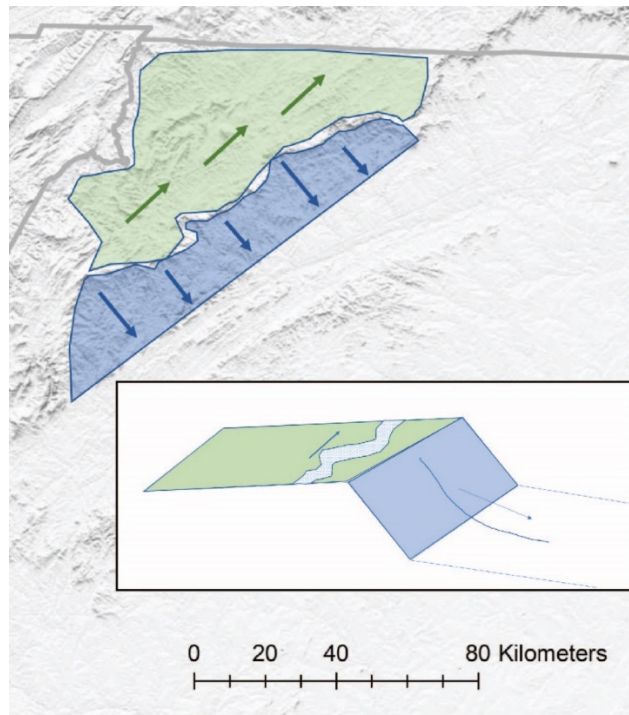


Figure 3 – Map showing different drainage directions above and below the escarpment. Streams on the face of the escarpment are typically steep and drain directly down-dip while streams above often flow along the escarpment. Inset diagram shows the asymmetrical geometry of these streams. The green area roughly outlines the New River drainage basin.

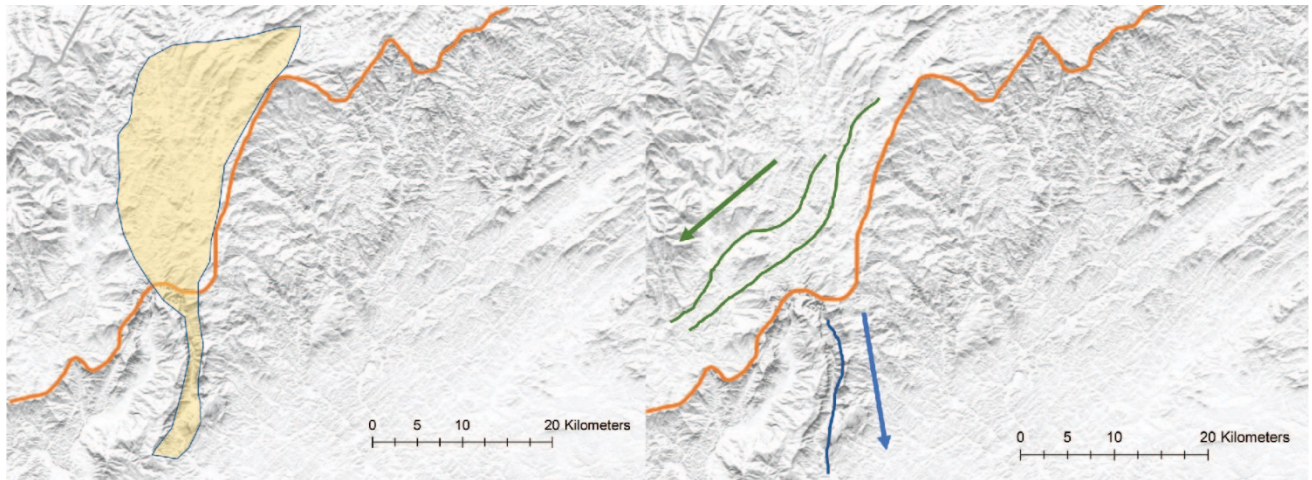


Figure 4 – On the left is the current Linville River drainage basin including its crossing of the top of the escarpment (orange line) – which is typically the Eastern Continental Divide. On the right is the likely drainage pattern if the upper portions of the Linville River followed regional patterns and drained into the North Toe River.

Pleistocene and Holocene Stream Evolution

Our work on the more recent evolution of Linville River and Upper Creek is not the focus of this field trip but will be included as a reference for those who might want to return to the area and explore the geomorphology. Additionally, our work in those drainages informs how we interpret the geomorphology of Wilson Creek since it is an adjacent drainage basin. We have mapped stream terraces in each of the drainages with a focus on Holocene deposition. We have also mapped anthropogenic sediments with the goal of understanding how landscapes respond to 19th and 20th century deforestation. In at least one location, we have exposed and dated Late Pleistocene sediments indicating that rare, older sediments exist and may contain evidence of how streams behaved in the Blue Ridge during that last glacial maximum.

The primary methodology of this research has been geomorphic mapping. All terraces along the Linville, in Upper Creek, and Steele Creek have been mapped. We have also strategically dug soil pits and cleaned stream bank exposures with the goal of using soil development to create relative ages for terrace surfaces. Where possible, we have calibrated these relative ages with radiocarbon dating. We are currently finishing an EDMAP grant to map all surficial units within the broader Wilson Creek field area, and this work includes OSL dating to better constrain the timing of sediment deposition along the Blue Ridge Escarpment.

Hurricane Helene

Hurricane Helene moved through the Blue Ridge of North Carolina on September 27, 2024. The storm was both a high precipitation and high wind event. Combined with precipitation from a stalled front the day before, a large portion of the Blue Ridge received more than 20 inches with a few sites reporting 30+ inches of water. The precipitation saturated soils driving flooding in narrow mountain valleys and landsliding on steep slopes. Rivers that experienced significant flooding (100+ year recurrence intervals) included the Swannanoa, the French Broad, the Cane,

the Toe, the Elk, and the Catawba. Meanwhile, a team headed by the USGS mapped over 2000 landslides in the 3 weeks after the event (Burgi et al., 2025) with the understanding that many more landslides existed that would need to be mapped in the coming years.

In the Wilson Creek area, the river rose to cover nearly the entire valley bottom and drove landsliding throughout the area. At this point, we have mapped over 50 landslides in the area while only examining areas immediately adjacent to a road. Meanwhile, the river itself experienced significant channel widening along with chaotic erosion and deposition in the channel. Log jams are common along both Wilson Creek and its tributaries. On hillslopes, we observe large swaths of trees blown down throughout the field area.

In the months after Helene, Davidson College students worked to collect as much data as possible – first as part of a field course focused on collecting data and then as part of a summer research season. In total, ~15 students worked to collect data to help us better understand the impacts of Helene by collecting highly perishable data. In the early months, we primarily worked in the area around the confluence of Harper Creek and Wilson Creek where there are a variety of features to subsample including debris flows, landslides, tree blowdowns, log jams, and known high water marks.

Saturday Field Trip

Stop: Wilson Creek

Our first stop is in the Wilson Creek area near the Harper Creek confluence (Figure 5). We'll have a couple hours to wander and look at the features discussed below. If you would like to wander on your own, that is fine but make sure you are close enough to know when we are back at the bus. If you want to stick with me, we'll examine log jams, evidence for channel widening, tree blowdowns, and landslides. We'll also walk past two debris flow scars and, if there is interest, we can look at a 100 ka terrace upstream. Thanks to Jazmine Cordon, Mena Tanner, Mary Holmes, Foster Thomas, Noah Landau, Bailey Scarlett, Torin Linton, Jingyan Chi, Anna Farmer, Susanna Payne, Graham Ponder, Neve Rauscher, Owen Lekki, and Hudson Sizemore their work in the field to collect this data and then to process it back at Davidson. I also want to thank collaborators who have come out in the field with us and provided valuable insight including Clarie Masteller (Wash U), Anna Marshall (UT-Knoxville), Brooke Hunter (App State), Scott Marshall (App State), Maya Stokes (Florida State), Ben Mirus (USGS), John Mazurek (USGS), Arthur Merschat (USGS), and Mark Carter (USGS).

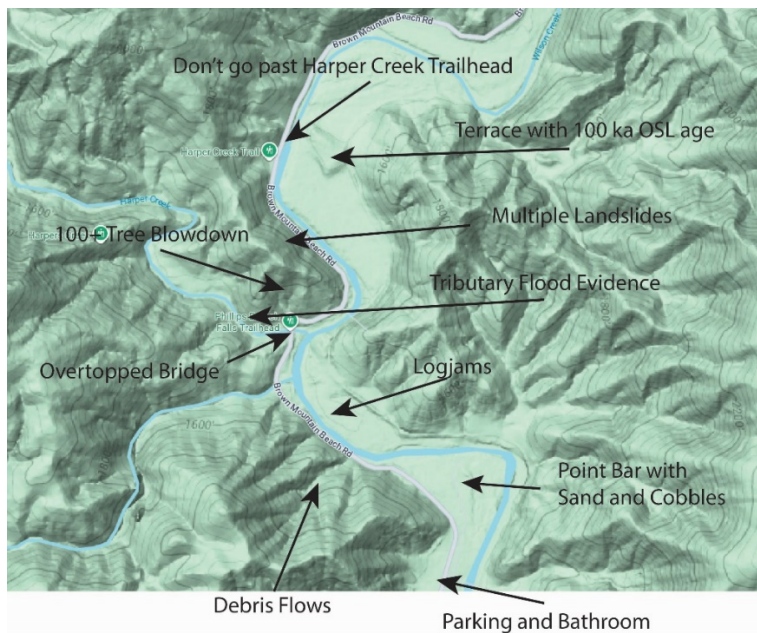


Figure 5. Map of the immediate area where we will be stopping for the Wilson Creek portion of the trip.

Wilson Creek Flooding

We took high water marks (HWM) in the fall of 2024 with funding from the NC Collaboratory along the Blue Ridge Escarpment including along Wilson Creek. We took water marks using an RTK wherever we observed the water reached on the valley sides (i.e., we did not take valley center marks even where they were obvious because we wanted to avoid inaccurate vertical GPS points). In most places in Wilson Creek, water filled the entire valley floor Figure 6). In the

narrow lower gorge, water was often near or over the road but there are especially deep portion where the road was above the water. At the Killians site (where we will park and walk from), seasonal residents kept trailers along the river, and all of these were lost in the flood water. Some houses here were damaged as well. Sedimentary deposits were extensive with aggradation of cobbles and/or sand often as deep as 1 m near the channel edges (Figure 7).



Figure 6. Red dots indicate high water marks well above the road the Killians property where the field trip will be stopping. Water would have filled the valley all the way to the far valley wall.



Figure 7. Sand and cobble deposition on the Killians property where we will visit during the field trip.

At the confluence of Harper Creek and Wilson Creek, the water reached the top of the bridge and eroded the approach to the bridge from both sides (although the structure itself survived). For months after the storm, residents routinely forded the river and drove up the the steep embankment on the northern side (Figure 8).

Wilson Creek Logjams

Emerging research over the past 20 years has highlighted the importance of woody material in streams for both ecological and morphological reasons. In spring and summer of 2025, we set out to do a systematic survey of woody debris in Wilson Creek (Figure 9). While the Army Corps of Engineers set out to remove most woody debris from river corridors (to the frustration of many ecologists and fluvial geologists), Wilson Creek has thus far not had much wood removal (some on private land) despite initial suggestions that it would be removed.



Figure 8. Local residents fording Harper Creek six weeks after Helene.



Figure 9. Photographs of logjams in the Wilson Creek area.

Our preliminary analysis of logjam data suggests significant changes between the headwaters of Wilson Creek and the main channel. For instance, average jam length (Figure 10) and average tree size is greater in larger rivers – likely as a result of increased energy downstream. Additionally, larger rivers tended to have more jams in the floodplains with tributaries having more logjams in and adjacent to the main channel (Figure 11) and logjams in larger rivers tended to be parallel to flow direction while in smaller streams wood was more likely to be perpendicular to flows and, perhaps, impede water more. Lastly, larger rivers had a greater number and percentage of living trees in the logjams (Figure 12). These trees typically tipped over in place and have not been transported. The typically either grew on islands or on now eroded channel banks. They likely serve an important stabilizing factor in stabilizing the system by catching sediment and wood.

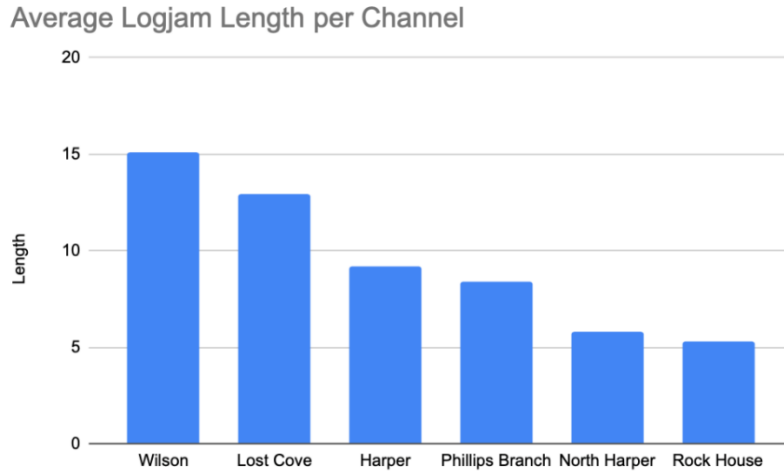


Figure 10. Average logjam length across various streams. Each stream to the right has an increasingly smaller basin area with Wilson as the largest and Rock House as the smallest.

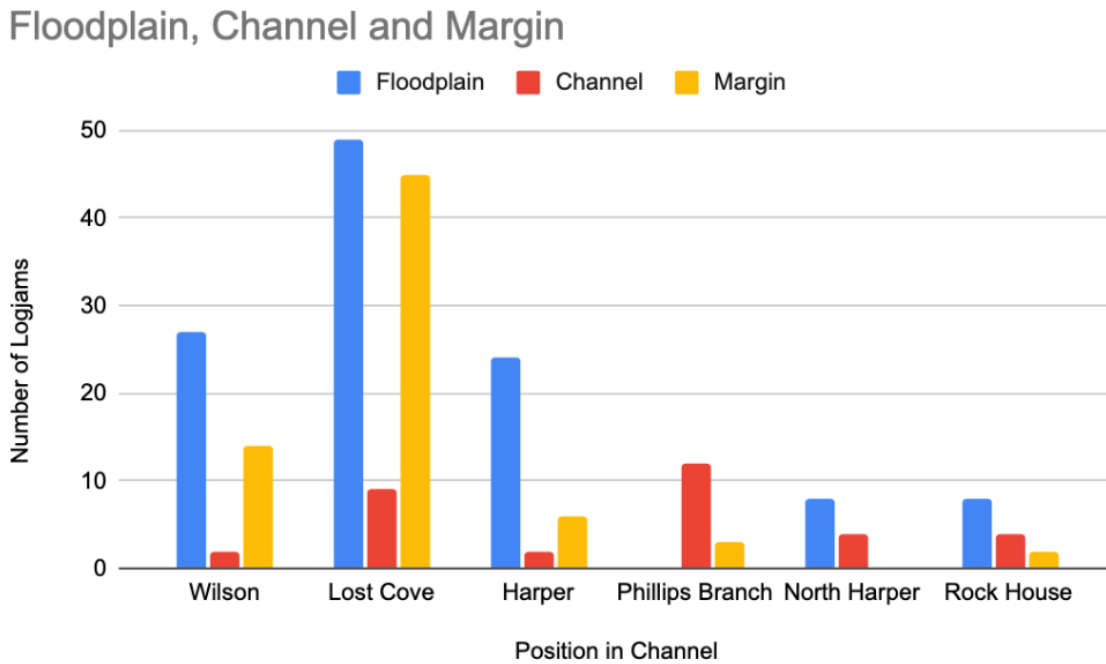


Figure 11. Logjam location across various streams with the largest basins on the left and smaller ones on the right.

Number of Living Trees

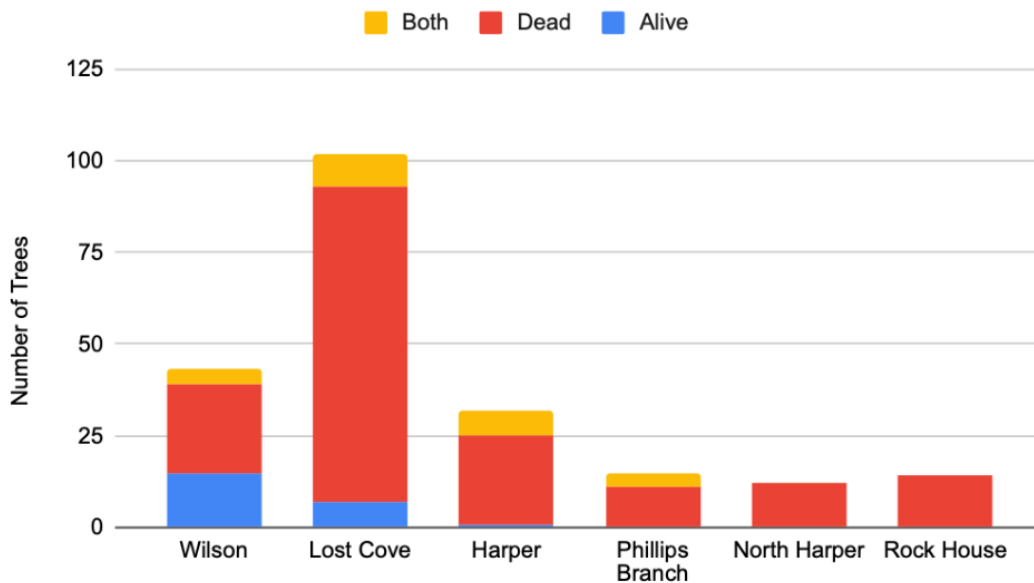


Figure 12. The number of living trees within logjams across a variety of stream basins.

Landslides in the Wilson Creek Area

The known threshold for landsliding in the Blue Ridge is when precipitation reaches 5 inches/24 hours. With up to 30 inches falling in 36 hours, the threshold was crossed for many hours with high chances of landsliding during the storm. To date, we have mapped 50+ landslides in the Wilson Creek area (Figure 13) without the use LiDAR differencing from post-Helene LiDAR (which has not yet been released). More than 95% of these landslides were mapped because they are visible from the road. We expect there to be 2-5x as many landslides once we can examine more remote areas. The majority of landslides occurred on human-altered hillslopes both because we were looking near roads and because altered hillslopes are more likely to slide.

In our preliminary dataset, we have been able to examine each of the 50 slides in the field (Figure 14) with more intense soil examinations at ~ 5 sites. Our results indicate that the majority of slides occurred near the saprolite-soil boundary indicating that subsurface flow may have been high at this layer due to differences in permeability.

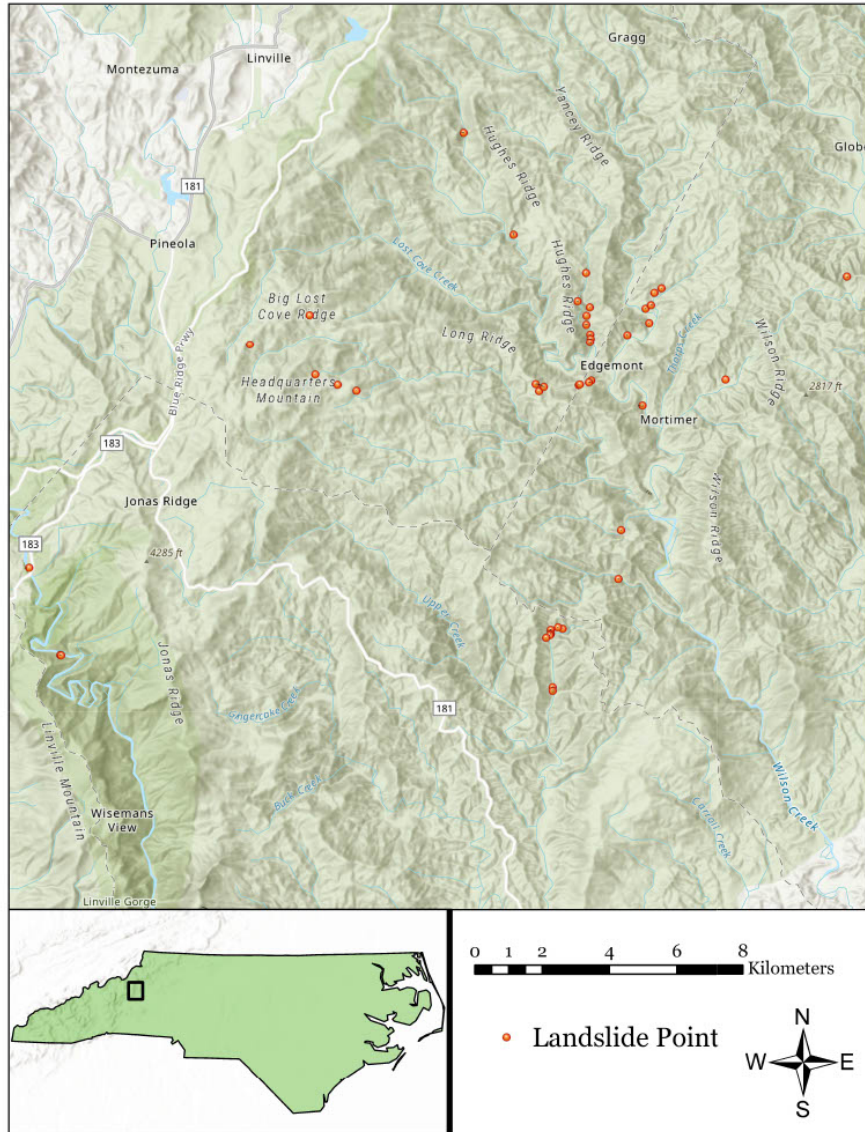


Figure 13. Distribution map of known landslides within the Wilson Creek watershed.



Figure 14. Photographs showing landslide scars in the Wilson Creek area.

Tree throws in the Wilson Creek area

We have mapped over 300 tree throws in the Wilson Creek area with the goal of better understanding tree damage and soil displacement. NDVI differencing data generated by Steve Norman at the USFS indicates that there are likely more than a million acres of blow down in the Blue Ridge with varying levels of damage. We have examined five different blowdown patches in the area and at each tree we measured tree diameter, hole diameter, hole depth, and tree orientation (Figure 15).

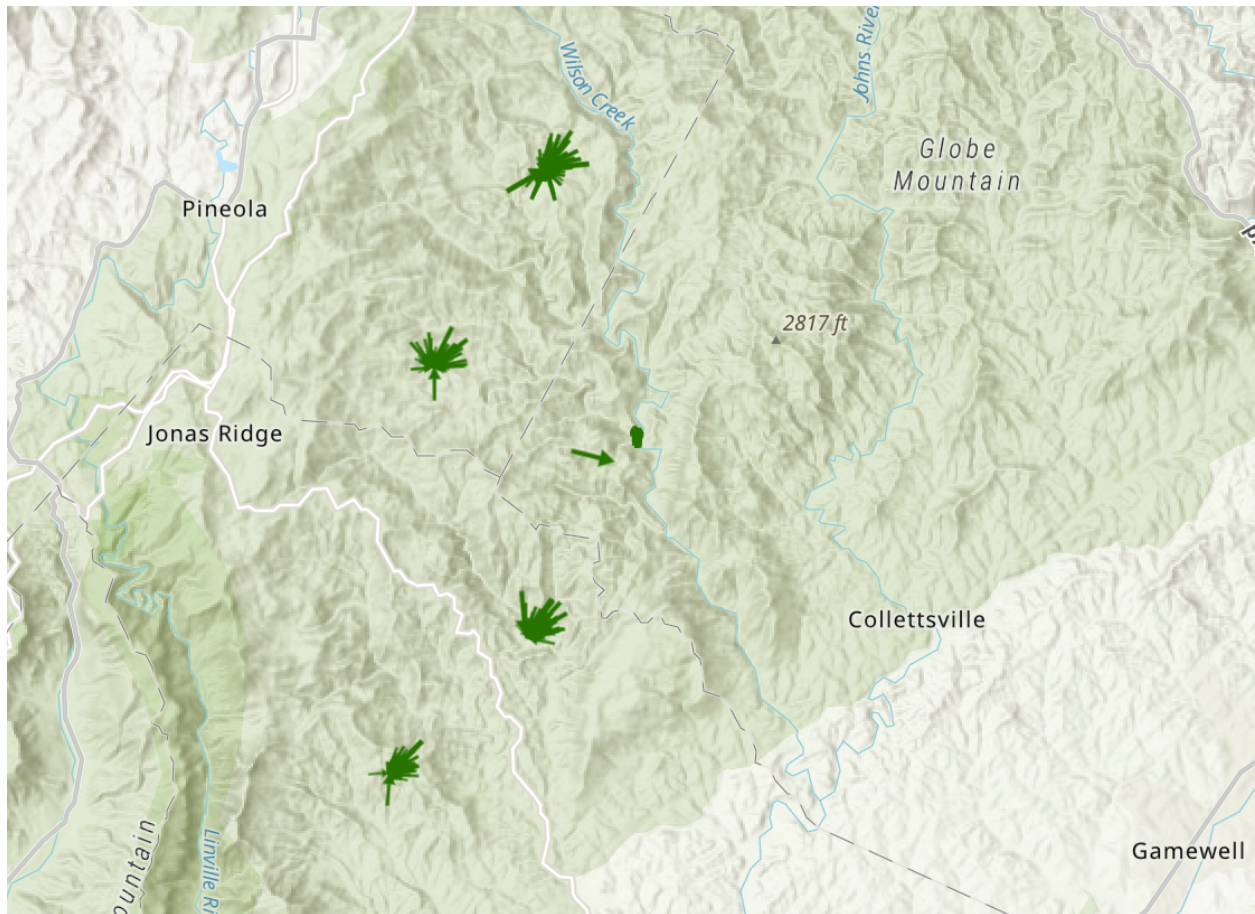


Figure 15. The five different locations where we have mapped all tree throws. Arrows point in the direction that the tree has fallen, and the size of the arrow represents the size of the tree throw.

The majority of tree throws fell towards the southwest (Figure 16) which is consistent with strong rotating winds from coming from the northeast. Most tree throws are on south-facing slopes – perhaps as a result of wind compressing on the tops of ridge and then flowing down the back of the ridge.

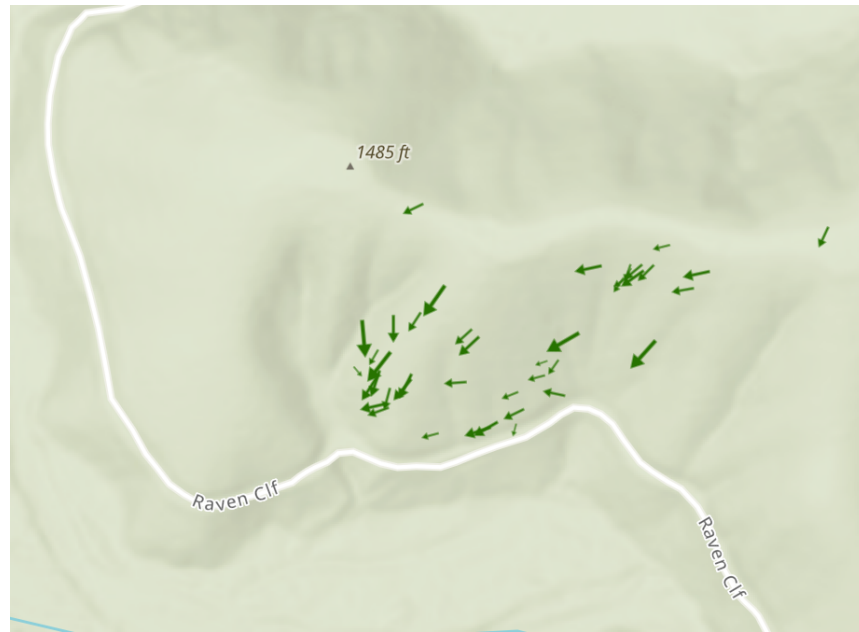


Figure 16. Trees in a single blowdown on a south-facing slope with arrows pointing in the direction of the fall. The vast majority are towards the SW.

The average tree throw disturbs 1.6 m^3 of soil indicating that blowdowns are a significant soil disturbance event (Figure 17). While very little of this soil appears to move downslope in the immediate aftermath of the storm, it is likely that some of it moves downslope in the following years. The odds of wildfires also likely go up with the increase in downed trees. Wildfires would very likely increase the odds of further sediment mobilization. Tree throws also commonly contain bedrock fragments (Figure 17) which is likely an important mechanism for bringing rock to the surface on hillslopes.

Optional Stop - NC181 and FS 982 – we will not be stopping here during our trip because it is inaccessible to buses, but it is a great place to visit and explore Holocene (and some Pleistocene) geomorphology.

Forest Service Road 982 is a dirt road that descends from NC 181 down to Upper Creek (Figure 18). There is a left turn at the bottom labeled in the figure below as Raven Cliff FS Road but more commonly signed as FS 197. Turning up this road will take you to a series of terraces that we have mapped and examined (additional terraces are present downstream but are less accessible).



Figure 17. Large tree throw mapped by students as part of a Davidson College class in the spring of 2025.

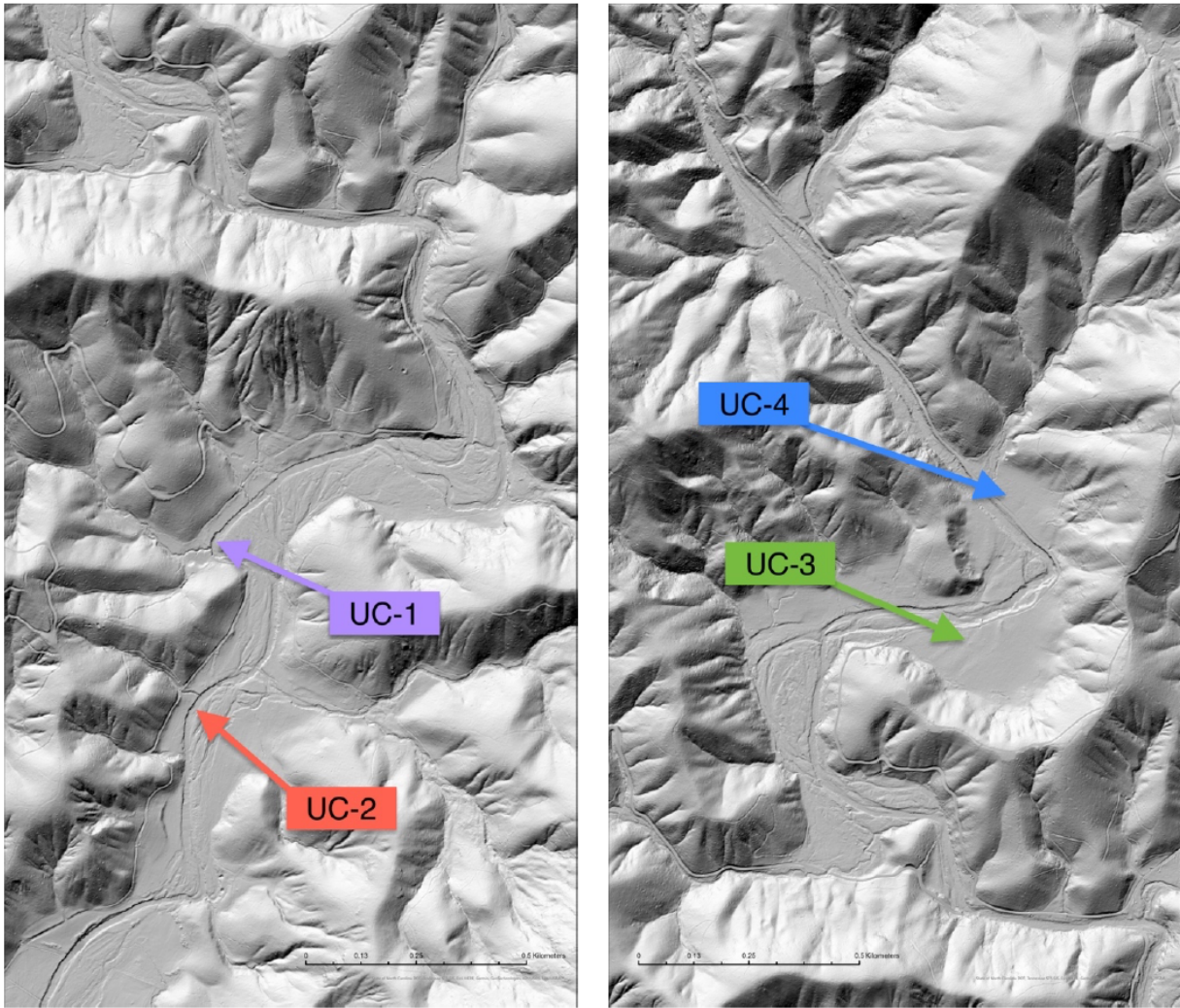


Figure 19 – Detailed LiDAR hillshades showing both the flat/smooth terrace unit and the rough/braided terrace unit. Labels show the location of exposures where soils and sediments were examined and where radiocarbon samples were taken from.

Typically, we would view the upper terrace (the smooth one in this case) as older than the lower, cobble rich surface. However, there is increasing evidence that the cobble surface extends under the overbank deposits (Figure 21) indicating that the overbank deposits are simple younger sediments draped over the older cobble layers. That said, it remains difficult to determine the relationship between the lower surface and the buried cobbles.

Floodwaters from Helene reached the lower terrace in this area but not the upper terrace. It is the only terrace that we have mapped across the Linville, Upper Creek, and Wilson Creek that was not inundated during Helene. This would suggest that it is much older and a true terrace as opposed to a “100 year floodplain” style terrace.

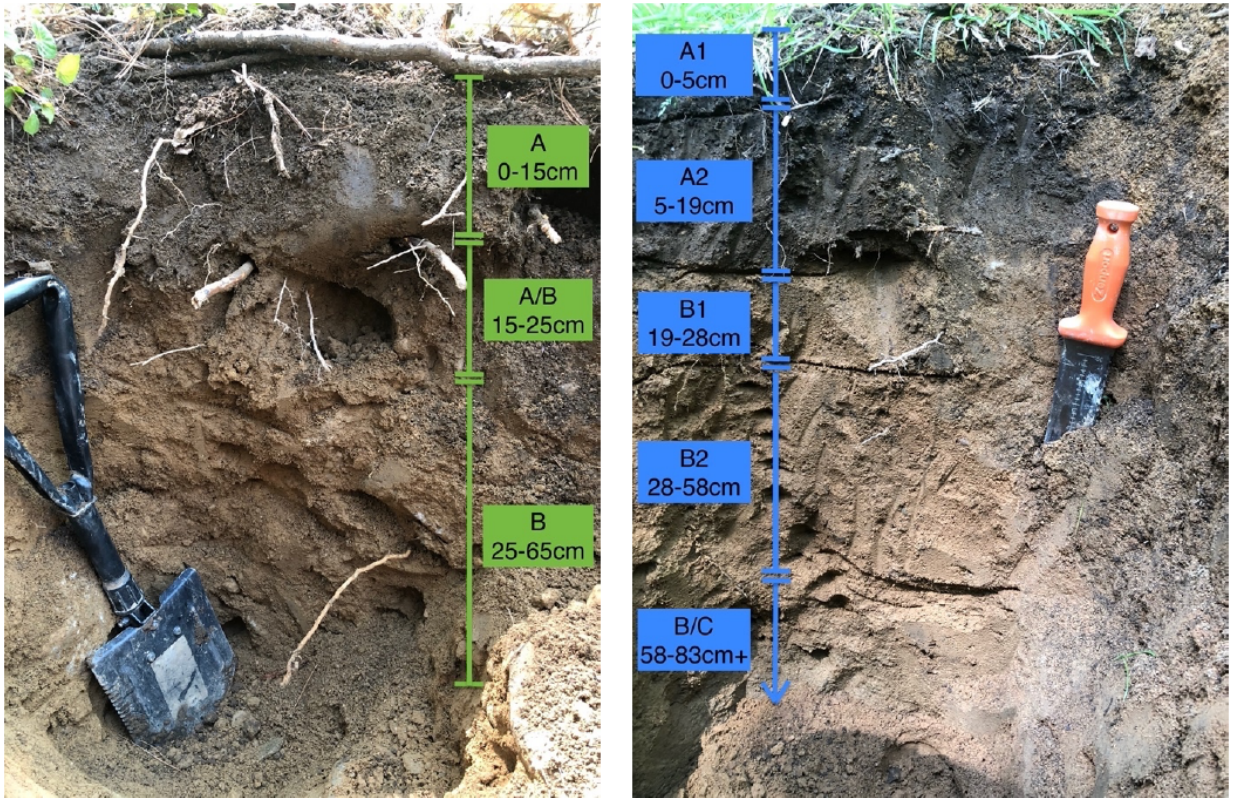


Figure 20 – Annotated soil profiles at sites UC-3 (left) and UC-4 (right). Horizonation fits a typical A/B/C pattern with moderate development in both A and B horizons.



Figure 21 – Cobble deposits underlie fine-grained overbank deposits. This may indicate that the lower, cobble-rich terrace extends underneath the smooth, overbank terrace. Alternatively, these cobbles could be unrelated to the lower cobble surface.

Downstream of FS 982 by about 2 km of stream length, we cleared two sections of exposed stream bank (UC-1 and UC-2 in Figure 19). UC-2 is similar to upstream upper terraces comprising fine-grained overbank deposits. In this location we have multiple radiocarbon ages (Figure 22) dating to ~3000 year BP near the bottom of the 2.5 m clearing to ~1400 years BP ~ 1 meter from the top. The three ages are in stratigraphic order and indicate consistent aggradation over the Late Holocene. UC-1 is upstream of UC-2 by roughly 1 km but is very different despite similar exposure heights.

UC-1 features massive grey clay near the base with very low organic content. Charcoal sampled from within the clay was dated at ~12.8 ka. Sediments overlying the grey clay are similar to what has been observed downstream. A recent OSL age from a gravel layer above the clay returned as 6,400 years old for both quartz and gravel both supporting the veracity of the underlying age and indicating this part of the valley floor is much older.

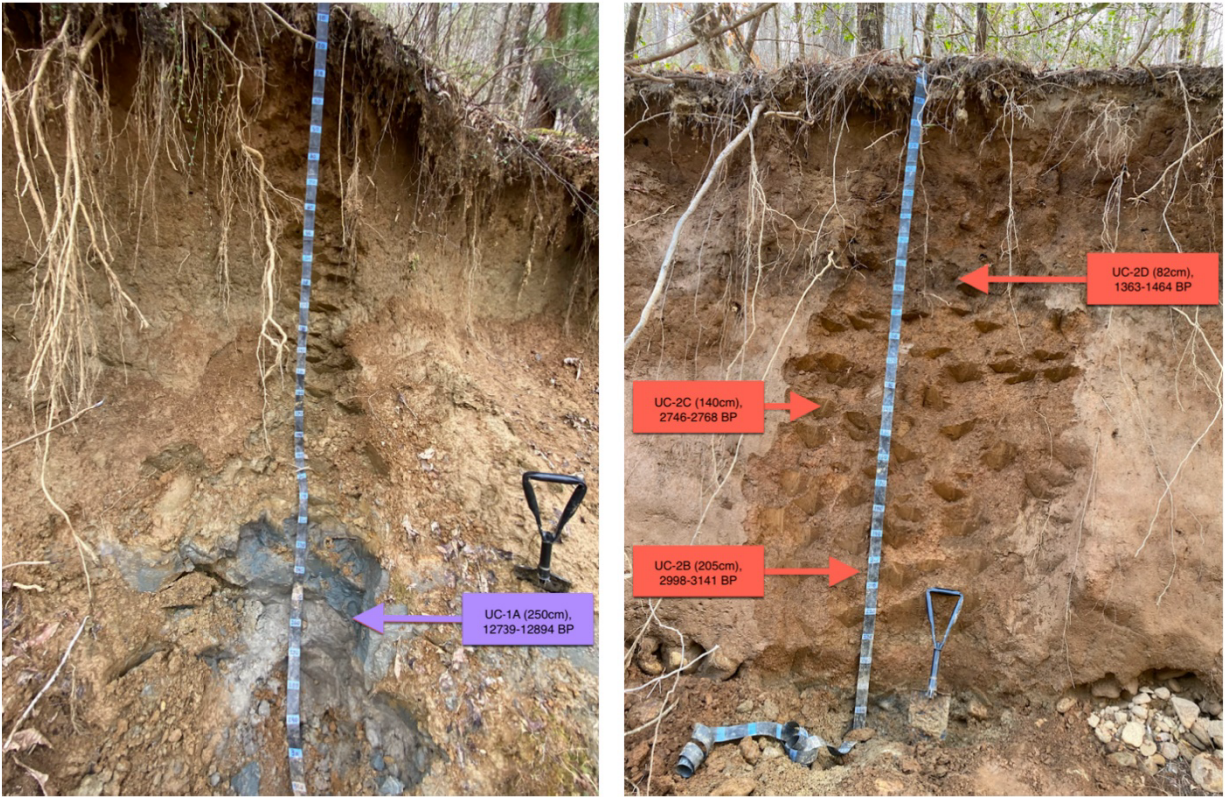


Figure 22. Exposures in stream banks at UC-1 (left) and UC-2 (right). UC-2 is generally fine grained with radiocarbon ages indicating consistent deposition throughout the Late Holocene. UC-1 contains massive clays at the bottom which were deposited ~12.8 ka.

It is hard to imagine what low energy environment could have existed within the high relief Upper Creek drainage. Our leading hypothesis is that the channel was at the far side of the valley at the time and a wetland formed at the base of the slope where a stream discharges. More broadly, it is interesting that Pleistocene sediments are preserved in the area because little is known about the Last Glacial Maximum in the Blue Ridge (other than that there were no glaciers). If Pleistocene sediments are common in valley bottoms, then these areas should be the focus of research and not the peaks that have more commonly been studied for evidence of periglacial geomorphology. The mid-Holocene age in the overlying gravels indicates that in the portions of Upper Creek where we see braided morphology, portions of the valley bottom can be deposited and then may remain unchanged for long periods of time.

Stop: Camp Creek Overlook Camp Creek Overlook (see road map; Figure 23) may not be one of the more inspiring pull-offs on the Blue Ridge Parkway, but it is an important site in understanding stream capture. **See the original Johnson (2020) provided at the end of the Saturday section for full details.**



Figure 23 – Road map showing the location of the Camp Creek Overlook.

The modern geometry of the upper Linville River features the main stem flowing north to south with tributaries flowing in from the east and west. It is relatively easy to line up tributaries east of the modern river with likely stream reaches to the west of the river. The first step in understanding if this previous drainage organization was possible was to determine if the two upstream tributaries (Duggers Creek and Camp Creek) are actually uphill from the Brushy and Threemile Creeks. Or in other words, would these hypothesized paleo-rivers have been able to flow downhill?

Both upstream sections are higher in elevation than their downstream counter parts. More importantly, both streams have flat upstream sections that grade across the valley to modern drainage divides on the other side of the Linville River. The Camp Creek Overlook is right at the dividing line between the upper portion of Camp Creek which grades across the valley towards Threemile gap and the lower portion of Camp Creek which flows down through a knickzone to the modern, incised Linville River. In other words, the modern Linville River has cut down to create the broader Linville Valley and tributaries following into it have had to respond by steepening their slopes.

At this stop you can explore the low gradient upper portions of Camp Creek including portions with modern day beaver dams. Climbing down from the overlook will provide the opportunity to view the knick-zone that has formed as Camp Creek has responded to the new, lower base level of the Linville River. Specifically, if you scramble down the informal trails below the parking lot, you can reach the river in the middle of a series of cascades. Further downstream, the stream continues to steepen before dropping into the Linville River Valley.

Stop: Brushy Creek Drainage Divide (aka Linville Falls Winery)

Linville Falls Winery is a convenient place for our lunch and has nice views of the landscape on top of the escarpment. The winery has been generous to host us and allow us to use their beautiful facilities as a stop. Please feel free to purchase a glass of wine to have with lunch (there are also snacks inside if you would like to supplement your lunch). You can also buy bottles of wine for later. Any way you can support the winery is appreciated.

Linville Falls Winery is adjacent to the Brushy Creek Drainage divide. The paleo Brushy Creek would have flowed from the east side of the current Linville River down through the modern Brushy River valley (Figure 24). This valley is underfit as it contains a very small stream that appears to have cut a very large valley – typically thought to be evidence supporting stream capture. More importantly, geologic maps (Bryant, 1965; Bryant and Reed, 1970) show large fluvial gravel deposits all along the modern, very small stream. Most suspiciously, one of these gravel deposits is at the drainage divide!

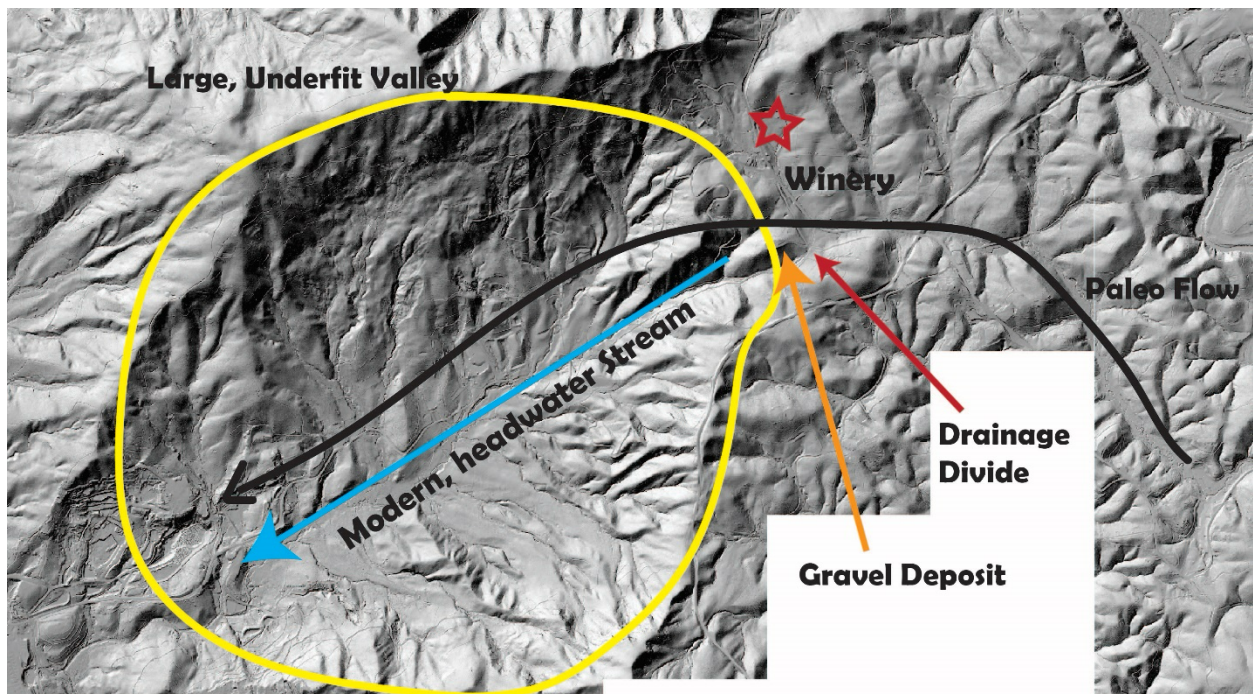


Figure 24. LiDAR derived hillshade map of Brushy Creek Canyon which is underfit. Note the location of the gravel deposit near the modern drainage divide. The winery is adjacent to this location.

The gravel deposits are very hard to view today as the uppermost one has a private residence born on it and the lower ones have been heavily disturbed by heavy mining activity at the Sibelco Mine (and the later construction of the adjacent airport). Nonetheless, it is possible to find large, rounded cobbles far from the modern stream along Brushy Creek Road. We sampled rounded cobbles and interpreted them to be made of quartzite – an interpretation supported by the Sibelco Mine geologist, Mark Adams. The only quartzite outcrops upstream are on the other side of the modern Linville River indicating that paleo-rivers must have crossed the modern Linville River. During the 2021 SEFOP field trip, some attendees thought that the cobbles might be derived from vein quartz – which is present on this side of the Linville River. Mark Adams indicated that he thought that the cobbles did not look like vein quartz within the Sibelco Mine,

but we have not made thin sections to confirm this one way or another. Indeed, the rounded gravel deposits themselves would seem to be evidence enough.

Threemile Canyon to the north has a similar capture story and the gravel deposits are easier to see there. Farm fields on either side of the road contain rounded cobbles well above the modern river. Because they are visible when fields are plowed but not when crops have been planted, Google Streetview is often the easiest way to view them. We sampled cobbles from these farm fields and interpreted them to be derived from quartzite located on the other side of the Linville River.

Linville Fall Winery is a useful place to think about the differences between the modern drainage pattern and the historic one. Specifically, the winery location itself is located in a different drainage basin than it was before capture. Currently, water from the winery flows off to the east and into the modern Linville River whereas historically this spot would have been part of the North Toe River drainage and water would have flowed through the Brushy Creek Canyon. Modern drainage into the Linville River has caused significant erosion on headwater streams and we can now observe a dendric drainage pattern well below the paleosurface. More bluntly, if you look to the east towards the Linville River, all of the low-lying topography must have been exhumed since the capture event happened.

Stop: Linville Falls

At this stop you have the option of hiking down to Linville Falls and viewing the waterfall and maybe the Linville Falls Fault. We will meet in the parking lot first and discuss the importance of the site. The easiest approach to the falls would be from the NPS parking lot but it, and the buildings there, were flooded during Hurricane Helene. Portions of the Blue Ridge Parkway and trails to Linville Falls remain closed. Instead, we are likely to use the USFS parking area and our destination will depend on what trails are open. The Upper Falls viewing area is often preferred as there is a clear exposure of the Linville Falls Fault. However, at the time that I am writing this (9/25) that trail remains closed. The alternatives include

The optional hike is a relatively easy one as it is roughly 1.0 miles round trip on the trail to “Upper Falls” on the map (Figure 25). Be aware that the 0.1 miles before the turnaround is on steep, sometimes slippery steps. On your return trip to the bus, make sure to head back to the main Blue Ridge Parkway parking lot and NOT the USFS parking area. We will announce a time to reconvene at the buses, please do not be late.

Stream capture in the upper Linville River increased the drainage area of the basin and therefore increased the discharge of the lower Linville. This caused increased erosion in the form of downcutting and led to the formation of Linville Gorge. In the lower portions of the valley, downcutting has resulted in steep hillslopes and cliff exposures. At the Linville Falls fault, the Linville River has not had the energy to erode through the harder Cranberry Gneiss resulting in the formation of Linville Falls. Since the timing of the capture event is unclear, it is also unclear how long the falls have been “stuck” at their current location. More specifically, it is unclear whether the current discharge of the Linville River is insufficient to move the knickpoint away from the fault or if we simply happen to exist in the moment that they are at the fault.

Today the falls mark the boundary between the upper Linville River where the slope is low and the lower Linville River where the river is much steeper (Figure 26). This controlling knickpoint allows the upper river to meander while the lower river is much straighter and more direct.

Linville Falls

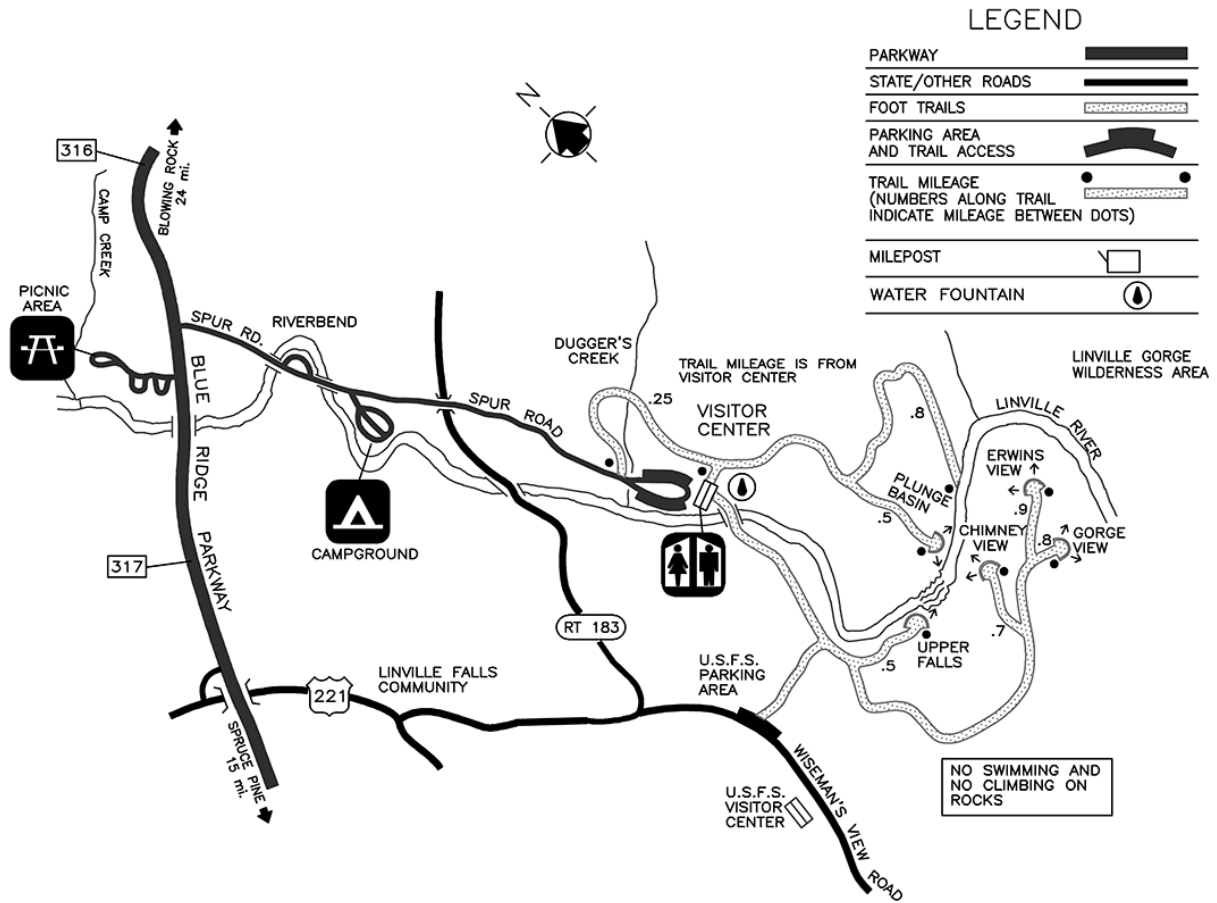


Figure 25. National Park Service hiking map of the Linville Falls area. We will park at the end of the Spur Road by the visitor center and bathrooms. On your way back to the buses, make sure you stay to the right to return back to this and avoid leaving towards the other parking area. Map from LGmaps.org

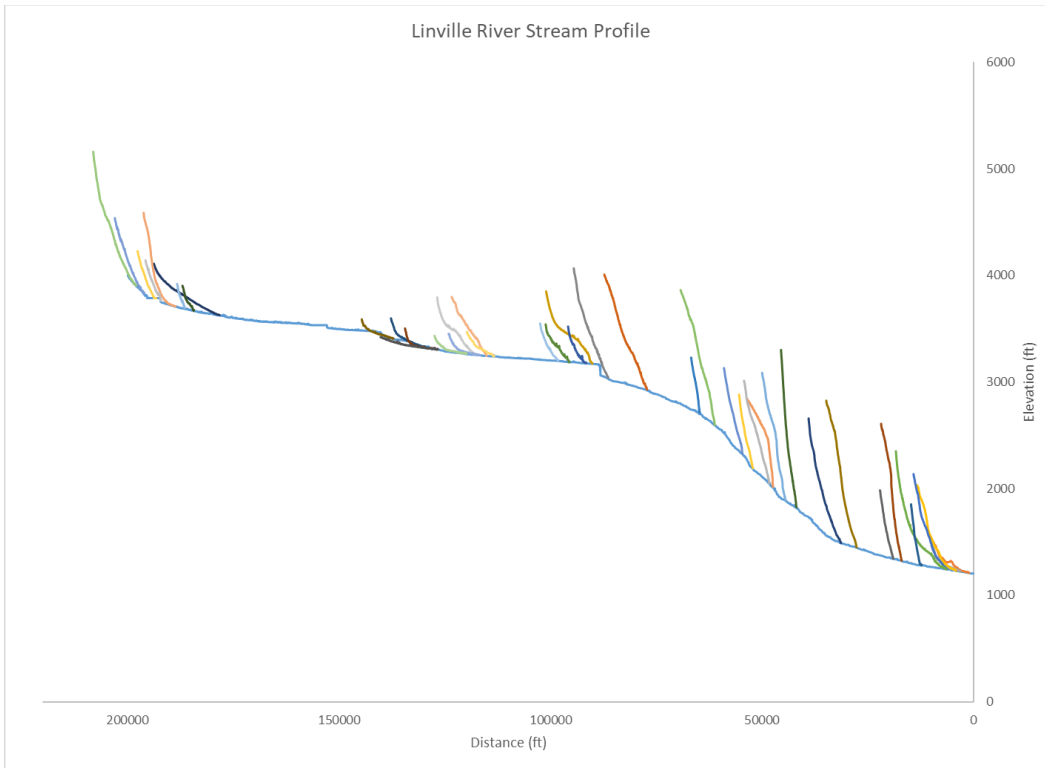


Figure 26. Profile of the Linville River with the Linville Falls knickpoint dividing the upper portion of the river from the lower portion of the river. Multicolored lines are major tributaries that flow into the Linville River which are steep in the gorge because of post-capture incision.

Optional Stop – Linville Gorge – we will not be stopping here during our trip because it requires a rugged, time-consuming hike. We are including our best understanding of local geology in case people would like to return to the site. The easiest way to get to the sites described here is via the Blue Dot trail originating either from Fonta Flora County Park or Lake James State Park.

In the lower portions of Linville Gorge, significant amount of sediment is stored as the profile flattens out (Figure 27). These terraces are very similar to those discussed earlier in Upper Creek, but we have dug additional exposures in the center of these surfaces (Figure 28) with more complete descriptions of soil morphology.

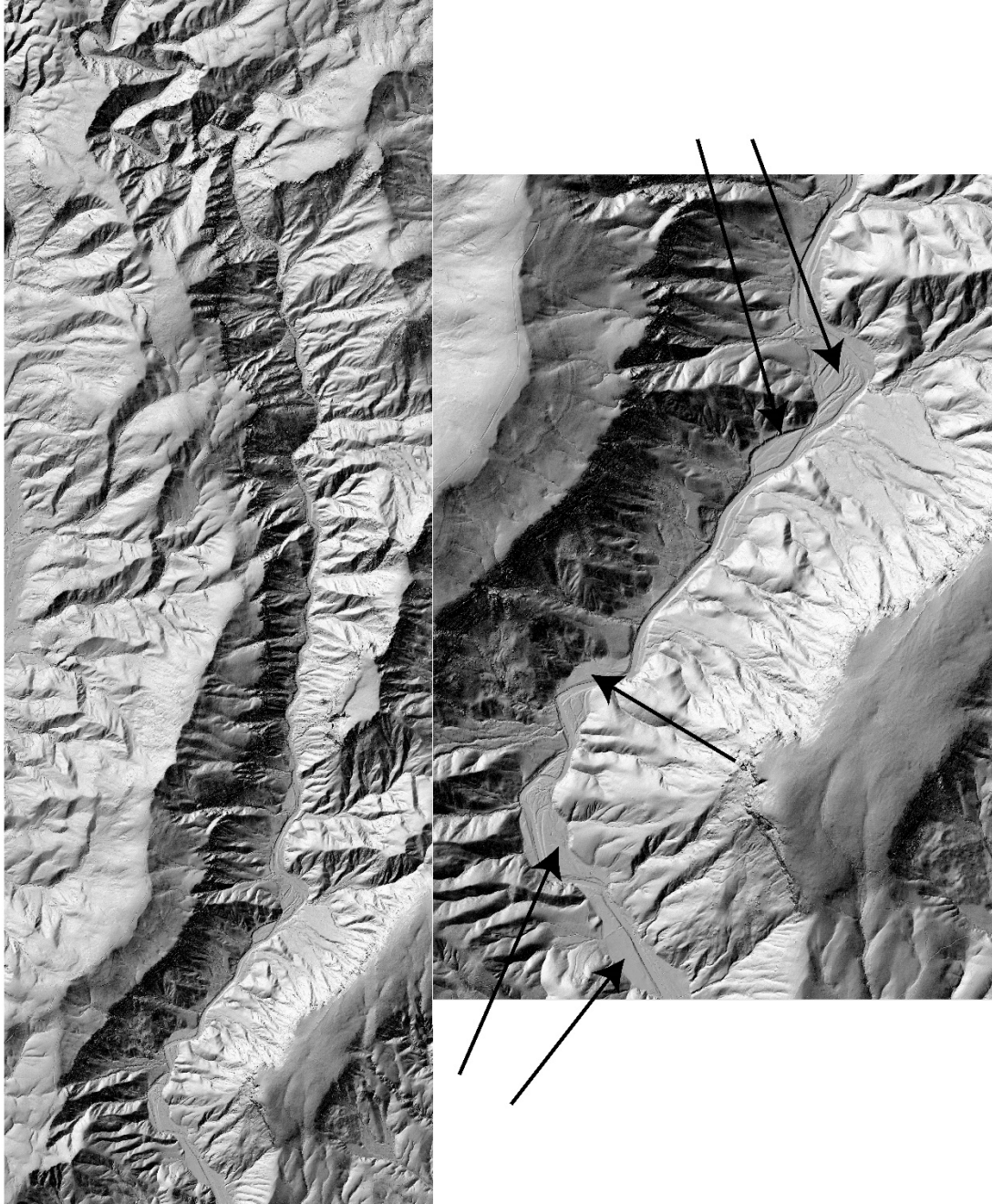


Figure 27. LiDAR derived hillshade of Linville Gorge. The right (inset) image focuses on the lowest portions of the gorge with arrows pointing to portions of the terrace.



Figure 28. Soil profiles dug in the middle of the terrace surface in Linville Gorge. These exposures provide unaltered views into the sediment as opposed to stream exposures which can be impacted by modern fluvial processes.

Terraces in Linville Gorge comprise sandy overbank deposits. We confirmed this interpretation both with radiocarbon dating (Figure 29) and soil morphology (Figure 30). Across all surfaces, we see consistently younger ages as depth shallows (Figure 29). Soil morphology features underdeveloped horizonation indicating cumulic soils and consistent aggradation. We have observed similar patterns in other mountainous areas where Holocene deposits are much finer than older sediments and are interpreted as overbank deposits (Johnson et al., 2023). These results are interesting because they seem to indicate that the channel has not significantly migrated during the second half of the Holocene.

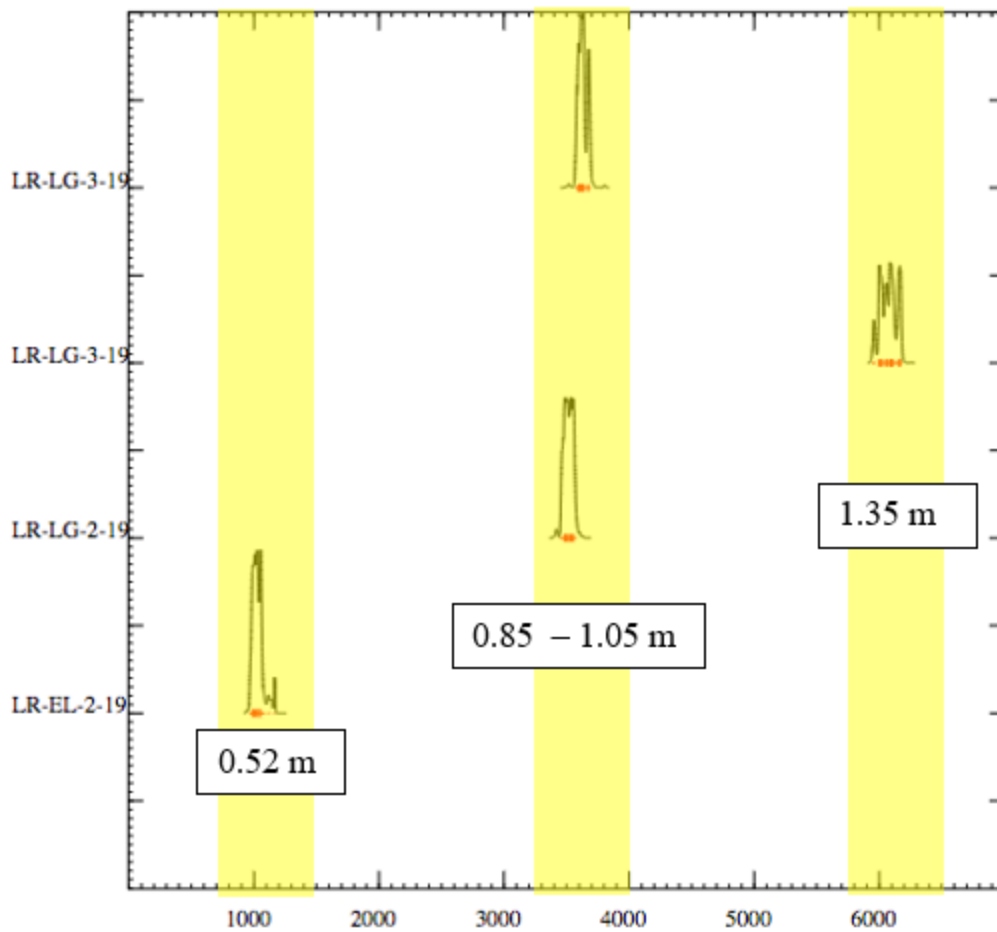


Figure 29. Across multiple terraces and profile locations, we see consistent aggradation. The left axis is the profile location ID while the bottom is calibrated years before present. Individual ages are represented by probability plots with depth ranges labeled in yellow.

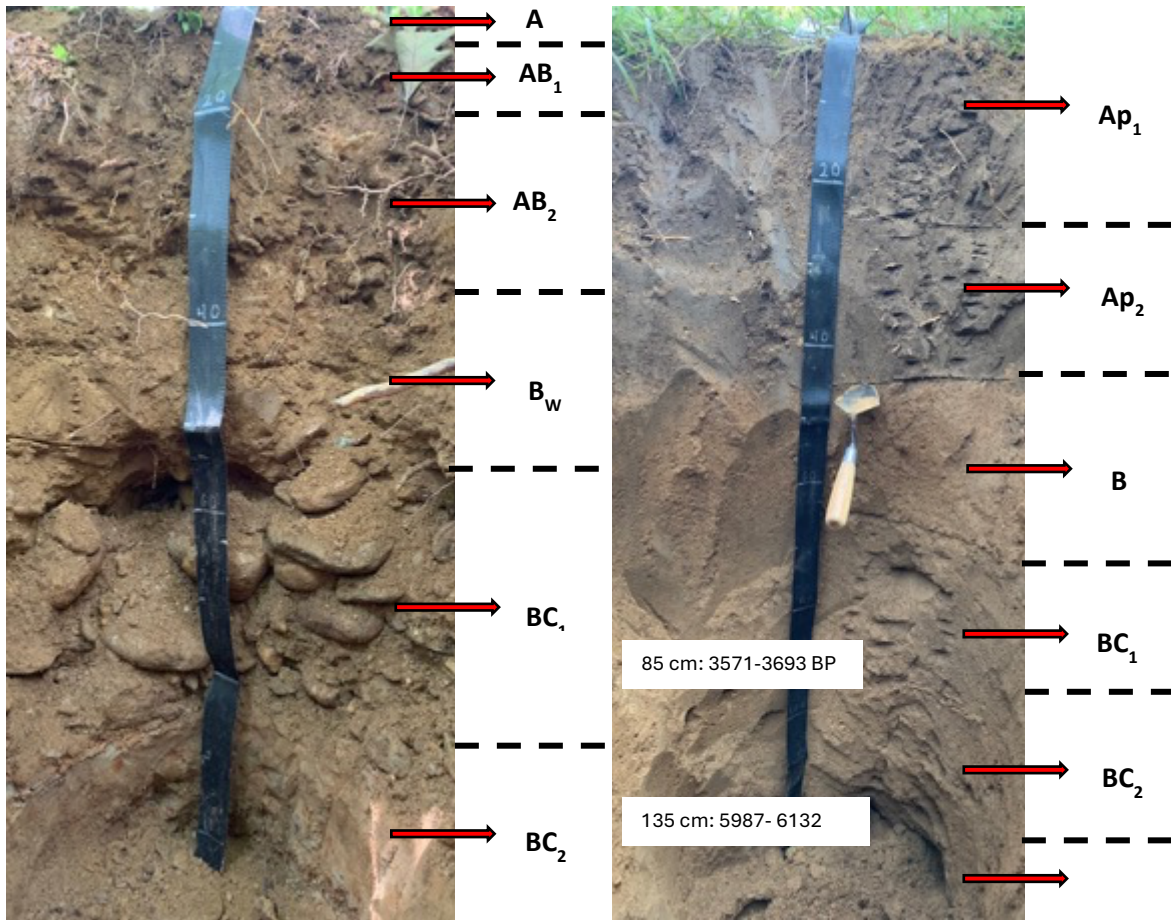


Figure 30. Soil profiles from Linville Gorge Terraces show consistent aggradation throughout the Holocene confirming that the fine-grained sediment is the result of overbank deposits.

Optional Stop: Fonta Flora Brewery and Paddy Creek Terraces

Terraces extend from the river valleys along the escarpment out into the Piedmont. While we have not studied these units extensively, it is likely that they correlate directly with sediments deposited within the canyons. This is true for each large river system flowing from the escarpment although most of the terraces for the Linville River are under Lake James.

While Paddy Creek has not been a part of our focus, Fonta Flora Brewery’s Whippoorwill Farm location provides a useful place to examine sediment along these old terraces. The brewery has allowed us access and it is a beautiful place to have a beer and think about the evolution of the fluvial system.

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Sunday Field Trip

QuartzCorp, Pine Mountain Quarry

Logistics: Closed toe shoes, long pants, and hard hats are required. CGS will have *some* hard hats to borrow. The group will depart from the hotel at 8:00 AM and return by 12:30 PM. Please use facilities and fill water bottles before leaving! The drive to the quarry is about 1 hour. Limited facilities will be available around 9:00 AM before entering the quarry.

Kinematics of the Laurel Creek Lineament and its role in Cenozoic topographic rejuvenation near Spruce Pine, North Carolina

Overview of the Laurel Creek Lineament

Geomorphological and structural evidence suggests that topographic rejuvenation has occurred along the belt of high elevation within the Blue Ridge Mountains of western North Carolina and the Valley and Ridge of Virginia, USA (e.g. Hill, 2013, 2018; Spotila and Prince, 2022) (Fig. 1). In western North Carolina, there are various sets of linear topographic lows that have faults and fractures that strike obliquely to the NE-SW striking structures associated with the formation and rifting of Pangea, indicating that these lineaments are younger. Previous studies suggest that these fracture systems have accommodated topographic rejuvenation (Hill, 2013, 2018; Langille et al., 2023) (Fig. 1).

These fracture zones appear to have some seismic activity (Hill, 2013) (Fig. 1). In 2005, an earthquake occurred in Hot Springs, North Carolina, along the Laurel Creek Lineament which shows that this is an active system (Figs. 1 and 2). In 2020, Sparta, North Carolina, faced a 5.1 magnitude earthquake that also occurred along an ~E-W oriented lineament system (e.g. Figueiredo et al., 2022) (Fig. 1).

The Laurel Creek Lineament extends east from Hot Springs to Spruce Pine, North Carolina (Fig. 1). Near Spruce Pine, it cuts through medium to high-grade metamorphic rocks of the Ashe Metamorphic Suite (AMS), which originated as sediment on the Iapetus Ocean floor prior to the Taconic orogeny, and the Silurian-Devonian Spruce Pine Plutonic Suite. On this field trip you will see these rock units as well as fractures associated with the Laurel Creek Lineament exposed within one of the QuartzCorp quarries.

Spruce Pine 7.5-minute quadrangle: Structural observations

The Laurel Creek Lineament is an ~E-W trending lineament that can be seen throughout the Spruce Pine quadrangle by joints and faults (Figs. 2 and 3). Jointing was documented throughout the quadrangle but is more pronounced in the more competent units (Fig. 4A). Fractures dominantly strike E-W with near vertical dips. Several steeply dipping faults had evidence of north side up motion (Langille et al., 2023). Offset rock units and asymmetric tension gashes

indicate the north block moved up relative to the south block (Fig. 4B and C). Foliations dominantly strike toward NE-SW, dipping shallowly toward the SE (Fig. 3B).

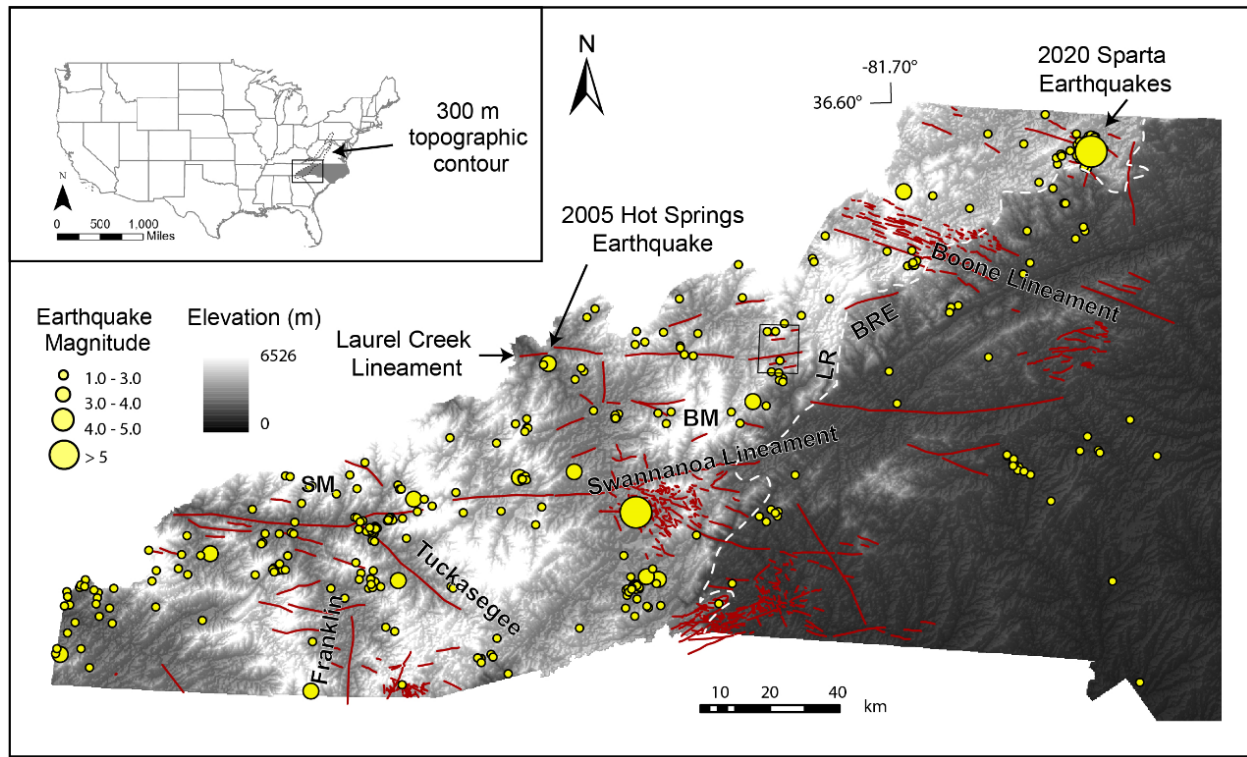


Figure 1. Lineaments and associated fractures in western North Carolina (red) with earthquakes from 1916 to 2023 (USGS). The black rectangle shows the Spruce Pine 7.5-minute quadrangle. SM, Smoky Mountains; BM, Black Mountains; BRE, Blue Ridge Escarpment; LR, Linville River. The inset map shows the location of western North Carolina within the lower U.S. and the elevated topography of the Blue Ridge (dotted line). From Langille et al. (2023).

Evidence for Topographic Rejuvenation

Notable topography within the Spruce Pine quadrangle includes the topographic low corresponding to the lineament and the higher elevations north of the lineament compared to the south (Fig. 5). Stream knickpoints and elevations were used to support an interpretation that north-side up motion on the faults in this quadrangle is expressed in the topography.

Knickpoints discordant with lithologic contacts and anthropogenic disturbances ($n = 24$) were identified on streams flowing south into the lineament (Fig. 6). The elevations of these knickpoints ranged from 782 to 1071 m, with peak frequency at 867 m (s.d. 70 m). A strong cluster (50%) of these knickpoints was found between 825 and 875 m (Langille et al., 2023). Streams on the south side of the lineament did not exhibit knickpoints associated with topographic disequilibrium and all were associated with anthropogenic disturbances or lithology (Fig. 6).

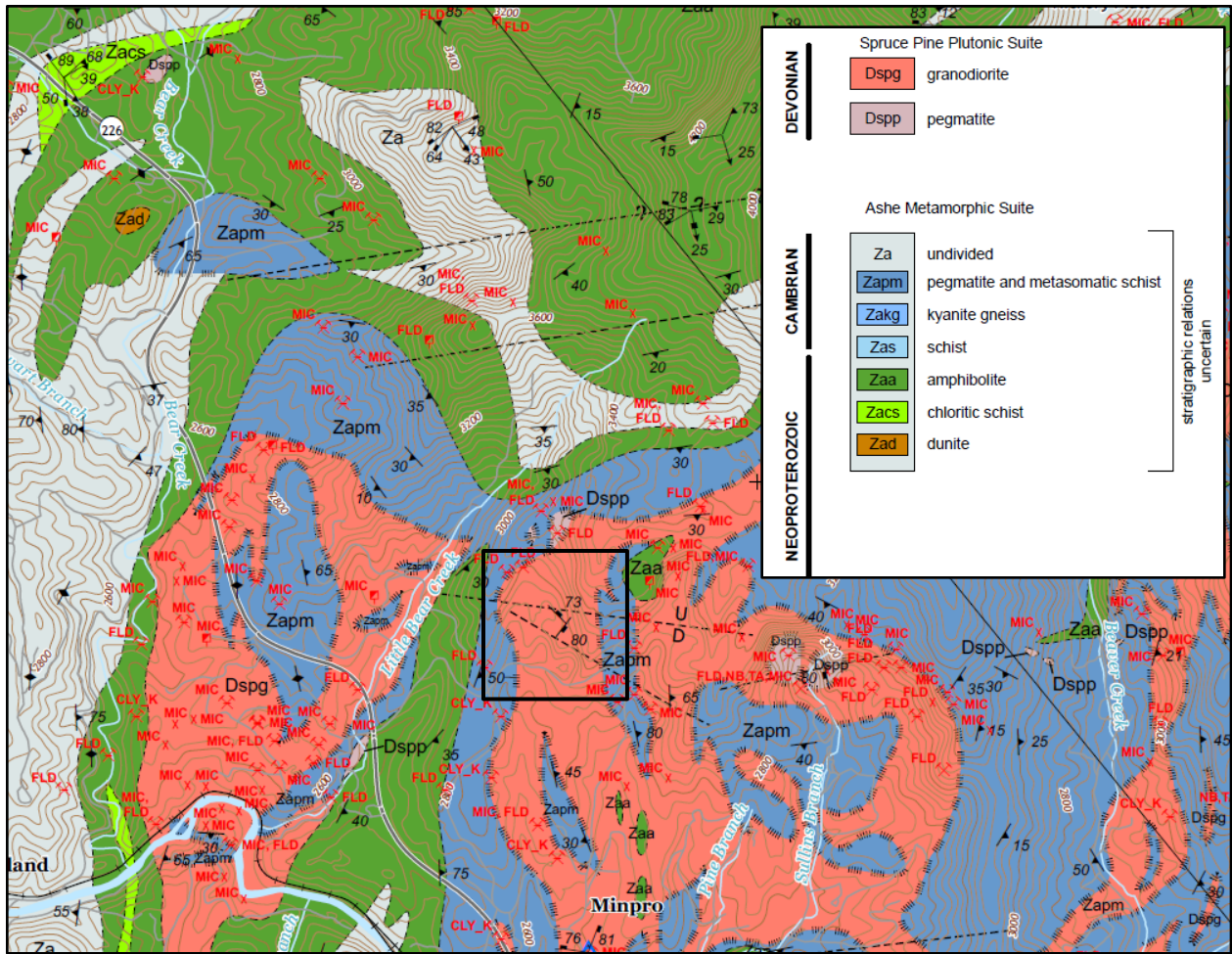


Figure 2. Portion of the Spruce Pine 7.5-minute quadrangle geologic map showing the location of the field trip (black box). From Langille et al. (2024).

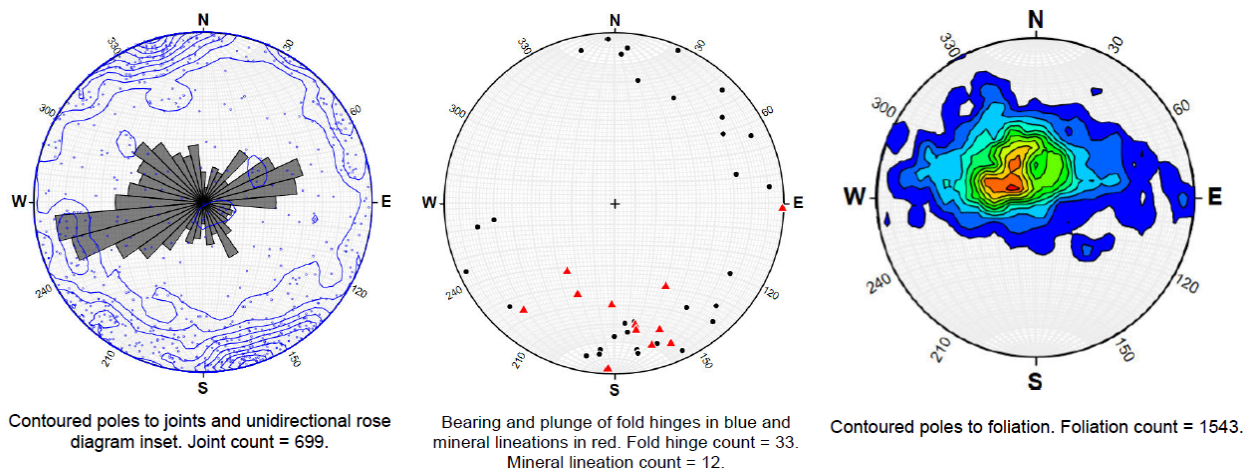


Figure 3. Structural data from the Spruce Pine 7.5-minute quadrangle from Langille et al. (2024).

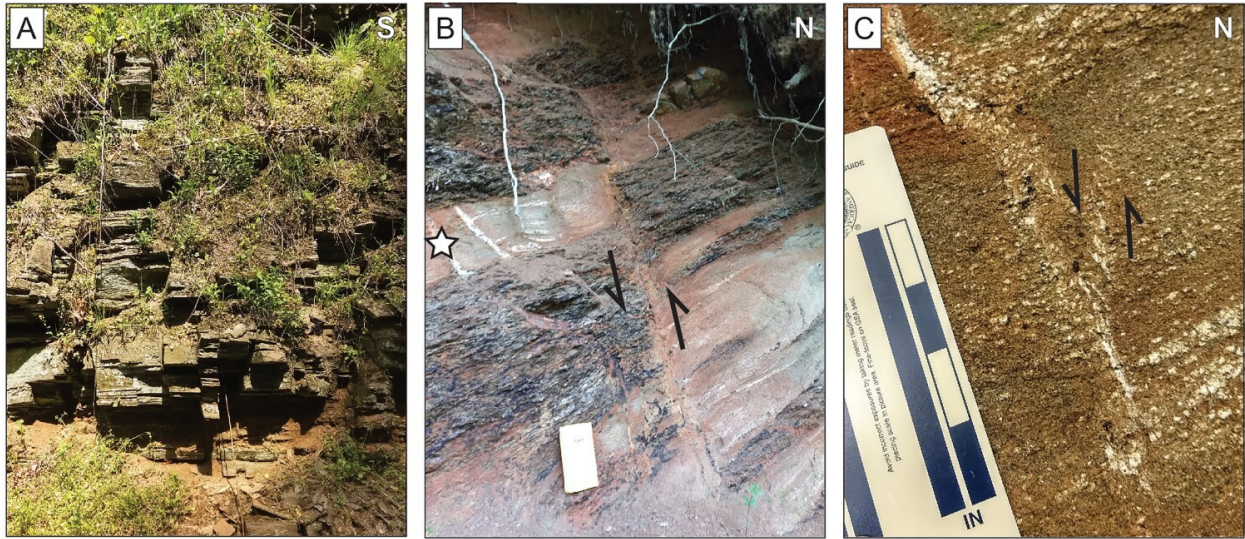


Figure 4. (A) Near vertical joints that strike toward 260° within amphibolite. (B) Steep dip-slip fault with 48 cm of offset with north block up. The star is the location of (C). (C) Tension gashes, shear sense noted as black arrows. From Langille et al. (2023).

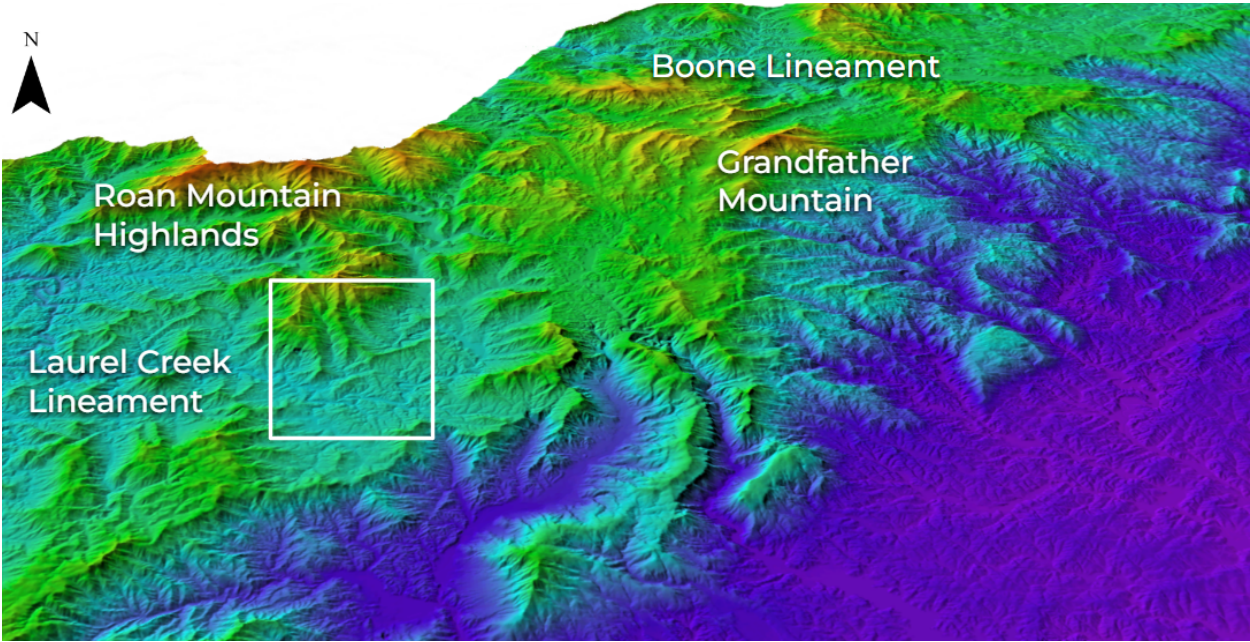


Figure 5. Oblique view of a hillshade elevation model for a portion of western North Carolina showing the topography around the Spruce Pine quadrangle (white box). Oranges are higher elevation and blues are lower.

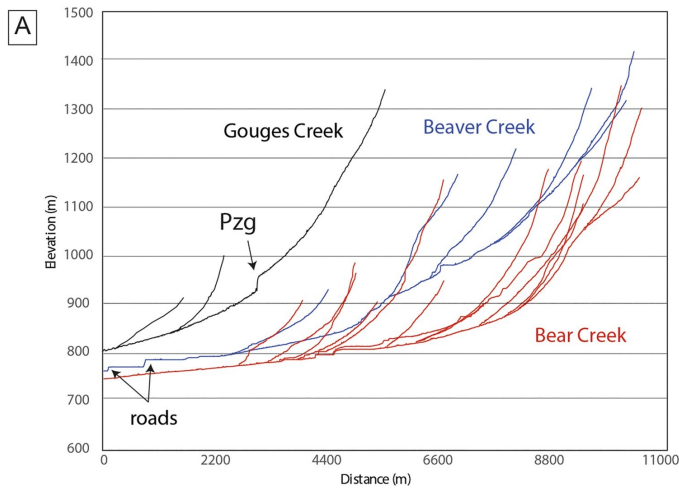
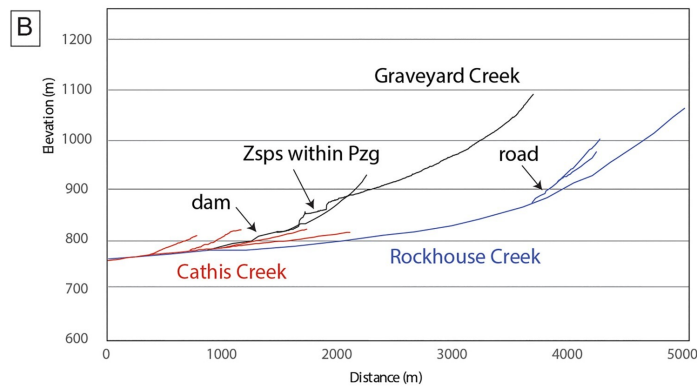


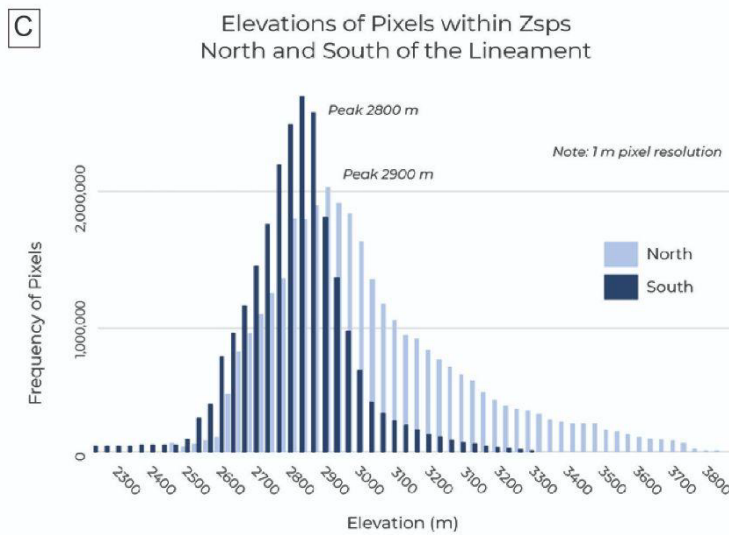
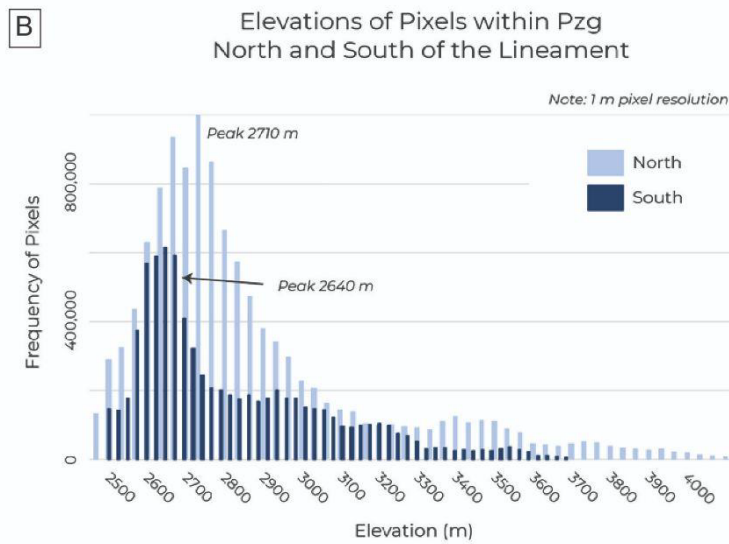
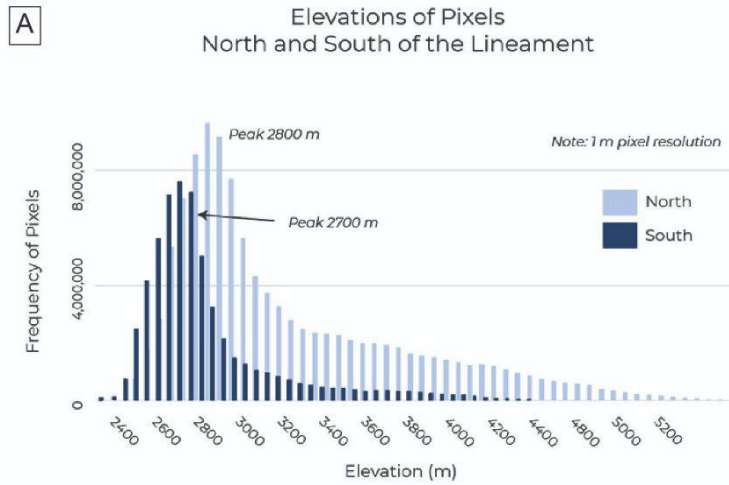
Figure 6. (left) Profiles of streams in the Spruce Pine quadrangle. (A) South flowing stream systems north of the Laurel Creek Lineament. (B) North flowing stream systems south of the lineament. From Langille et al. (2023).



Knickpoints not correlated to lithology occur only within the block north of the lineament, consistent with north-side up fault motion. This combined with the strong cluster in knickpoint elevations supports the interpretation that the knickpoints are associated with a change in base level on the north block only.

Base level can be changed in various ways including river capture, as seen from the Day 1 field trip, or topographic uplift. Johnson (2020) documented paleo-river deposits that show the Linville River captured streams that previously flowed into the North Toe River, southeast of Spruce Pine. This increased the flow into the Linville River, resulting in downcutting within the Linville Gorge. Knickpoint initiation in the Spruce Pine quadrangle is more likely associated with north-block up motion as opposed to river capture because there is no evidence of knickpoint initiation on streams that flow into the Laurel Creek Lineament from the south block.

Pzgs and the AMS occur both north and south of the lineament within the quadrangle. Pzgs as a granodiorite is relatively more resistant to erosion than the AMS, which could result in a higher-than-average surface elevation within this unit. If lithology alone explained the erosional expression, then elevations north and south of the lineament should be similar. Figure 7 shows the surface north of the lineament is on average 100 m higher than the surface south of the lineament.



Within Pzg, the surface north of the lineament is 70 m higher than to the south. Similarly, the surface composed of the AMS north of the lineament is 100 m higher than to the south (Fig. 7). This demonstrates that lithology alone does not explain the difference between elevation. This data suggests a 70–100 m uplift of the north block best explains the topographic expression.

Figure 7 (left). Comparison of pixel elevation frequencies north and south of the Laurel Creek Lineament. (A) Comparison of all pixels, (B) pixels within the granodiorite (Pzg), and (C) pixels within the Spruce Pine schist (Zsps).

QuartzCorp Pine Mountain Quarry

The units in the Spruce Pine quadrangle include granodiorite (Pzg) and pegmatite (Pzp) of the Silurian-Devonian Spruce Pine plutonic suite and metagraywacke, schist, gneiss, amphibolite, and dunite of the Neoproterozoic AMS (Fig. 2). You will see the Spruce Pine Plutonic Suite exposed within this quarry with local exposures of the AMS. These rocks have brittle fractures associated with the Laurel Creek Lineament (Fig. 8A).

Spruce Pine Plutonic Suite (Pzg). Pzg includes medium to coarse-grained granodiorite and is dominantly composed of quartz, plagioclase feldspar, and muscovite. Less abundant are garnet, biotite, tourmaline, and REE minerals, although garnet is locally abundant in some outcrops. Pzp consists of coarse- to large-grained pegmatite dominantly made of quartz, plagioclase feldspar, and muscovite. Rare occurrences of thulite and phrenite were observed. Epidote was found mineralized within joints throughout Pzg and Pzp (Fig. 8B).

Ashe Metamorphic Suite (AMS). The AMS in the Spruce Pine quadrangle includes aluminous chloritized schist (Zacs), dunite (um), aluminous mica schist (Zas), Spruce Pine schist (Zsps), biotite mica gneiss (Zmb), and amphibolite (Zaa). Exposures of AMS around the plutonic suite are composed of Zsps and Zaa. Zsps is light to dark gray, coarse-grained schist with muscovite, biotite, quartz, feldspar, and garnet. Coarse grained micas and shear textures such as S-C fabrics and ~1–5 cm rotated porphyroclasts are distinctive of this unit. Zaa is dark gray to black, fine to medium grained, foliated amphibolite composed of hornblende, quartz, plagioclase, with some garnet and epidote.

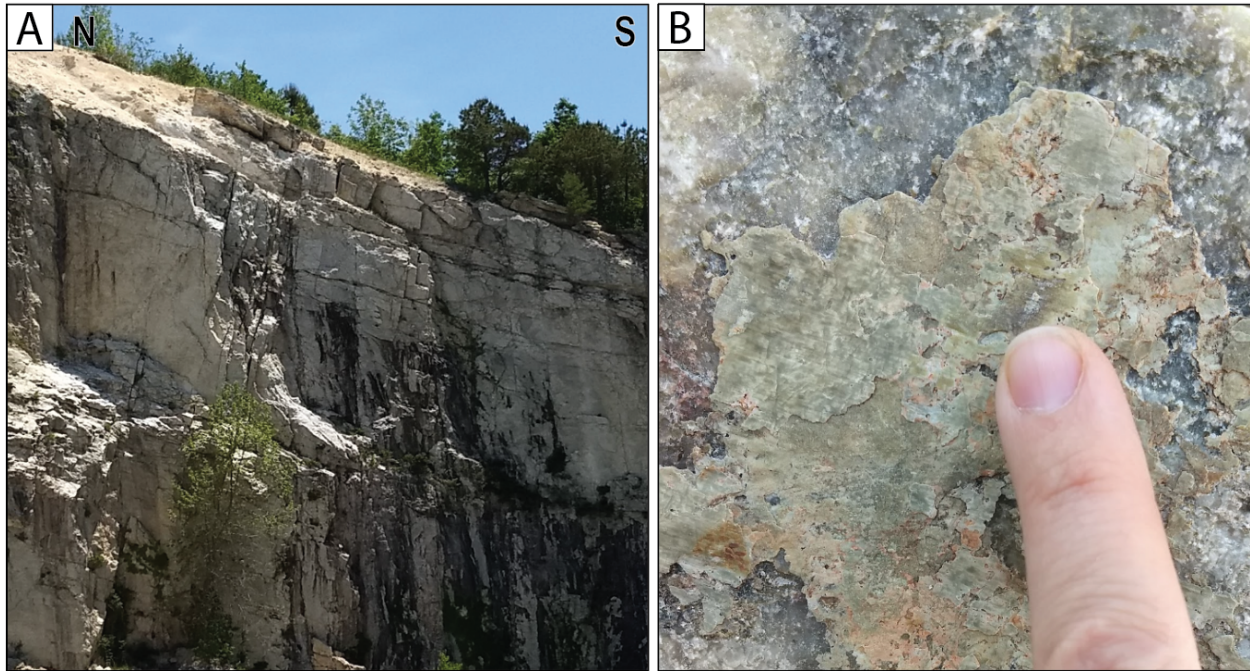


Figure 8. (A) E-W striking fractures exposed in the Pine Mountain Quarry. (B) Fault slickenlines on epidote within (A).

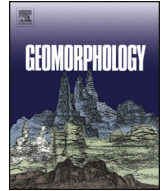
Acknowledgments

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Appendix



Stream capture and the geomorphic evolution of the Linville Gorge in the southern Appalachians, USA

Bradley Johnson

Davidson College, Environmental Studies, United States of America

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ABSTRACT

The Linville River, in the Blue Ridge of North Carolina, flows across the Blue Ridge Escarpment and through Linville Gorge, a unique topographic feature within the southern Appalachians. The upper portion of the drainage effectively shifts the Eastern Continental Divide away from the escarpment crest. This shift is similar to other locations along the escarpment where streams flowing towards the Piedmont have captured drainage area from low-relief streams that drain towards the west. Here, we examine the upper Linville River for evidence of drainage captures that would have shifted drainage area away from the Toe River and into the Linville River. We used LiDAR data to reconstruct stream profiles for possible drainage pathways and examined cobble deposits near the headwaters of the North Toe River. Within those deposits on the west side of the Linville River, we found quartzite cobbles that must have been sourced from bedrock exposed only on the east side of the modern Linville River. This indicates that portions of the Linville Valley above Linville Falls historically drained to the west into the North Toe River. Headward erosion above Linville Falls resulted in downcutting and multiple stream captures. These captures more than tripled the drainage area of the Linville River, which would have significantly increased discharge downstream. This increase in discharge likely drove the geomorphic evolution of the modern Linville Gorge including resultant downcutting and associated hillslope processes and helps to explain the prominence of Linville Gorge.

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1. Introduction

Asymmetry along the Blue Ridge Escarpment in the southern Appalachians drives unique stream geometry whereby streams above, and to the west of, the escarpment are higher in elevation but feature lower relief (Prince et al., 2011). Meanwhile, drainage basins on the face of the escarpment, and their streams, are much higher in relief and are generally smaller than those atop the escarpment. Headward erosion at the crest of the escarpment occasionally allows streams flowing into the Piedmont, with significantly lower base level, to capture low-gradient streams situated above the escarpment. This mechanism is important in the evolution of drainage networks broadly, especially in regions with strong drainage divide disequilibrium (Willett et al., 2014).

Regionally, this drainage capture mechanism is useful in understanding the evolution of the Blue Ridge Escarpment (Prince et al., 2010) – especially as research about escarpment retreat continues to engage new possible mechanisms (Colberg and Anders, 2014; Gunnell and Harbor, 2010). Drainage capture can also drive knickpoint formation (Harbor et al., 2004; Zaprowski et al., 2001) that, in turn, can be an important mechanism for creating steep slopes and maintaining

high relief in a post-orogenic landscape (Gallen et al., 2011). Overall, drainage capture provides an additional mechanism to answer the existing questions about how the Blue Ridge maintains relief long after its formation (Gallen et al., 2013).

The Linville River crosses the Blue Ridge Escarpment with the upper valley flowing across high elevation, low relief terrain whereas the lower valley flows through Linville Gorge and down to the Piedmont. For a river to traverse the escarpment requires a significant shift in the drainage divide away from the top of the escarpment. Drainage capture remains one of the few mechanisms that allows for this type of drainage divide shift (Prince et al., 2010, 2011). Further, drainage capture remains an important mechanism in understanding escarpment retreat along the Blue Ridge (Bishop, 1995; Prince et al., 2010). The geometry of the Blue Ridge Escarpment is highly irregular indicating that retreat is impacted by a variety of factors including bedrock type, structures, climate, and individual geomorphic events such as stream capture.

Such a capture would have had significant geomorphic consequences along the Linville River. Specifically, incision in the upper valley would have reversed drainages and caused downcutting along the valley. The significant increase in drainage area would have increased discharge and may have contributed to the carving of Linville Gorge. A shift in the drainage divide would have had significant impacts on stream ecology and speciation in the region (e.g., Thoma, 2005). Specifically, a

E-mail address: brjohnson@davidson.edu.

drainage capture in the Blue Ridge Mountains would have transferred drainage area from the Gulf of Mexico towards the Atlantic Ocean. In a high relief environment, such a change would significantly impact the species present in fresh water.

Here, we examine the Linville River for evidence of drainage capture and a resultant shift in the Eastern Continental divide. To do so, we use LiDAR data to construct possible paleo stream profiles and determine possible stream capture pathways. Further, we examine abandoned fluvial deposits and determine source areas for cobbles found in those deposits. In doing so, we recreate the most likely paleo-pathways for streams in the region and recreate the most likely scenarios for the evolution of the Linville River.

2. Field area

The Linville River is located within the southern Blue Ridge Mountains (Fig. 1), a sub-division of the southern Appalachian Mountains defined by rough topography formed from erosion within metamorphic and igneous rocks. The southern Blue Ridge was not glaciated during

the Quaternary. Without glacial erosion, the majority of geomorphic work has been done by dendritic stream networks and hillslope processes (Mills and Allison, 1995). Above the escarpment, low-relief uplands persist and are highly chemically weathered with areas of saprolite up to 30 m thick (Leigh and Webb, 2006). Holocene terraces and, in places, legacy sediments (Leigh and Webb, 2006; Price and Leigh, 2006) are common along streams throughout the region.

The Linville River is most well-known for its namesake gorge, an old-growth wilderness area designated in the original Wilderness Act of 1964. Linville Gorge drops steeply off the Blue Ridge Escarpment cutting through Cambrian meta-sediments that have been thrust over Precambrian meta-sediments and gneissic basement rocks (Fig. 2). Above Linville Falls, the knickpoint that divides the lower gorge-bound river from the upper reaches, the river runs along strike of the Linville Falls Fault that divides Cambrian quartzite to the east from over-thrust Precambrian gneiss to the west. The river meanders away from the Linville Falls Fault towards the northeast. Linville Falls exists precisely at the intersection of the Linville River and the Linville Falls Fault. Thus, it would appear that the change from Precambrian schist and gneiss to Cambrian

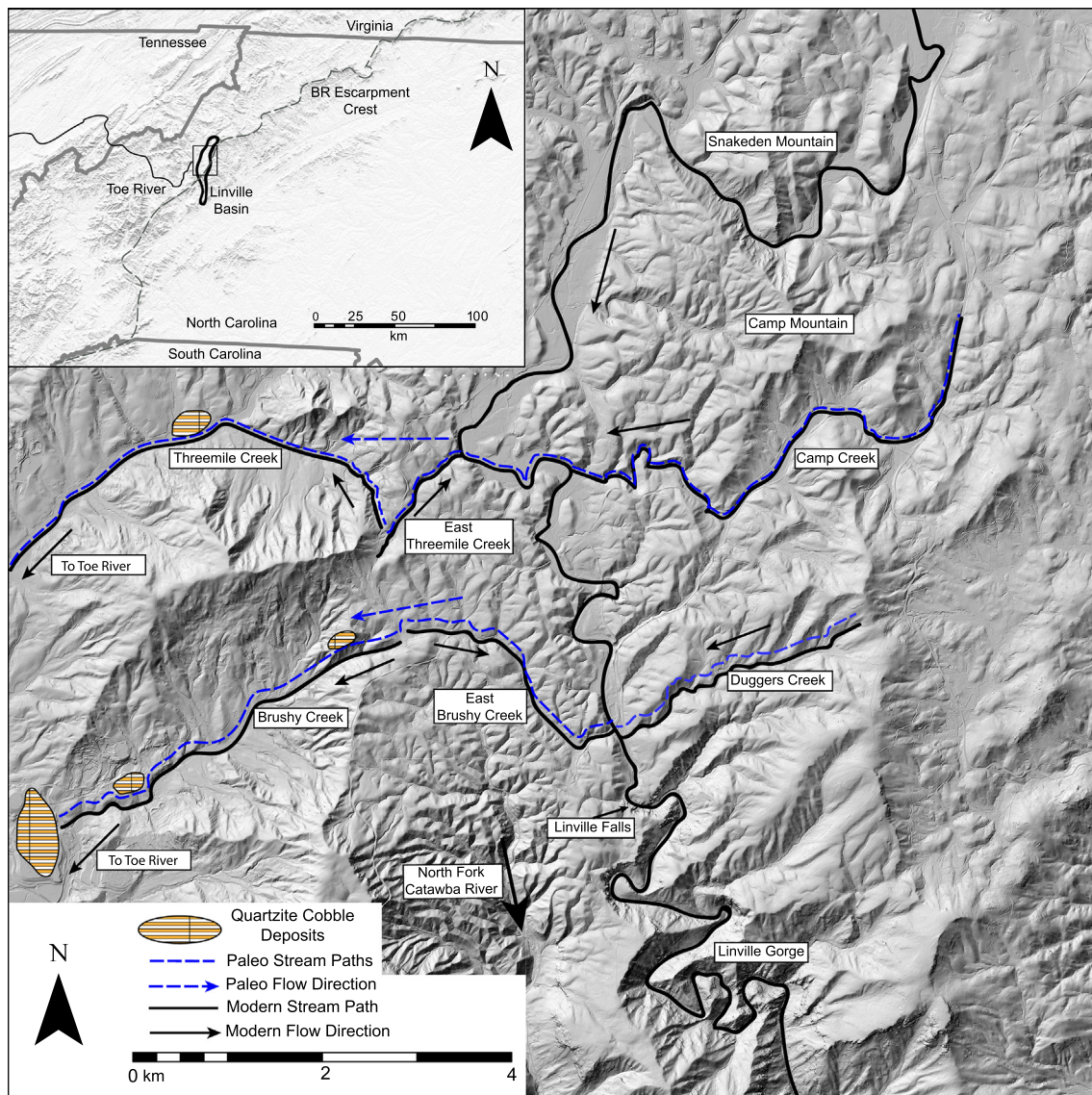


Fig. 1. Map of the upper Linville River Valley highlighting modern streams (solid, black lines) and paleo streams (dashed, blue lines). Quartzite cobble deposits are shown as boxes with striped pattern. All quartzite source areas lie east of modern Linville River. Inset map highlights the entire Linville River basin and the extent of the larger map. The crest of the Blue Ridge (BR) Escarpment is marked with a dashed line whereas state boundaries are thicker, solid lines. The line to the west of the field area shows the path of the North Toe, Toe, and Nolichucky rivers.

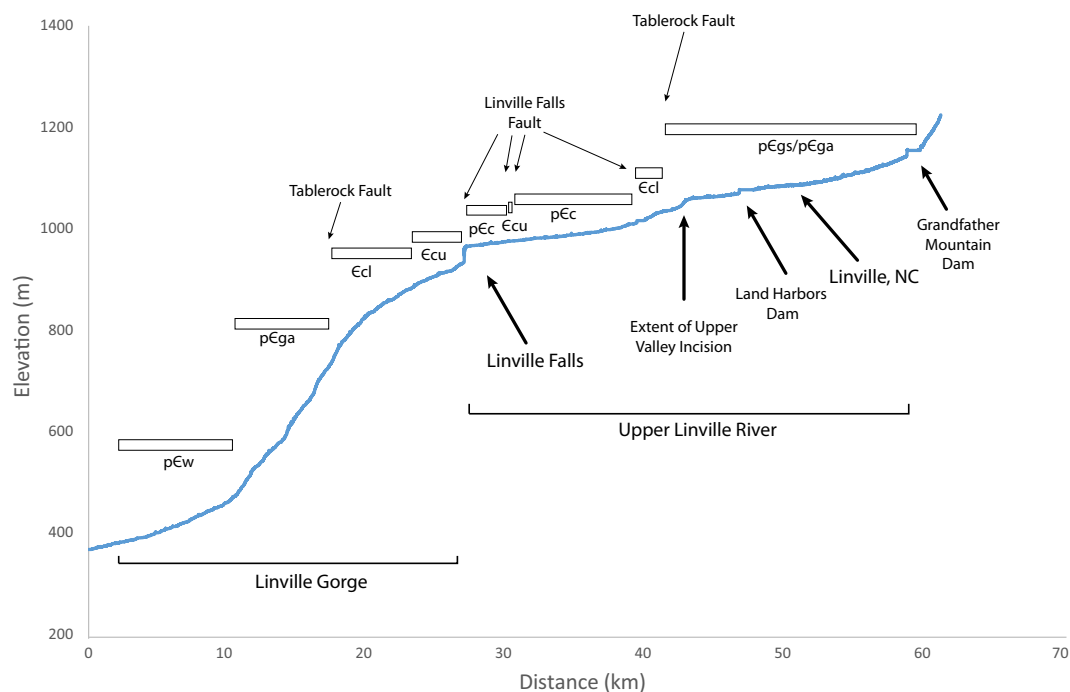


Fig. 2. Profile of the entire Linville River including bedrock under each reach as mapped by Reed (1964). Units include: pEgs/pEga – Precambrian Grandfather Mountain Formation – siltstone, phyllite, and arkose; Ecl – Cambrian Chilowee Group – quartzite; pEc – Precambrian Cranberry Gneiss; Ecu – Cambrian Chilowee Group – quartzite; pEw – Precambrian Wilson Creek Gneiss.

quartzite downstream controls the current location of the knickpoint (Reed, 1964). Above the Linville Falls knickpoint, the Linville River generally meanders across a valley dominated by alluvial deposits (Bryant, 1965). Below the falls, the river flows on bedrock with occasional alluvial deposits (Reed, 1964).

Weaver (1896) previously noted that the upper Linville River may have flowed to the west before its capture by the lower Linville River. However, that publication also postulated much greater drainage rearrangements including the assertion that the Linville River drained through the Toe River, which then flowed up the South Toe River and over the escarpment. Little physical evidence exists for this drainage pattern but the idea seems to be based on the assumption that drainage reorganization was primarily driven by uplift of the Blue Ridge Mountains. Ross (1971) also mentioned the possibility of the current Linville River flowing towards the west and into the Toe River based on biological data but provided few details.

The underlying idea from these earlier authors is that fundamental stream courses have not changed since sometime between the Jurassic and the Eocene (Judson, 1976; Ross, 1971) when the Appalachians tilted up and pushed more water to the east. These relatively simple ideas that streams change direction based exclusively on doming have been superseded by a more complex understanding of drainage evolution. Even earlier, Davis (1903) recognized the importance of capture and mentioned a possible future capture of the upper Linville River by a tributary of the Catawba – ignoring that the Linville River is already a tributary of the Catawba. More recent work suggests that southern Appalachians were likely tectonically active as recently as the Miocene (Gallen et al., 2013). More importantly, drainage captures do not require tectonic activity (Prince et al., 2011) and drainage reorganization within the Appalachians could be expected because of disequilibrium (Willett et al., 2014) regardless of tectonic activity. As such, drainage reversals in the region are likely and limited ecological data suggest a previous connection between the Linville and Toe rivers (Ramsey, 1965; Thoma, 2005).

The North Toe River, west of the modern Linville River (called the Toe River by Weaver, 1896), is the most likely previous pathway for

the upper Linville River. Flowing west, the Toe River becomes the Nolichucky River before reaching the confluence with French Broad and ultimately the Tennessee River. Any prehistoric ties between the Linville and the Toe rivers would represent an important ecological pathway between the greater Tennessee and Catawba-Santee River systems.

3. Methods

We used publicly available LiDAR (light detection and ranging) data to examine the upper reaches of the Linville River and relevant tributaries for possible ancestral drainages. For each possible drainage, the same LiDAR elevation data were used to construct profiles and estimate ancestral stream profiles to determine where former relief would have enabled east to west drainage. More directly, we examined whether surface elevation east of the modern Linville River was higher than surface elevation along the modern Toe River. Profiles were smoothed using running averages to minimize noise associated with the high sampling rates of LiDAR. Smoothing profiles also minimizes the topographic signatures of roads and other human structures along the profile. A few points had elevations altered by as much as 15 m vertically, but the average alteration was 1.5 m. Although we only present profiles of a limited subset of streams here, we examined many others.

Gravel deposits were examined in the field and cobbles were sampled for further analysis. Specifically, sampled rocks were compared with published descriptions of geologic units both from the local geologic mapping (Reed, 1964) and from descriptions of correlative units (Bloomer and Werner, 1955).

4. Observations

Two low-relief drainage divides exist immediately to the west of the Linville River upstream of Linville Falls (Fig. 1). An unnamed tributary of the Linville River (here called East Brushy Creek) immediately upstream of Linville Falls flows from the northeast initiating from a saddle. To the west of the saddle is Brushy Creek, a westward draining stream that

appears underfit for its valley. Immediately west of the saddle, 3 km down the valley, and near the mouth of the confluence with the North Toe River (~4 km down-valley), Reed (1964) mapped gravel deposits as Quaternary in age ~5 m above the modern river.

The gravel deposits consist of rounded cobbles visible from the road but located on private property. Many of the mapped gravel deposits lie immediately adjacent to pegmatite containing high-purity mica, feldspar, and quartz (Maurice, 1940; Swanson and Veal, 2010). For this reason, many of these deposits have been removed as overburden during mining since they were mapped in the 1960s. Nonetheless, limited sampling of the deposits indicates that they include rounded and sub-rounded quartzite cobbles with coarse, sugary texture (Fig. 3). The rock type, and more specifically the texture, is consistent with the description of Cambrian quartzite mapped to the east (Reed, 1964; Fig. 4) – the only known source of quartzite in the area. Specifically, a variety of quartzite expressions exist within the upper and lower Chilhowee Group along with interbedded phyllite and conglomerate. The shape and size (up to 30 cm diameter) of the cobbles is consistent with deposition by a moderate- to high-energy fluvial system.

The second low-relief drainage divide lies to the northwest of the town of Linville Falls. The westward-draining creek is named Threemile Creek while the eastward-draining creek is unnamed (East Threemile Creek here). Threemile Creek comprises three headwater tributaries that combine before the confluence with Fork Creek, which is flowing from the north. Whereas no gravel deposits exist in the uppermost portion of the Threemile Creek Valley, Reed (1964) mapped a large gravel deposit on the north of the road above the confluence with Fork Creek.

In addition to the mapped gravel deposits, unmapped gravel deposits also extend to the south side of the road. As with Brushy Creek, the deposits lie on private property with limited access. The terrace is not vertically exposed but instead spreads across a flat farm field. Sampling along the road again indicates that sugary, coarse-grained quartzite cobbles are present within the deposit. As before, the cobbles are up to 30 cm in diameter and are rounded to sub-rounded (Fig. 3).

The modern upper Linville River Valley creates a topographic depression that prevents streams on the east side from draining across and to the west. We use paleo stream profiles to examine possible drainage paths originating on the east side of the modern valley and flowing to the west side of the valley (Fig. 5).

Headwaters for the hypothesized Paleo Brushy Creek would likely have been situated to the east of the modern Linville River Valley. The

most likely candidate headwater stream is the unnamed creek (referred to here as Duggers Creek) that drains over Duggers Falls. This creek currently has a steep lower reach and a low-gradient upper reach. The topographic profile of the upper reach projects across the valley to the headwaters for the modern Brushy Creek. A reconstructed profile for Paleo Brushy Creek (Fig. 5A) projects from the upper valley across the modern drainage divide at a relatively uniform gradient.

Possible headwaters for the Paleo Threemile Creek are more difficult to identify because the incised Linville River Valley is wider to the north, limiting preservation. However, the most obvious possibility is Camp Creek due east of East Threemile Creek. As with Duggers Creek, the lower portion of Camp Creek grades to the modern Linville River whereas the upper portions of Camp Creek grade across the valley to the headwaters of Threemile Creek (Fig. 5B). The valley for upper Camp Creek is wide and its valley walls have gentle slopes compared with the lower reaches, which are narrow with steep sides. The reconstructed profile for Paleo Threemile Creek projects from the upper valley on the east, across the modern Linville River Valley, towards the drainage divide (Fig. 1).

Overall, we examined profiles for many possible headwater streams to the east of the Linville River Valley. Only Duggers Creek and Camp Creek have significant low gradient reaches in their other valleys. Profiles of other major creeks are steeper and grade directly to the modern Linville River Valley.

5. Discussion

5.1. Stream capture in the upper Linville Valley

Quartzite cobbles within both the Brushy Creek and Threemile drainages could not come from within the modern drainages that exclusively drain mica schist and gneissic bedrock (Reed, 1964). Quartzite cobbles could only have been transported from rocks in the upper or lower Chilhowee Group, which are exposed to the east of the modern Linville River (Figs. 4 and 5). In fact, the Chilhowee Group dips to the west so the contact extends farther to the east if it is projected up towards the paleo surface. Further, because the Chilhowee Group exposures narrow and become absent to the north (Bryant and Reed, 1970), the quartzite boulders could only have come from the east. Because the only source for quartzite cobbles now found in tributaries of the Toe River is currently east



Fig. 3. Split quartzite cobbles sampled from terraces along Brushy Creek (left of hammer) and Threemile Creek (right of hammer).

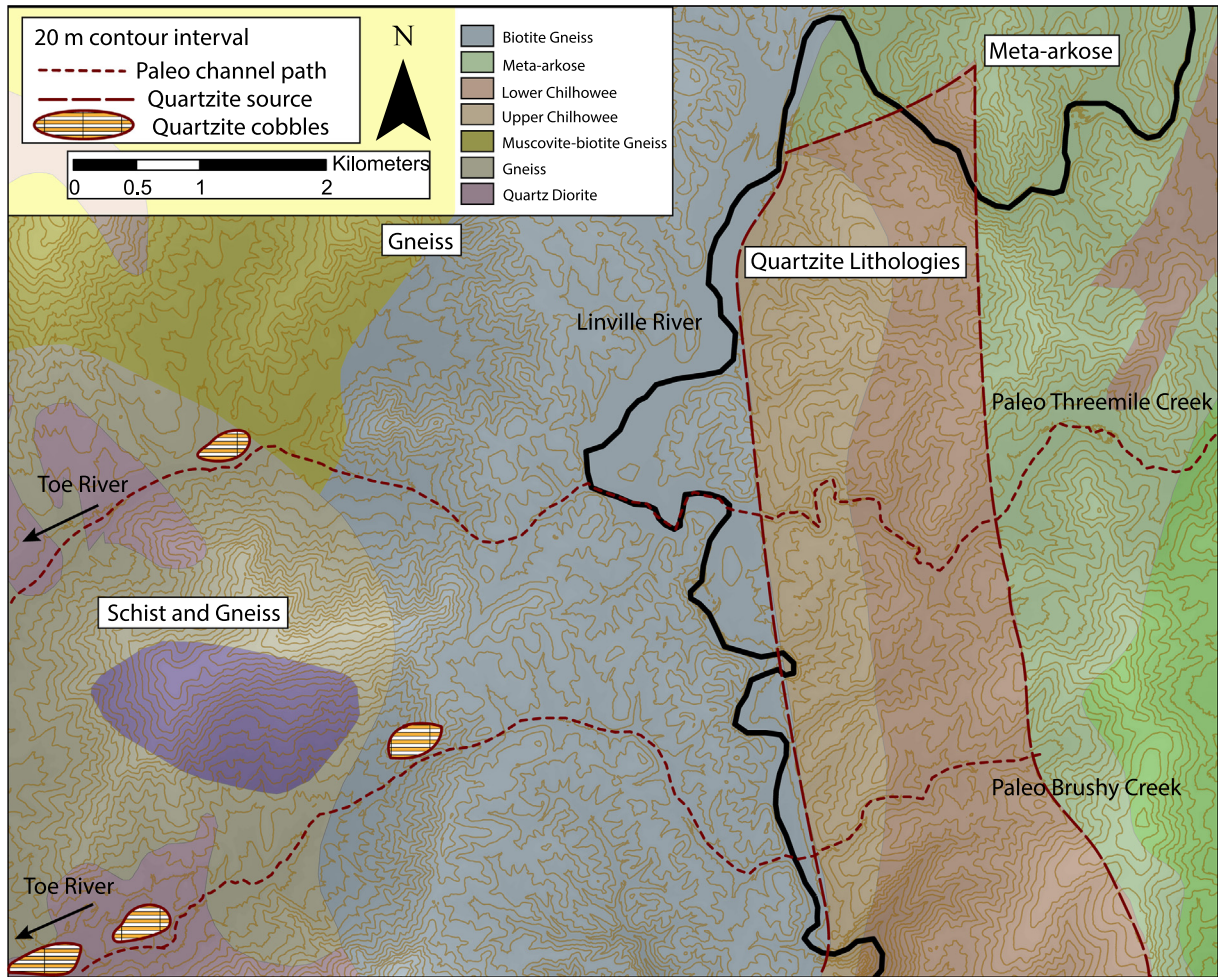


Fig. 4. Contour map (20 m interval) showing the topography and geology of the Upper Linville River Valley. The long dashed lines outline the area for quartzite whereas the short dashed lines indicate the proposed pathways for the paleo rivers. The modern Linville River is indicated by a solid line. Geologic layers are from the Geologic Map of North Carolina (North Carolina Geological Survey, 1985).

of the modern Linville River, we conclude that the eastern portion of the upper Linville River once drained towards the west and into what is now the North Toe River. Disequilibrium in base level between the

Blue Ridge Escarpment and the Blue Ridge highlands allowed the Linville River to erode headwardly and capture drainage area from the Toe River.

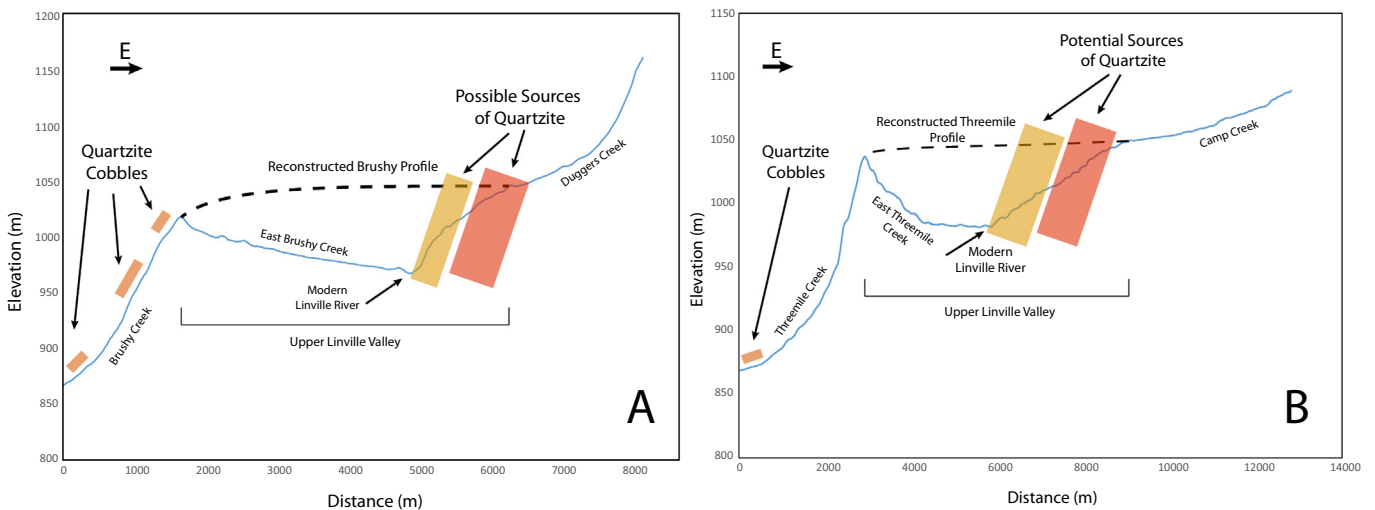


Fig. 5. Cross section of the upper Linville Valley including reconstructed paleo stream profiles for (A) Brushy Creek and (B) Threemile Creek. Sources and sinks for quartzite cobbles are shown to highlight that historic drainage must have crossed the modern Linville River.

As headward erosion occurred, the valley for the Linville River eroded to a new base level controlled by Linville Falls. Although the knickpoint at Linville Falls prevents deep incision in the upper valley, the upper valley still experienced roughly 65–80 m of downcutting from the paleo surface (compared with ~600 m of incision in the gorge). As downcutting above the falls migrated headwardly, individual streams and their drainage area were captured from south to north (Fig. 6).

The reconstructed profile from Brushy Creek across the Linville Valley to Duggers Creek shows correlations between a low gradient upper valley to the east and the drainage divide to the west. The reconstruction indicates that the ancestral drainage likely flowed nearly directly to the west. Specifically, as Duggers Creek adjusted to the new base level by cutting down, East Brushy Creek reversed direction to flow eastward towards the newly incised Linville River Valley.

Similarly, the reconstructed profile for Camp Creek correlates across the Linville Valley west to the current headwaters of Threemile Creek. Specifically, the wide, low-relief upper reaches of Camp Creek project towards the drainage divide at the headwaters of Threemile Creek. In the lower portions of Camp Creek, a canyon has been cut to adjust to the modern incised base level of the Linville River. This east to west drainage for Paleo Camp Creek parallels that of the Paleo Brushy Creek drainage to the south. Both Paleo Camp Creek and Paleo Brushy Creek both would have had significant increases in slope west of the modern drainage divide. This may be the result of the bedrock transition from quartz-rich gneiss to mica schist and mica-rich gneiss (Reed, 1964), but it should be noted that the location of the mapped contact does not precisely match the change in gradient.

It is also possible that the Paleo Brushy Creek originated to the north, paralleling the modern Linville River, and that the evidence for that

earlier location was not preserved. However, we prefer the geography described above because it is consistent with the physical evidence and because it may help explain the unique modern drainage pattern. Specifically, it provides an explanation for the origin of the deep canyon to the south of Snakeden Mountain.

As incision of the Linville River proceeded northward by knickpoint migration, it could have captured multiple small tributaries before capturing the Paleo Threemile Creek. This capture appears to have initiated the propagation of two knickpoints, one migrating to the east up Camp Creek and one to the north migrating up the modern Linville River. This northward migrating knickpoint appears to have eroded headward as it cut the modern canyon through Snakeden Mountain. On the east side of Snakeden Canyon, the new, lower base level appears to have then captured its own drainage. The result is the modern drainage pattern that nearly forms a full circle around Camp Creek Mountain (Fig. 6).

5.2. Implications for Linville Gorge

Before the capture of Brushy Creek and the creation of the upper Linville Valley, the drainage area of the Linville River at the mouth of the gorge was ~45 km². Today, the upper valley alone drains ~115 km² indicating that captures have more than tripled the size of the drainage of the Linville River. Although captures would have increased drainage area incrementally, each of these captures would have significantly increased discharge within Linville Gorge. We might assume that capture of the upper drainage area would have increased the rate of knickpoint migration (Crosby and Whipple, 2006), yet the knickpoint remains stalled at the bedrock transition. Lithological control on the location of a knickpoint is relatively common (e.g., Miller, 1991) but it remains unclear whether Linville Falls exist at its current location because

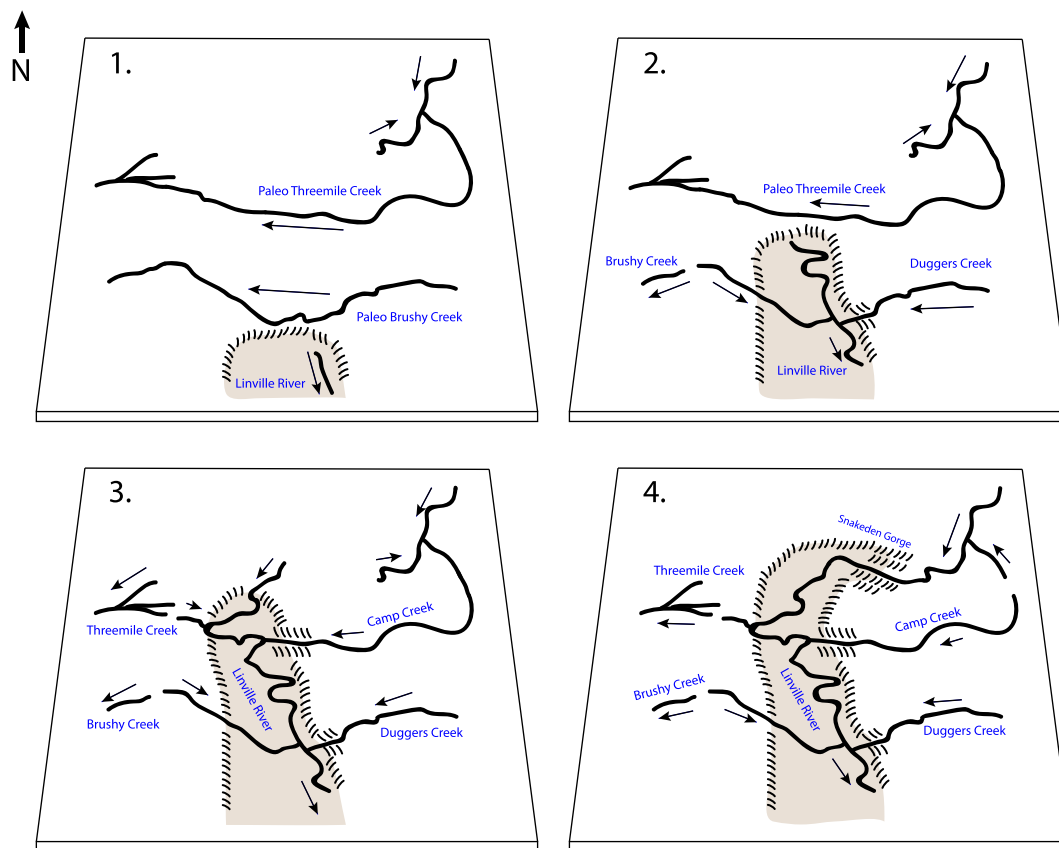


Fig. 6. Simplified conceptual diagram showing the most likely reorganization of drainages through time including (1) the geography prior to any captures, (2) the capture of Paleo Brushy Creek, (3) the capture of Paleo Threemile Creek, and (4) incision of Snakeden Gorge and reversals to the east of the gorge. Shading shows the downcutting of the upper Linville Valley above Linville Falls that allows for capture.

the river lacks the stream power to drive further knickpoint migration or simply that continued migration requires more time.

The location of Linville Falls functionally prevents additional drainage captures farther upstream. The upper Linville River has very little accommodation space available because of the base level set by the falls. The headwaters of the Toe River, which remain available for capture to the north, lie at about 1100 m asl – a similar elevation to the current headwaters of the Linville River. Thus, capture will not be possible in these upper reaches unless the knickpoint at Linville Falls is able to migrate headwardly.

Whereas the Linville River must have had enough discharge to drive headward erosion and complete the initial capture, the increase in discharge since the first capture has likely played a large role in the creation of Linville Gorge. Increased discharge likely allowed for erosion below Linville Falls, deepening the valley, and creating the gorge. Downcutting would have introduced positive feedbacks between hillslope and channel processes that would have aided in further downcutting. Specifically, downcutting of the river would have initiated new hillslope processes (Gallen et al., 2011) including an increase in mass wasting – a common geomorphic process in the Blue Ridge (Liao et al., 2011; Wooten et al., 2007, 2016). Rock falls and debris flows induced by an increase in hillslope steepness would have slowed erosion in the short term while increasing erosion through abrasion in the longer term (Glade et al., 2019; Howard, 1998). For instance, hillslope processes would have played a critical role in delivering the Cambrian quartzite, which is resistant enough to form the large cliffs that define the gorge, from the rim to the bottom of the gorge where it could be used as an erosive tool once it was broken into small enough clasts to be transported.

Immediately to the west of the Linville River, the North Fork of the Catawba River provides a window into what the Linville River might have looked like without capture. The North Fork came within 1 km of capturing Brushy Creek (Fig. 1) before the Linville River did so and it runs nearly parallel to the Linville River. In fact, it is possible that Brushy Creek was first captured by the North Fork, although this would be difficult to prove as no clear physical evidence of such a capture exists.

Because the North Fork of the Catawba River follows a similar path and drains similar topography as the lower Linville River does, the North Fork may provide insight into what the Linville River looked like before its increase in discharge. The North Fork valley is much wider and the river exhibits much more moderate stream gradients. Whereas some of these differences in morphology are likely the result of different bedrock, the North Fork of the Catawba River nonetheless provides insight into differences in the evolution of the two valleys.

5.3. Timing

Little constrains the timing of the capture of the Toe River, although comparisons can be made to other events in the region. Prince et al. (2011) compared quartzite clasts in terrace deposits with terraces along the New River dated ~1–2 Ma (Ward et al., 2005). Interestingly, these clasts on the New River Terrace are from the Antietam quartzite, which directly correlates to the local Chilhowee quartzite used in this study. Although it is difficult to compare relative ages of clasts across multiple studies using simple field descriptions and photographs in previous work, we interpret our clasts to be at least as young as those in Prince et al. (2011). This interpretation is based on the observation that the quartzite cobbles found along Brushy and Threemile creeks are dense with little sign of pitting or weathering. Large clasts are difficult to split, contain moderate iron oxide staining inside, and produce a relatively high-pitch noise when struck (Crook, 1986). The cobbles are also similar to those on alluvial fans in Virginia (Whittecar and Duffy, 2000), which were also imbedded in soils with 7.5 YR hue, and were interpreted to be 0.1–1 Ma in age. Although there is considerable uncertainty, we find these comparisons to be reasonable and indicate capture to have initiated within the last two million years.

It is quite possible that the captures occurred in the second half of the Quaternary. Incision above Linville Falls, which has created the upper Linville Valley, appears to have moved ~14 km upstream from the falls (Fig. 2; “extent of upper valley incision”). If we assume a capture initiation age of 1 Ma, then the retreat rate is only 1.5 cm/yr – quite reasonable given that much of this retreat would have occurred in alluvial valleys. However, this estimate is complicated by the fact that Snakeden Canyon needed to be cut and there may have been east-west bedrock ridges that slowed incision between Paleo Brushy and Threemile creeks.

An additional approach for estimating the timing is to compare incision rates on the upper Linville River with published incision rates for the region (Mills, 2000). Incision in the upper Linville River Valley averages between 65 and 80 m when the paleo-surface is compared with the modern surface. Plotting these rates on the published incision rates from Mills (2000) indicates capture between 3 and 5 Ma – much older than other estimates. Thus, incision along the Linville River appears to be much more rapid than other published rates in the region. This is likely the result of the fact that paleo-drainages were propped up by much higher local base levels to the west. The modern Linville River is still rapidly responding to its new base level in the Piedmont.

We also compared soil color on the terrace deposits (one of the few soil datapoints we could collect while sampling cobbles) with a published relative chronosequence from the area (Mills and Allison, 1995). Our soil hue of 7.5 YR is consistent, and perhaps less developed, than their youngest fan surfaces. However, a lack of age control makes it difficult to make firm conclusions about timing.

Overall, we favor relatively young capture initiation (1–2 Ma with preference for last 1 Ma) with relatively rapid northward incision thereafter. If the captures were very recent, OSL ages may provide a clear timing but it is likely that these events occurred outside of the useful OSL range. Linville Gorge may contain evidence to limit the timing of capture, but there is currently a ban on all research within the Linville Gorge Wilderness area.

6. Conclusions

Asymmetry along drainage divides is known to be a driver of stream capture in the Appalachian Mountains (Prince et al., 2010). The profile of the Linville River, with low-relief upper reaches and high relief lower reaches within Linville Gorge, provides evidence that the modern river crosses the line of asymmetry – an indication of previous captures and shifted drainage divides. Preserved evidence of older east-to-west drainages remain in the upper Linville River Valley, providing evidence for the proposed captures.

Reconstructed river profiles, mapping of abandoned cobble deposits (Reed, 1964), and sampling of cobbles from those surfaces support a previous drainage pattern from east to west and more recent capture by the Linville River to the south. Most convincingly, quartzite cobbles found on terrace deposits and drainage divides west of the modern Linville River could only have come from quartzite bedrock to the east of the modern Linville River. Thus, we conclude that two west-draining tributaries of the Toe River were captured by the Linville River during headward erosion.

The results of this capture include drainage reversals for small creeks to the west of the upper Linville River, downcutting by small creeks to the east of the upper Linville River, and a significant increase in the size of the Linville River drainage basin. The increase in drainage area likely drove much of the geomorphic evolution of the Linville River by increasing discharge and altering gorge incision rates and related hillslope processes. As the high relief topography of the post-orogenic Appalachian Mountains remains widely discussed (e.g., Gallen et al., 2013), we provide evidence here of the role stream capture played in the creation of the very high relief Linville Gorge.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at <https://doi.org/10.1016/j.geomorph.2020.107360>. These data include the Google maps of the most important areas described in this article.

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