Zoned uplift of western North Carolina bounded by topographic lineaments

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Abstract

JESSE STUART HILL : Zoned Uplift of Western North Carolina Bounded by Topographic Lineaments
(Under the direction of Kevin Stewart)

East-west-, southeast-northwest-, and north-south-trending lineaments separate zones of differential uplift and rejuvenated topography in the western North Carolina Blue Ridge Province. Sometime in the Miocene, over 200 m.y. after the birth of the Atlantic Ocean, the Blue Ridge of western North Carolina was uplifted, likely not as a broad uniform section of the crust, but rather as blocks bounded by conjugate fracture zones that today form the Swannanoa, Laurel Creek, Tuckasegee, Franklin, and other unnamed lineaments. The Swannanoa and Laurel Creek are two east-west lineaments visible in satellite imagery for 250 and 120 km. These previously recognized but poorly documented structures contain lineament-parallel outcrop-scale joints and dextral-normal faults formed from a near-vertical principal stress consistent with the focal mechanism from a 2005 earthquake. Streams draining into the lineaments have recorded uplift-related local base level change as knickpoints upstream of active topography and downstream of relict landscapes.

I would like to first thank my advisor Kevin Stewart for his encouragement and enthusiasm for the pursuit of curiosity and excellence. Thanks to Jason Barnes and Jonathan Lees for helping make this a multi-faceted project. This project would not have been possible without the financial support of the UNC Department of Geological Sciences, the Martin Annual Research Fund, the Robert Butler Memorial Scholarship, and a student research grant from the Geological Society of America. Thanks to Bart Cattanach, Rick Wooten, and Nick Dozdog for sharing the NCGS data and taking me out into the field. Special thanks to George Allen, Sean Gallen, Keehoon Kim, and Jonathan Syrek for helping me with programming and mapping issues. I would like to thank, above all, Tallulah and Acadia, for all things beyond words.

This work is dedicated to my father, Richard Hill, a fan of science and wonder.

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Introduction

Mountain belts reach their maximum elevation as continental collisions thicken the lithosphere and form deep roots. Eventually, all mountain belts collapse and rugged terrain transforms into rolling hills and eventually into plains (Dewey, 1988). Although most mountain building is associated with active plate boundaries, topography can be rejuvenated in ancient mountain ranges in several ways, including isostatic rebound following deglaciation (e.g. Nelson et al., 2007), lithospheric delamination (Farmer et al.,2002), and development of mantle plumes (Roy et al., 2009; Erlanger et al, 2012).

Topographic lineaments are low-lying linear features on the surface of the Earth that form through various mechanisms. Some lineaments correspond to the traces of faults, while others form parallel to folds where less-resistant rocks are at the surface. Lineaments can be zones of anomalous magnetic signatures (e.g., King and Zietz, 1978). They can form along fracture zones, some of which are inherited from lithosphere-scale buried transform faults or lateral thrust ramps (Pohn, 1998). In New England, many lineaments have been explained by origins such as fold axes, fault traces, or lithologic contacts, but some lineaments lack a known origin (e.g. Shake and McHone, 1987).

The Appalachian Mountains have a complex tectonic history, with the last major collisional event ending ~270 Ma and rifting starting in the Triassic and continuing into the early Jurassic. (Hatcher, 2005, Wagner et al., 2012); yet at least hundreds if not thousands of meters of the topographic relief has persisted into the present day. Much of the regional geomorphology can be explained by known geologic features formed during Paleozoic and older orogenies, but the topographic lineaments in the southern Appalachians remain enigmatic (Figure 1).

The goal of this work is to highlight zones of varying topographic style bounded by linear valleys formed in a passive margin setting hundreds of million years after orogenesis and subsequent rifting. Although previous authors have explained the origin of the lineaments in North Carolina as differential erosion along fracture zones or faults, until now there has been a lack of detailed documentation of the associated structures (Hadley and Nelson, 1971; Hack, 1982; Southworth, 1995; Dennison et al., 1997; Merschat, 1997; Dennison and Stewart, 2001). Through structural and kinematic analyses of fractures and faults, river longitudinal profile comparisons, and compilation of existing geologic and geophysical data, I propose to shed light on some previously recognized but poorly understood structures and their role in the evolution of the southern Appalachians.

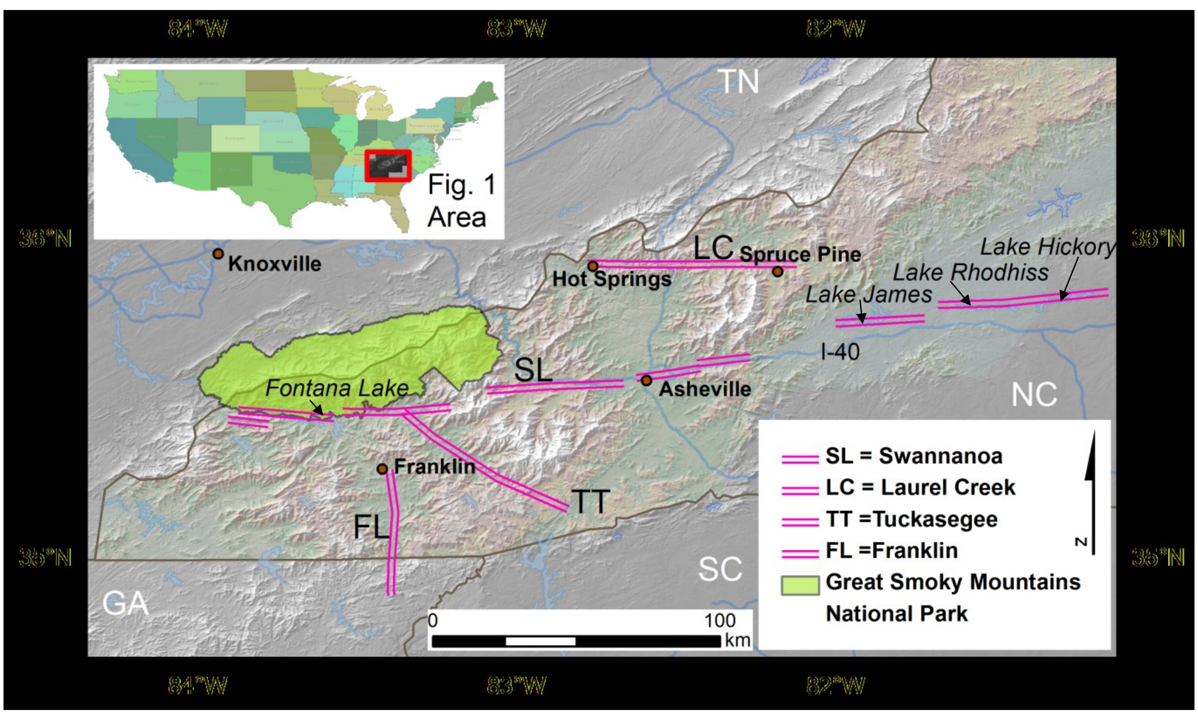

Figure 1: Digital elevation model of western North Carolina, and adjacent South Carolina, Georgia, and Tennessee with traces of major lineaments. Note how the Swannanoa lineament is not one continuous feature, but rather a series of en echelon trenches.

Geologic and regional setting

Many topographic lineaments ranging from tens to hundreds of kilometers in length crosscut the SW-NE-trending southern Appalachian orogenic belt, mostly within the Blue Ridge but some in the Valley and Ridge and Piedmont provinces (Figure 1). Visible in satellite imagery and on topographic maps, the two longest E-W lineaments in western North Carolina are the Swannanoa and Laurel Creek, spanning ~250 km and ~120 km, respectively. The Swannanoa lineament starts in the west at Fontana Lake and ends at Lake Hickory, NC. The Laurel Creek lineament runs from Hot Springs, NC in the west to Spruce Pine, NC. The Swannanoa and the Laurel Creek lineaments cut the landscape on the southern and northern end of the Black Mountains, the highest range in the eastern US.

The Blue Ridge province of North Carolina is made mostly of metamorphic rocks that have recorded multiple Wilson cycles and were faulted and overprinted in at least two and possibly three Paleozoic orogenies, commonly known as the Taconic, Acadian (this may have been isolated to the northern Appalachians), and Alleghanian (e.g. Miller et al., 2006). Topographically, the Blue Ridge has over 1200 m of relief and is easily visible in satellite imagery and digital elevation models (Figure 1). Much of the Swannanoa and Laurel Creek lineaments cross the heterolithic Ashe Metamorphic Suite, composed of medium- to high-grade metamorphic rocks (Abbott and Raymond, 1984; Merschat, 1997; Miller et al., 2006) and the Cartoogechaye terrane, which is described as a high-grade gneiss (Figure

2; Southworth et al., 2012). To the south of the Great Smoky Mountains National Park, the Swannanoa traverses the Neoproterozoic Great Smoky Group (Southworth, 2012).

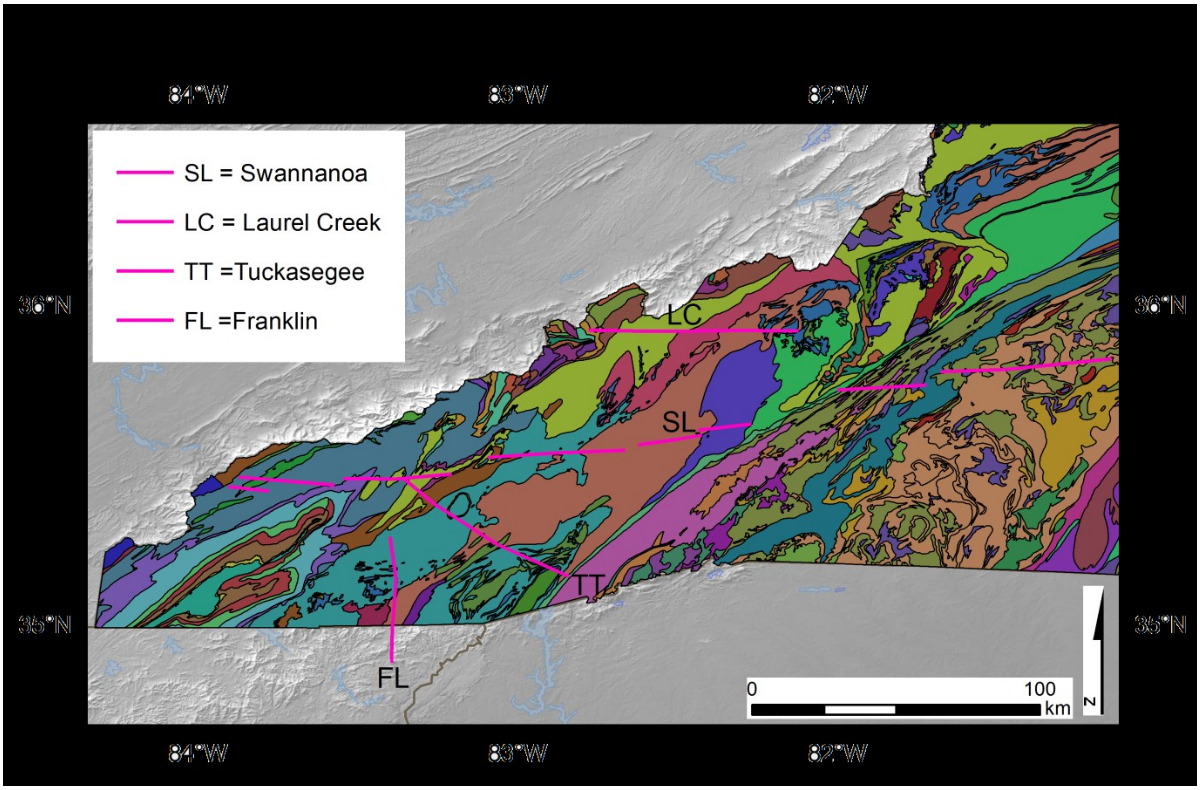

Figure 2: Geologic bedrock map from NCGS (2005) showing the major lineaments. Individual rock units are continuous across the lineaments.

Previous interpretations of the lineaments of western North Carolina

Hack (1982) attributed the prominent Swannanoa and Tuckasegee lineaments (Figure 2), which he called “trench valleys”, to enhanced erosion along brittle fracture zones associated with older faults.   Hadley and Nelson (1971) mapped a segment of the Laurel Creek lineament as a right-lateral fault, but more recent mapping shows no fault or offset contacts along the lineament (Robinson et al., 1991). Southworth (1995) noted the presence of a down-to-the-south, east-striking normal fault on the northern shore of Fontana Lake that parallels the Swannanoa lineament and cuts both bedding and cleavage.

Merschat and Wiener (1988) reported a NW-SE-trending joint set and a lesser E-W-trending set in their study of the Canton, NC quadrangle (traversed by the Swannanoa lineament) and Sandymush, NC quadrangle. Merschat (1997) interpreted the Laurel Creek lineament to be the result of fracturing and faulting but he did not present any structural data to support this interpretation. Gay (2000) noted three sets of lineaments trending NW-SE, N-S, and E-W in western North Carolina were located, and the en echelon pattern of the Swannanoa lineament. Joints measured in an outcrop near the western end of the Laurel Creek lineament have a dominant E-W set (Hatcher, 2006). Earlier attempts to determine the structural origin of the major lineaments yielded no convincing evidence for either the age or origin of the lineaments.

Jointing within the Blue Ridge Province of North Carolina

Methods

The orientations of fractures were measured in a 5 km swath along the lineaments to test the idea that the lineaments are fracture-controlled features. Data were collected for planar features that occurred in sets; isolated fractures were excluded. Joints were measured at 17 outcrops along the Laurel Creek lineament (Figure 3). In the Swannanoa lineament joints were measured at 86 outcrops (Figure 4). Joints along I-40 near Canton, NC and from the nearby Enka quarry (unpublished data from Kevin Stewart) were added to the dataset for a total of 1,756 measurements (Figure 5). More fractures were measured along the Swannanoa lineament, due to its greater length. The joint patterns within the lineaments were then compared to 16,994 joint measurements collected by the North Carolina Geological Survey (NCGS) over the past forty years in western North Carolina (Figure 5).

Results

The fractures within the Swannanoa lineament have a mean strike of 106° and the most common dip direction was to the north (Figure 6). Fracture data collected in a previous study near Canton, NC, in the Swannanoa lineament have a mean strike of 82° and dip to the south. Fractures in the Enka quarry near Asheville, NC, also within the same lineament, have a mean strike of 77° and dip to the southeast (Figure 6).

The fractures in the Laurel Creek lineament have a bimodal distribution of fractures with a dominant E-W set and a lesser SE-NW set. The dominant set is parallel to the Laurel Creek lineament, and has a mean strike of 88°. The most common dip direction of the Laurel Creek fractures was to the south (Figure 6).

The rose diagrams and equal-area plots of the joint data graphically display differences between joints within the lineaments and elsewhere in the Blue Ridge. To quantitatively test if these data are from the same population, an f-test was performed at 95% confidence with the following null and alternative hypotheses:

H_0: joints within the lineaments have an equivalent variance to joints outside the lineaments

H_1: joints within the lineaments have a non-equivalent variance to joints outside the lineaments

Based on a resultant f-value = 1.001 with a critical value at 0.942, the null hypothesis is rejected and it can be inferred that the joints from within the lineaments come from a different population than the joints found elsewhere in the Blue Ridge. Because the f-test resulted in a rejection of the null hypothesis no additional simple statistical tests such as a t-test were performed (Davis, 2003). Although the mean values are similar in these two data sets, the f-test result shows that the variances of the data are statistically not equivalent and are from different populations.

Discussion

Once a fracture zone is formed it may erode more quickly because fractured rock is easier to weather and erode. The Laurel Creek and the Swannanoa lineaments trend generally E-W, but the two lineaments have some differences worth mentioning. The Laurel Creek lineament can be mapped as a single lineament, while the Swannanoa is a slightly N-of-E-trending zone of en echelon, E-W-striking lineaments (Figures 1 and 2). Fractures within the Laurel Creek lineament dip to the south and within the Swannanoa lineament they dip to the north. However, the fractures in the Swannanoa lineament measured by Kevin Stewart dipped primarily to the south and the southeast. Other than the Enka quarry, which contains only minor E-W fractures despite its close proximity to the Swannanoa lineament, a strong positive correlation exists between the orientations of the lineaments and the outcrop-scale joint sets within them. The E-W fractures at the outcrop scale are likely the controlling factor for the map-scale expression of the lineaments.

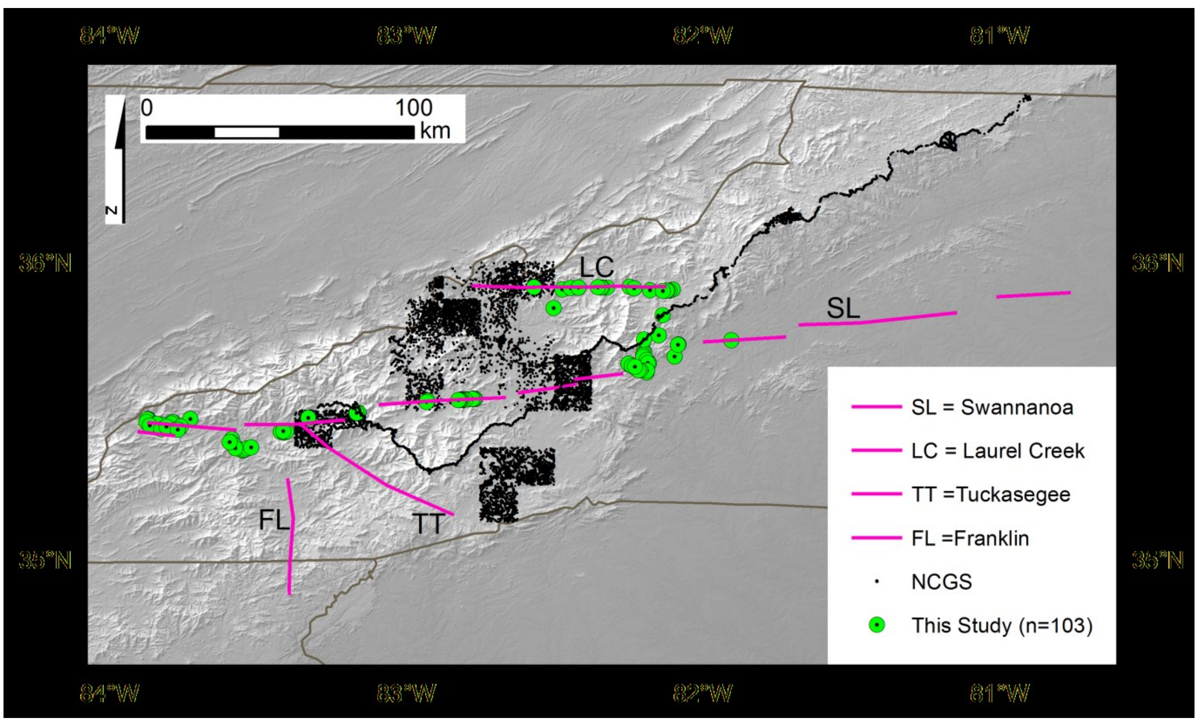

Figure 3: Black dots show locations of joints measured by the North Carolina Geological Survey (n=16,994) over the past 40 years. Green circles are from this study.

Figure 4: East-west striking joints in the Swannanoa lineament south of the Great Smoky Mountains National Park. Field notebook is 19 cm tall and picture is looking to the northwest.

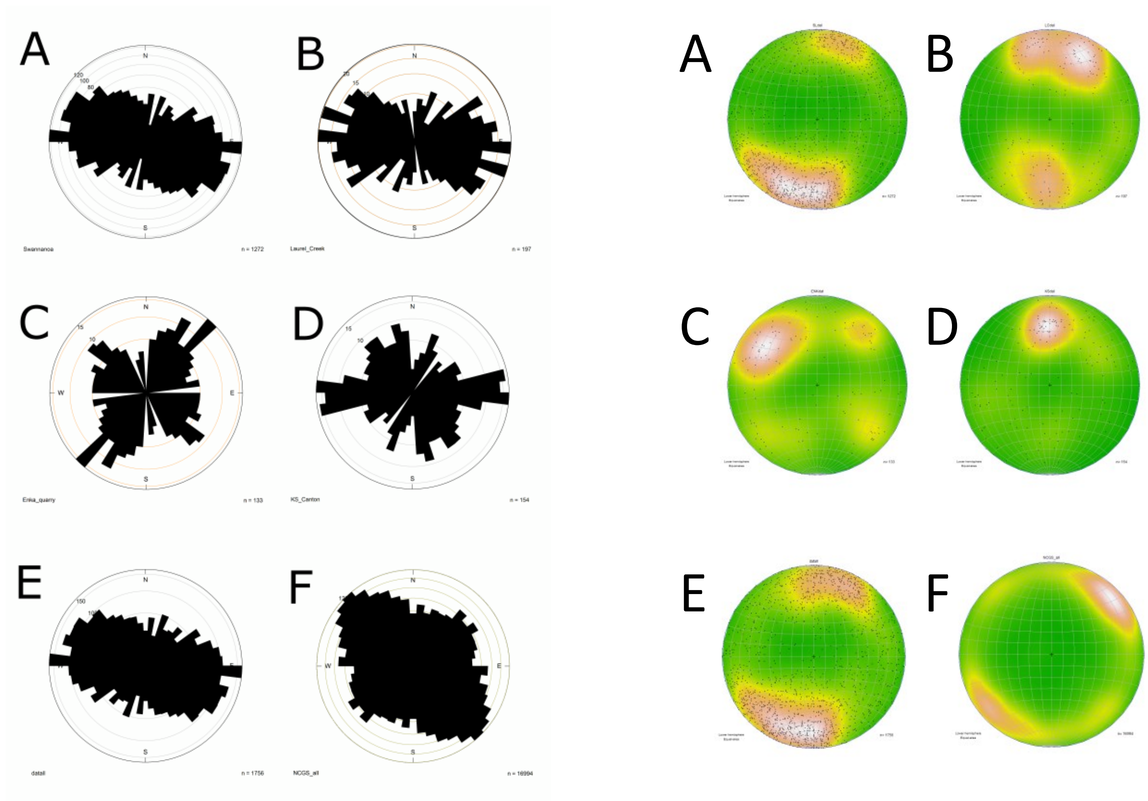

Figure 5: Symmetrical rose diagrams and lower-hemisphere equal-area Schmidt plots of fracture orientations from: (A) Swannanoa lineament (n = 1,272); (B) Laurel Creek lineament (n = 197); (C) Enka quarry (n = 133); near Canton, NC (n = 154); all combined sites within the lineaments (n = 1,756); North Carolina Geological Survey (n = 16,994).

Paleostress inversion

Methods

Although most of the outcrops along the lineaments contain only fractures and isolated E-W faults, there is an outcrop along the Swannanoa lineament, to the east of Canton, NC, that contained thirteen E-W-striking faults (Figure 6). Faults with slickenlines were used for paleostress inversion and kinematic analysis to estimate the principal stress directions and relative magnitudes at the time of fault movement (Figure 7; Angelier, 1990). Paleostress analysis may also help constrain the time of formation of the lineaments, if the calculated stress regime can be linked to known stress fields of the past or to modern earthquake focal mechanisms (Zoback, 1992; Garihan et al., 1993, Chapman, 2005). Assumptions in paleostress analysis include: 1) all faults formed under the same stress state, 2) slickenlines are parallel to the direction of maximum shear stress on the fault plane, and 3) movement along one fault did not affect the movement of other faults. Minimizing the angle between the predicted (theoretical) and observed (slickenlines) slip direction yields a best-fit stress tensor. A detailed explanation of the mathematics behind the paleostress inversion can be found in Angelier (1990) and is summarized in Appendix 1.

Results

The best-fit stress tensor has a maximum compressive stress (σ_3) close to vertical, which agrees with the observation that these are normal faults. The trend and plunge of the principal stresses are: σ_1 = 090/19; σ_2 = 003/10; σ_3 = 121/ 69 (Figure 7). In this example, the engineering naming convention of principal stresses was used, where σ_3 is the greatest compressional stress, and σ_1 is the least compressional stress. Because there is no *a priori* knowledge of the absolute magnitudes of the stresses, only the relative magnitudes can be calculated. The stress-shape ratio is 0.244 and indicates that the magnitudes of σ_1 and σ_2 are similar.

Discussion

Although the most-common brittle features found at the study locations were fractures, the minor E-W faults play an important role in the recent history of the Blue Ridge. There are likely more of these dip-slip faults than the 13 found near Canton, NC. If the displacement for each fault was small, then these features may have eluded geologists mapping with the goal of sorting out the complicated Proterozoic and Paleozoic histories of the dominantly SW-NE trending Appalachian mountain range. The paleostress inversion of the faults near Canton resulted in greatest compressional stress close to vertical, which is consistent with normal faulting. Within the Laurel Creek lineament, focal mechanisms from a 2005 earthquake near Hot Springs, NC, also had a vertical greatest compressional stress direction (Chapman, 2005) and a possible focal plane parallel with the lineament. Normal faulting along the lineament could explain some of the juxtaposition of high- and low-relief zones on opposite sides of the lineaments.

Fontana Lake defines much of the southern border of the Great Smoky Mountains National Park. The mountains to the north of the lake have a greater relief than the terrain on the southern side of the lineament. Southworth (1995) reported E-W normal faults in the Swannanoa lineament near Fontana Lake that cut older beds and cleavage. This lake is ~120 m deep in places, so it is plausible that there are more of these faults hidden underwater.

To the current knowledge of the author, there are no mapped offset contacts across the lineaments attributed to faulting. Existing geologic maps show few offset contacts across or along the lineaments (Southworth et al., 2012), which may indicate they are fracture zones with insignificant motion or fault zones with mostly dip-slip motion. Although this study focused on the two largest lineaments, there are hundreds of smaller lineaments that may form a network of minor faults along which vertical displacement may have been distributed. Other small E-W striking faults were found at outcrops, also with normal motion, but the paleostress inversion was not performed because these were isolated faults and not clearly part of a coeval population (Figure 8). There are some faults within the Swannanoa lineament showing strike-slip motion parallel to the NW trending lineaments (Figure 9). The majority of isolated east-west faults discovered in the Swannanoa lineament had dextral-normal motion.

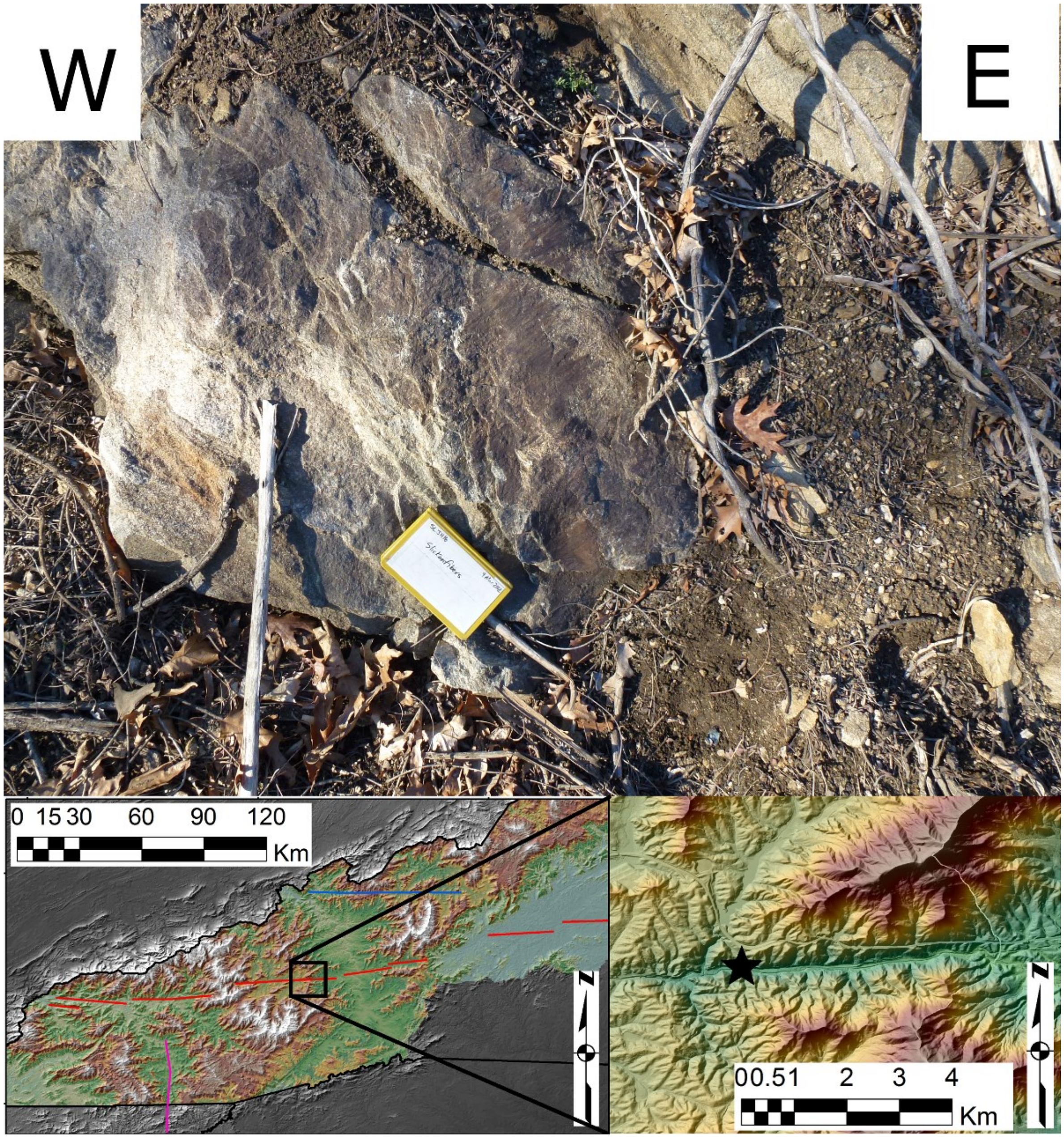

Figure 6: Footwall of fault with slickenlines found east of Canton, NC (field notebook is 19x12 cm). The black star in the lower right image marks the outcrop location. This outcrop contained 13 minor faults with similar orientations. Note the slickenlines trending to the bottom left of the image with a stepping-down pattern, indicating dextral-normal motion.

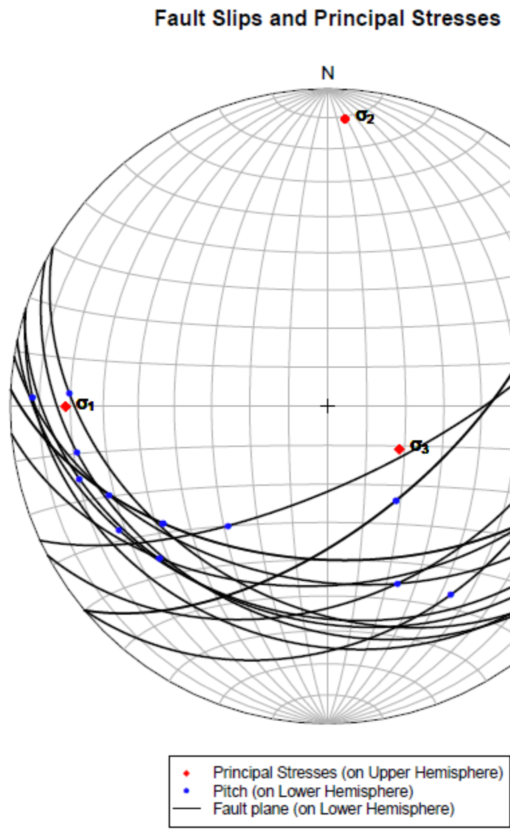

Figure 7: Equal-area plot of thirteen faults in the Swannanoa lineament near Canton, NC. The faults have a dextral-normal sense of slip resulting from near-vertical maximum compressive stress. The data are plotted on a lower-hemisphere equal area plot but the principal stresses are plotted in the upper hemisphere. The stress-shape ratio = 0.244, indicating similar magnitudes between σ_1 and σ_2.

Figure 8: East-west striking fault cutting pegmatite dike in the Ashe Metamorphic Suite along the Swannanoa lineament near Canton, NC. East is to the right.

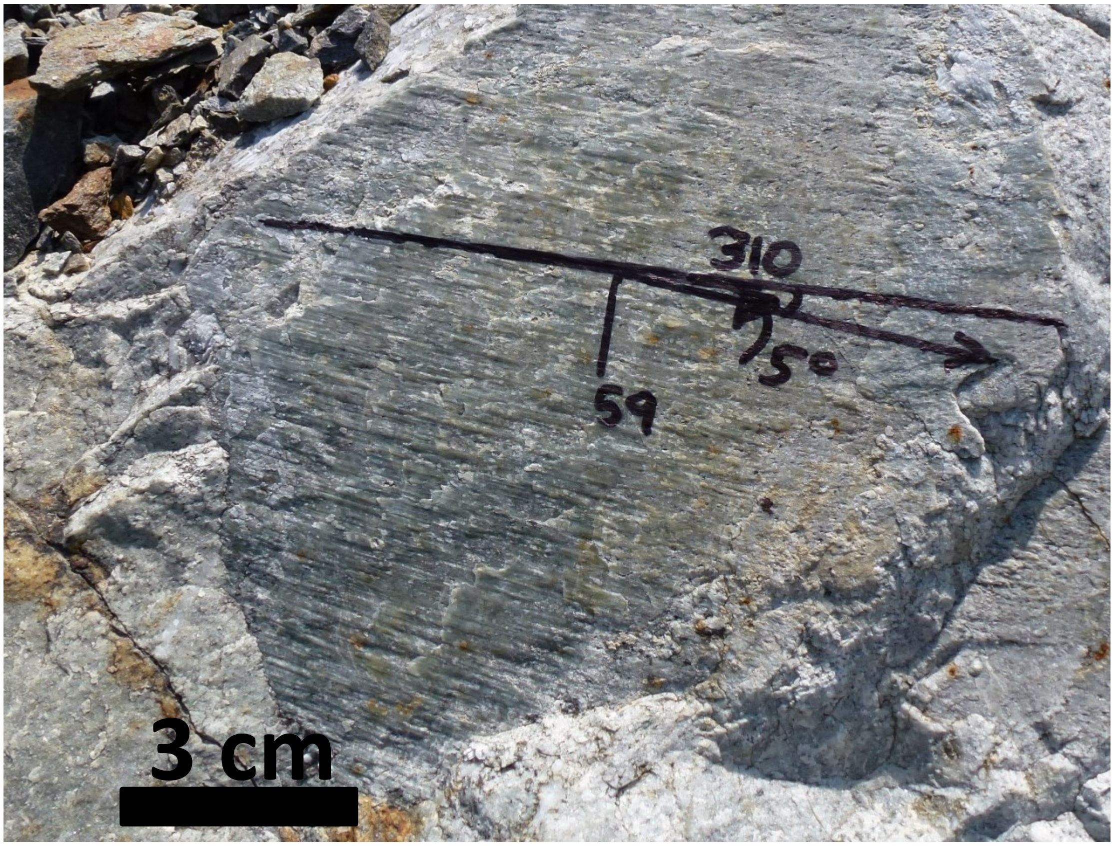

Figure 9: Dextral strike-slip fault within the Swannanoa lineament.

Earthquakes associated with the lineaments

Earthquakes in the Blue Ridge of western North Carolina were compiled from the National Earthquake Information Center via the USGS Earthquake Hazard program website (http://earthquake.usgs.gov/regional/neic/). These data span from 1979 to 2012, and range from magnitude 2.0 to 3.6 with hypocenters located from 1 to 13 km depth. It is worth mentioning that many of these locations were determined from distant seismic stations and the accuracy may be poor. The locations of recent earthquakes are more aligned with the Laurel Creek than the Swannanoa (Wagner et al., 2012).

The paleostress inversion of the faults near Canton resulted in greatest compressional stress close to vertical, which is consistent with dip-slip faulting. Focal mechanisms from a 2005 earthquake near Hot Springs, NC, within the Laurel Creek lineament, also had a vertical greatest compressional stress vector (Chapman, 2005). Dip-slip faulting along the lineament could explain some of the juxtaposition of high- and low-relief zones on opposite sides of the lineaments.

Hot Springs, NC, located along the Laurel Creek lineament, was cited as indirect evidence of fractures extending to a depth of 1200-1800 m based on 38°C water at the surface and a geothermal gradient of 26°C/km (Merschat and Wiener, 1988). Hot water at the surface does not necessarily imply that the water traveled up a planar fracture as it can rise in a complicated series of conduits, with the possibility of some lateral migration. In the three days prior to a 2005 earthquake the water in the hot springs rose by ~2°C, and boiling and steaming springs were reported after a 1928 earthquake (Chapman, 2005). At least a dozen earthquakes have occurred near the Swannanoa and Laurel Creek lineaments since 1979, according to USGS earthquake records (Figure 10; NEIC, 2013).

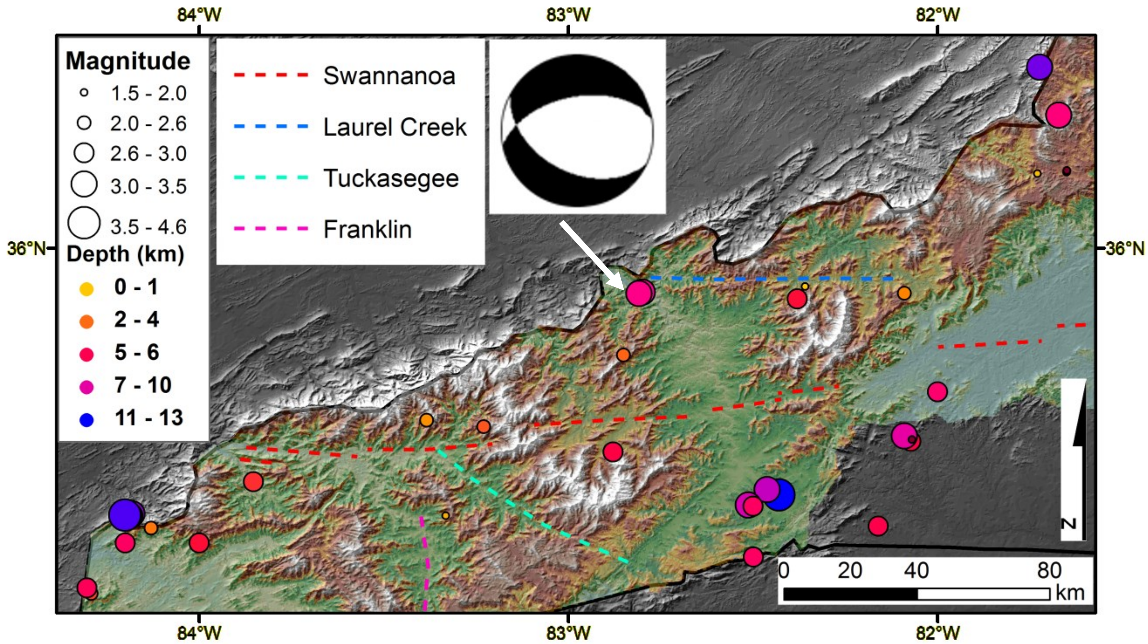

Figure 10: 1979-2013 earthquakes from the National Earthquake Information Center database. The location of earthquakes in the Blue Ridge province roughly correlates with the Laurel Creek lineament. The focal mechanism is from a 2005 event within the Laurel Creek lineament marked with the white arrow (Chapman, 2005).

Longitudinal Stream Profiles and Normalized Steepness Maps

Methods

With high-resolution LIDAR data (horizontal resolution of ~6 m and a vertical resolution of ~1/3 m) obtained from the NC Floodmaps program (http://www.ncfloodmaps.com/) a discretized slope map was produced using three topographic parameters. The first parameter was defined as areas with both elevations less than 1000 m and slopes less than 3 degrees. These areas correspond to possible lineaments. The second topographic style was defined as areas with elevations greater than 1000 m and slopes less than 10 degrees, and was used to find possible relict landscapes in the upper reaches of drainage basins. The third topographic style was defined as areas higher than 1000 m with slopes greater than 10 degrees. These areas correspond to high topography that is steep (Figure 11).

ArcMap v.10 hydrology tools were used to find the steepest path from the headwaters of each stream and the results were imported into R, an open-source computing language, to draw stream profiles and calculate normalized steepness values (k_{sn}). A detailed description of the normalized steepness analysis of stream profiles can be found in many recent geomorphology papers (e.g. Kirby and Whipple, 2001; 2012, Duvall et al., 2004, Gallen et al., 2013). Essentially, 'steepness' refers to the slope of the stream normalized to the drainage area. For a reference concavity index a value of 0.45 was used in order to compare streams across the Blue Ridge province. The equation below describes the relationship between slope (S), steepness (k_{sn}), drainage area (A), and reference concavity index (θ).

$$S = k_{sn}A^{-\theta}$$

To constrain the timing of any recent movement associated with the lineaments, knickpoint migration of nearby streams can be used as a proxy for uplift and departure from stream equilibrium. To attempt to establish an estimate of the most-recent pulse of local uplift, a geomorphological study of knickpoint migration and distance from the lineaments may be utilized (Gallen et al., 2011, Gallen et al., 2013, Miller et al, 2013). If the lineament corresponds to a fault separating a down-dropped and up-thrown block, knickpoints within the streams, initiated by faulting, would migrate upstream to bring the stream profile back to equilibrium in response to the change in base level.

The streams were added back into ArcMap to compare the location of possible knickpoints with locations of lithological contacts. To avoid confusion between lithologically controlled and transient knickpoints, streams to the north of the Swannanoa lineament in the Great Smoky Mountains National Park were selected that mostly lie within the Neoproterozoic Copper Hill formation (Southworth, 2012). Streams were extracted from the Santeetlah Creek basin to the south of the Swannanoa in Graham County, NC.

Results

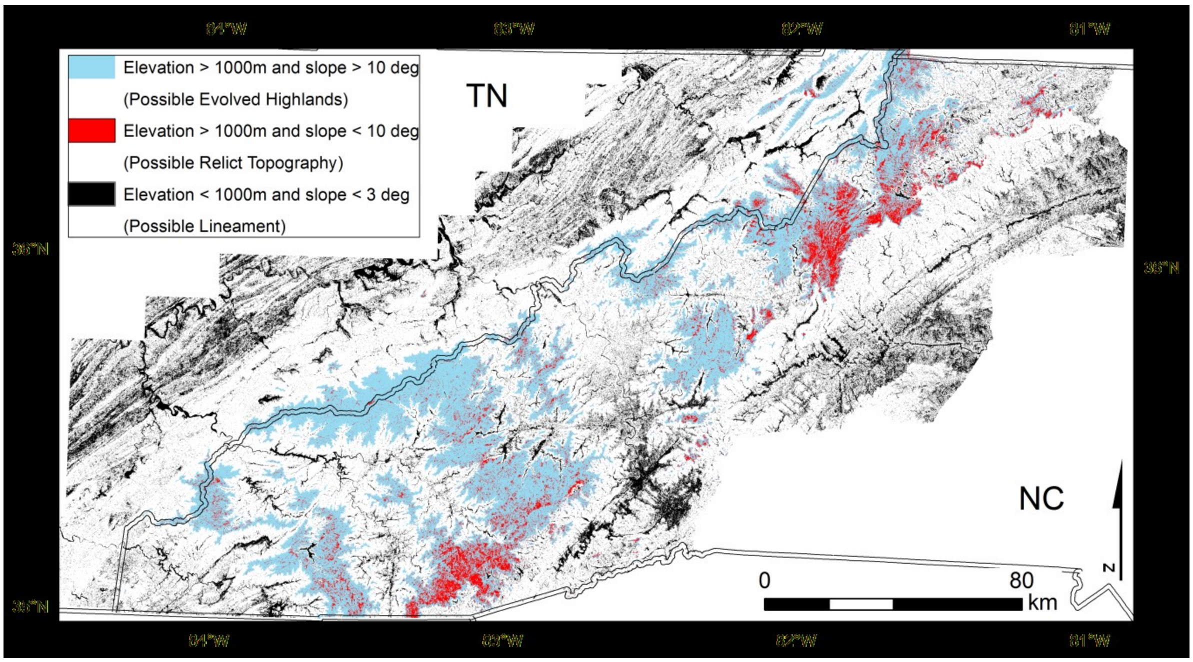

Figure 11: Discretized slope map of the Blue Ridge of western NC and TN. This map shows zones of high elevation and low slope bounded by topographic lineaments.

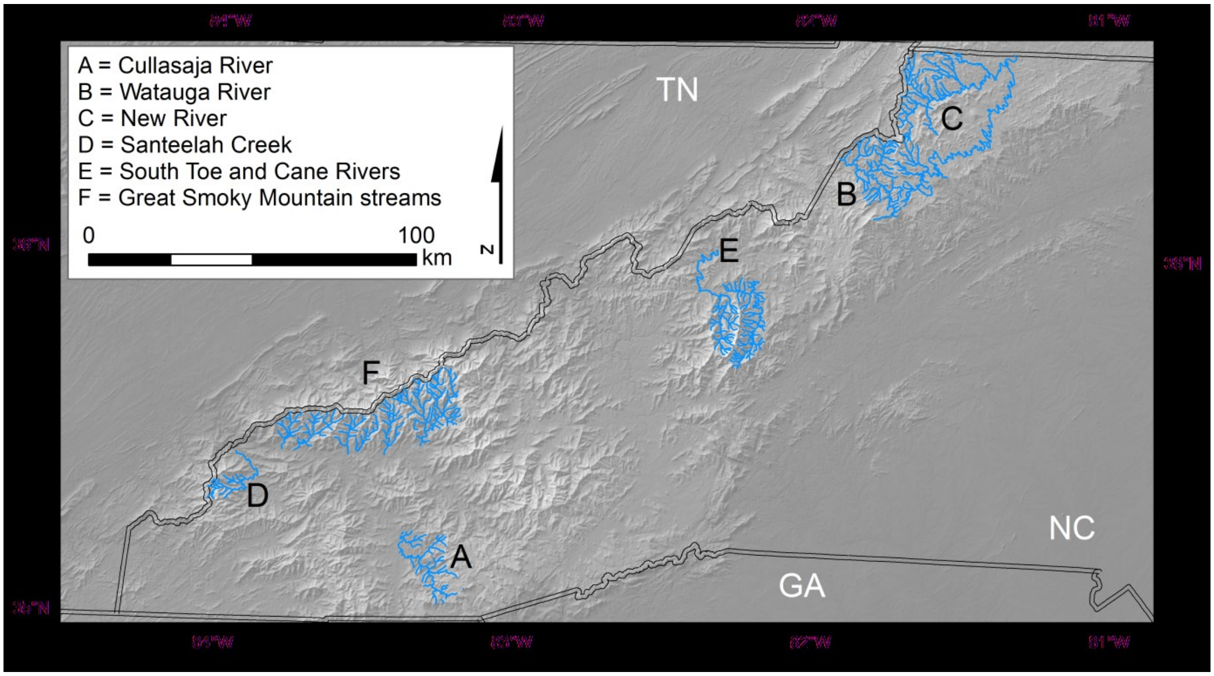

Figure 12: Shaded relief map showing locations of drainage basins that were analyzed.

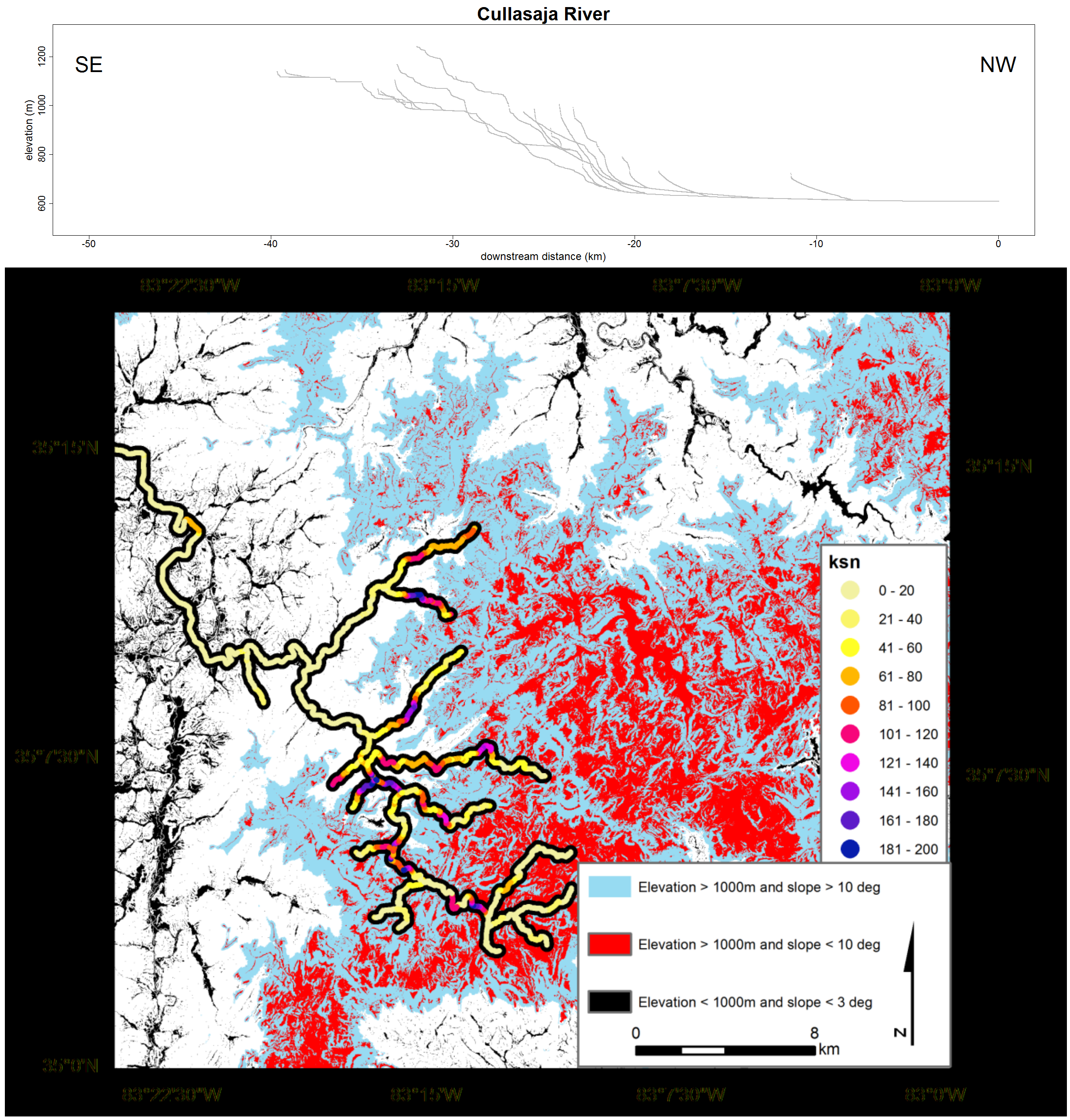

Figure 13: Longitudinal profile (top), density plot of normalized steepness (middle), and discretized slope map of the Cullasaja River basin with the streams colored by normalized steepness (k_{sn}) (bottom).

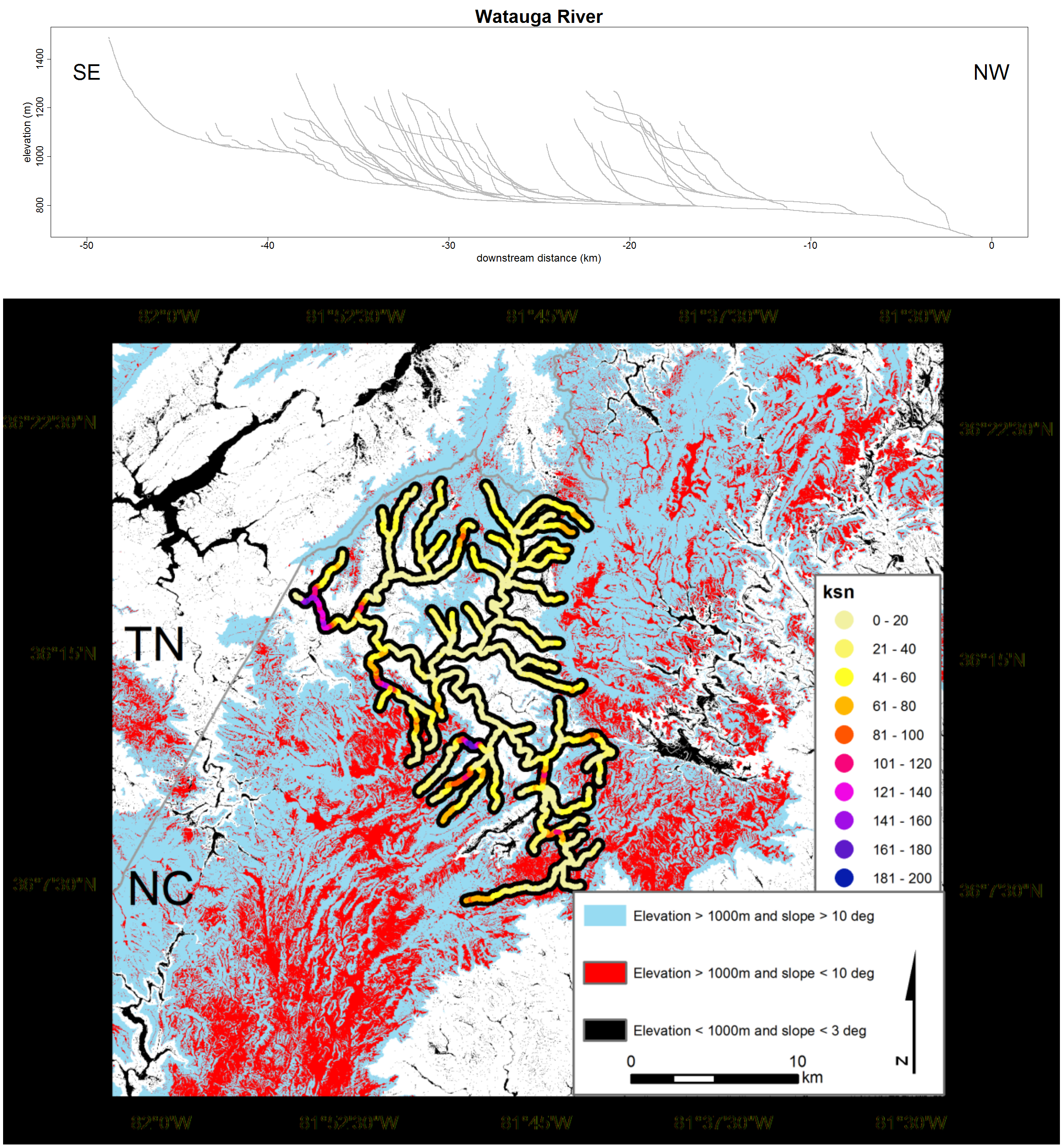

Figure 14: Longitudinal profile (top) and discretized slope map of the Wataugа River basin with the streams colored by normalized steepness (k_{sn}) (bottom).

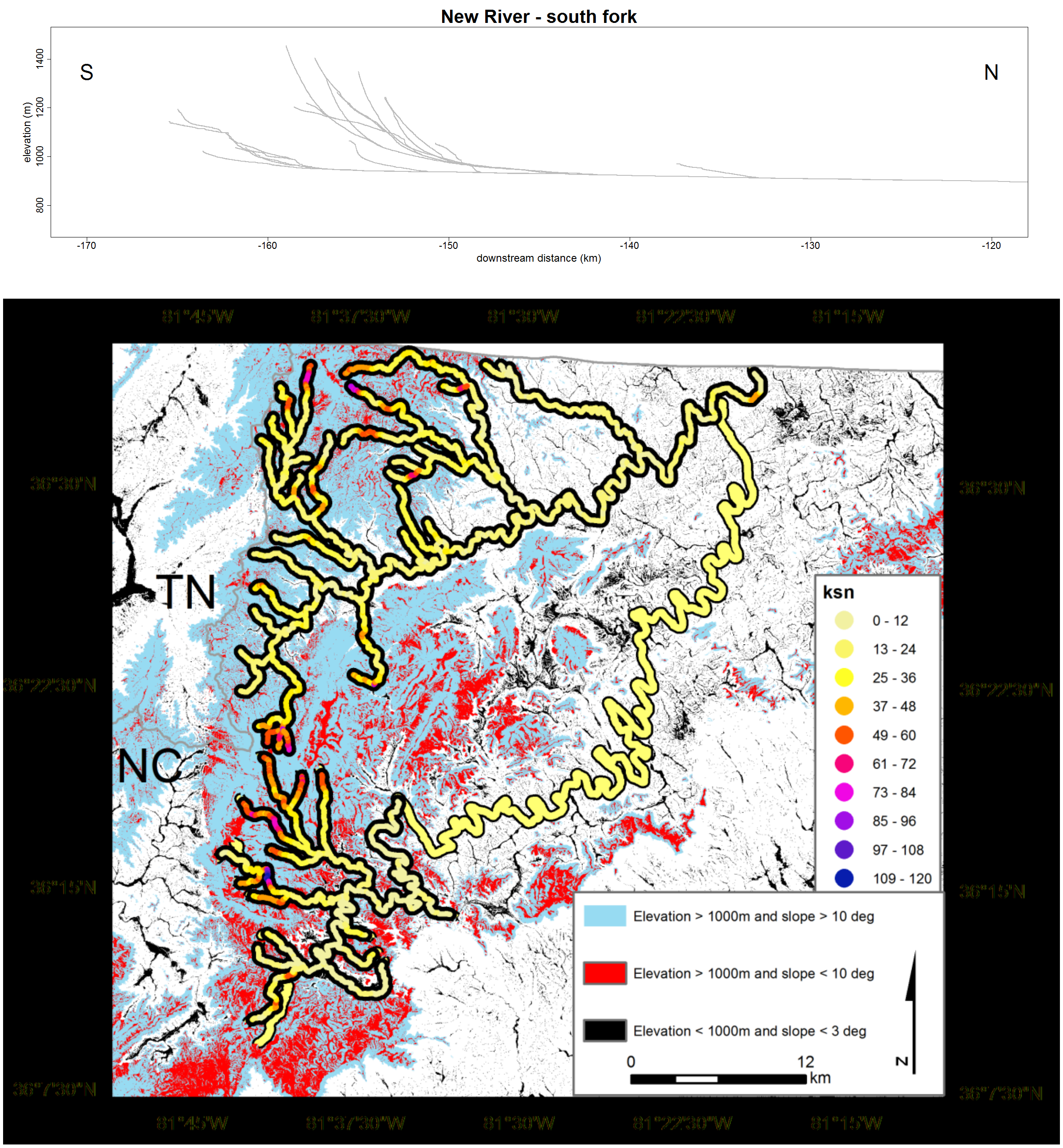

Figure 15: Longitudinal profile (top) and discretized slope map of the New River basin with the streams colored by normalized steepness (k_{sn}) (bottom).

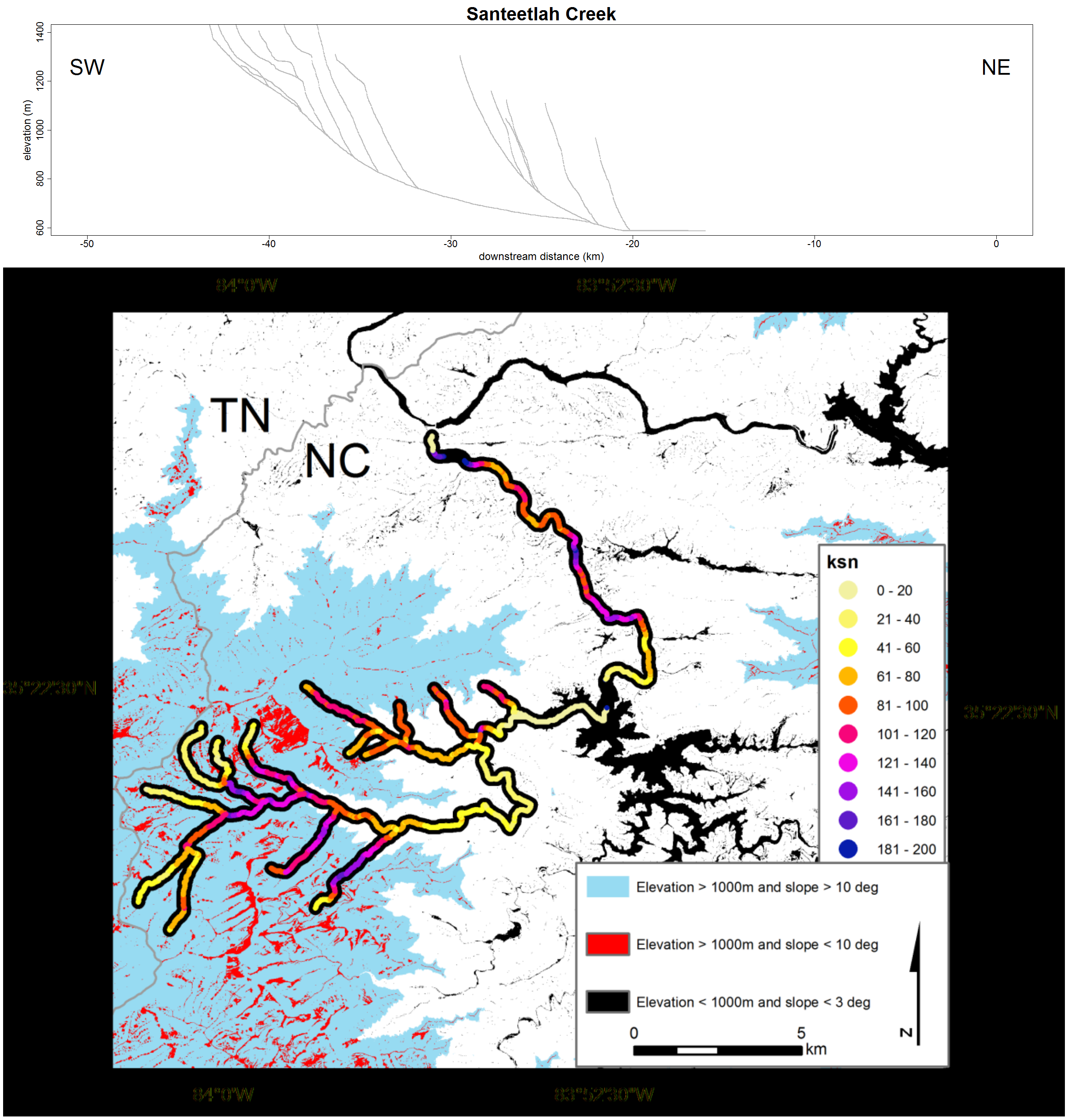

Figure 16: Longitudinal profile (top) and discretized slope map of the Santeetlah River basin with the streams colored by normalized steepness (k_{sn}) (bottom).

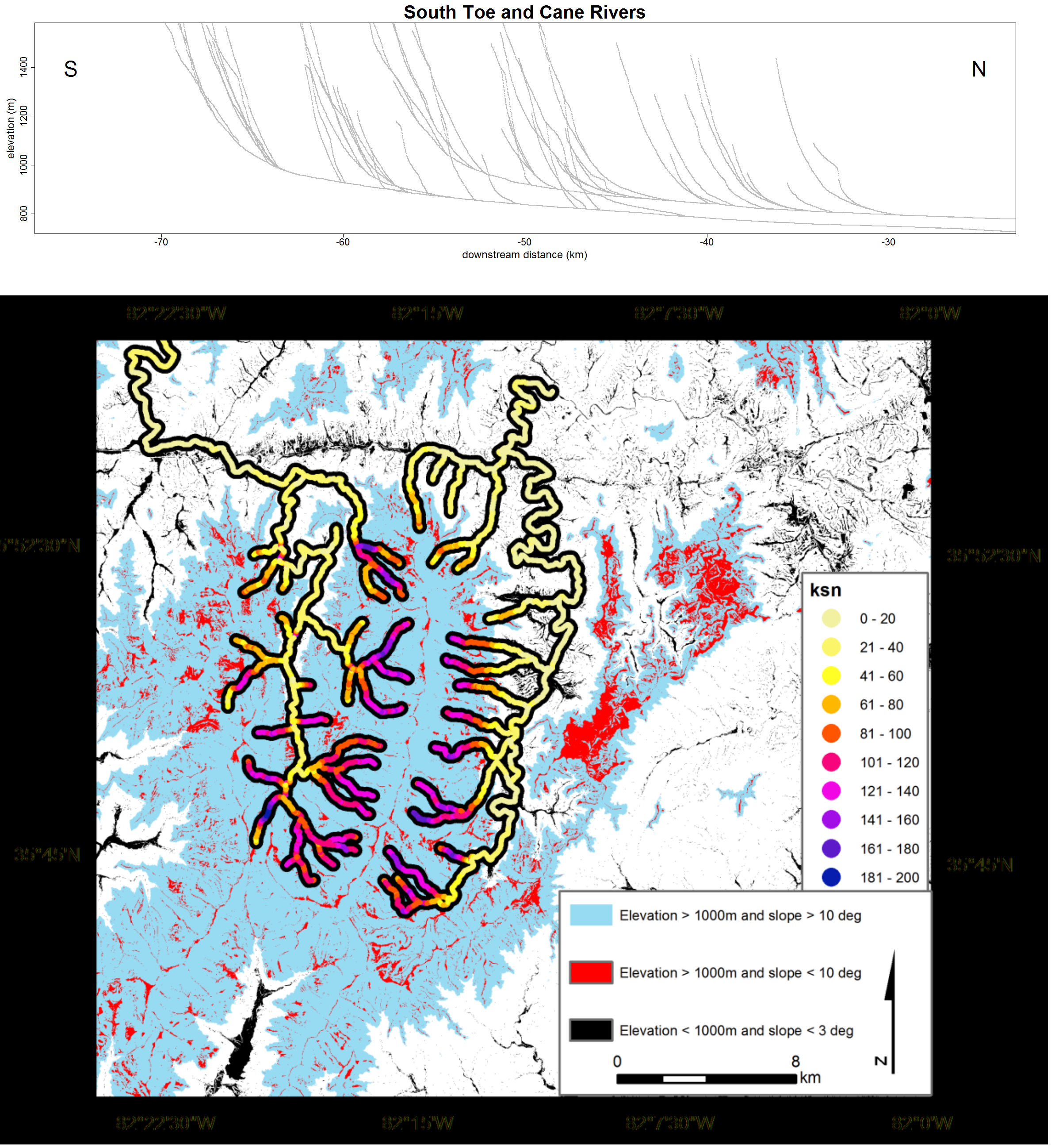

Figure 17: Longitudinal profile (top) and discretized slope map of the South Toe and Cane River basins with the streams colored by normalized steepness (k_{sn}) (bottom).

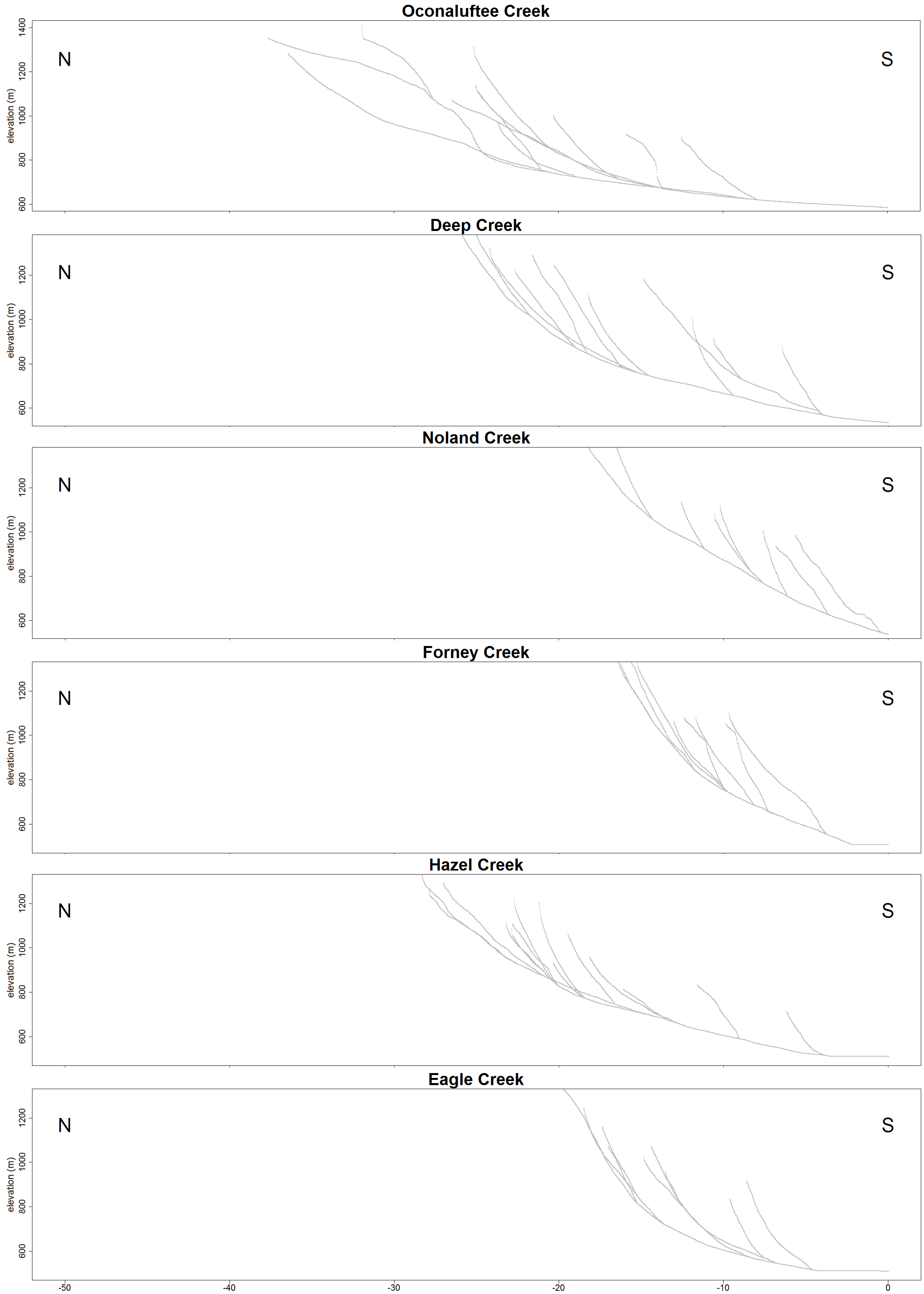

Figure 18: Longitudinal profiles of streams in the Great Smoky Mountains.

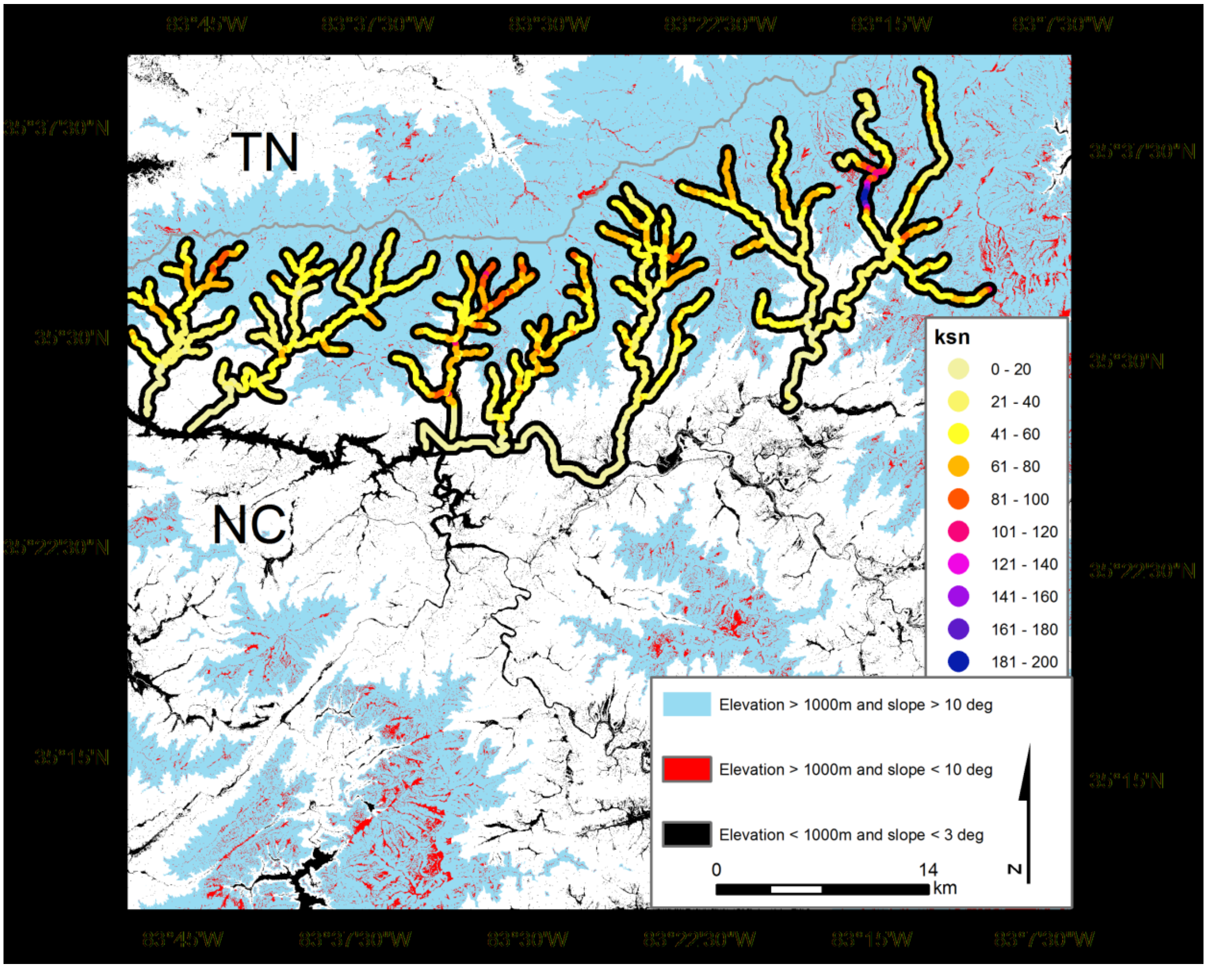

Figure 19: Discretized slope map of the Great Smoky Mountains with the streams colored by normalized steepness (k_{sn}) (bottom).

Discussion

Cullasaja River

The Cullasaja River drains into the north-south Franklin lineament and eventually into the Swannanoa lineament (Figures 12 and 13). Streams in the Cullasaja river basin were the focus of a recent study in which plots were produced using the StreamProfiler tool and Matlab, and were interpreted to have experienced a base-level change in the Miocene (Gallen et. al, 2013). The successful replication of the longitudinal profiles produced by Gallen et al. using R instead of Matlab validates the alternative methods used in this paper to connect the formation of the lineaments with Miocene uplift and topographic rejuvenation of the Blue Ridge (Figure 12). A normalized steepness map of the Cullasaja River Basin was produced using R script and the same knickpoints described by Gallen et al., (2011, 2013) were identified (Figure 12). Based on the degree of disequilibrium in the stream profile and the extensive high-elevation, low-slope region upstream of the knickpoints, this region is interpreted to be the furthest from equilibrium and reflects some of the most recent uplift in the region.

Watauga River and New River

Similar to the Cullasaja River, the Watauga River contains knickpoints upstream of active landscapes and downstream relict topography. The knickpoints in the Watauga and New Rivers are found at elevations of 1000 – 1300 m, and do not usually correspond with lithologic contacts (Figure 13 and 14). The areas upstream of these knickpoints have low k_{sn} values and are interpreted to be relict landscapes similar to those described in the Cullasaja by Gallen et al. (2011, 2013). The relict topography found upstream of the New River is less extensive and likely was uplifted earlier than the landscape upstream of the Watauga knickpoints.

Santeetlah Creek

The streams along the Santeetlah Creek basin have knickpoints only at the uppermost reaches and are graded below (Figure 15). Similar to the Cullasaja, Santeetlah Creek contains a low-relief relict landscape upstream of the knickpoints. This relict landscape is smaller than the area above the Cullasaja knickpoints and may be the remnant of an older uplifted terrain that has almost been totally dissected by streams approaching equilibrium. Below the Santeetlah knickpoints the slope is generally high, but there are meandering streams which were likely incised and have migrated laterally little since pre-

Miocene uplift. When the profile of the relict stream profile was projected the change in relief was ~750m. This change in base level is greater that the ~480 m estimate given by Gallen, et al. (2013), likely because Santeetlah and not the Cullasaja profiles were continued all the way to the Swannanoa lineament.

South Toe and Cane Rivers

The South Toe and Cane Rivers have similar downstream profiles and steepness maps (Figure 16). There is no evidence of transient knickpoints in these streams and there are highly sinuous sections of the South Toe River which look similar to those in the Santeetlah Creek Basin, which were likely captured due to uplift. These streams drain into the Laurel Creek lineament and are west of the continental divide, so the explanation of stream capture by escarpment migration can be eliminated (Spotila et al., 2004).

Great Smoky Mountains streams

Six different streams were extracted and analyzed in the Great Smoky Mountains National Park in Swain County, NC (Figure 17 and 18). These streams, from east to west are the Oconaluftee River, Deep Creek, Noland Creek, Forney Creek, Hazel Creek, and Eagle Creek. The headwaters start above 2000 meters and drain southward into the Swannanoa lineament below 330 meters, giving them the highest relief of any streams analyzed in this study.

The streams of the southern Smoky Mountains lack any knickpoints that cannot be explained by lithology and have longitudinal geometries that have reached or are close to equilibrium. Plus, the area above these streams is much steeper and no relict landscape can be found.

Interpretations of post-Paleozoic uplift in the Blue Ridge Province and North Carolina lineaments

The cause of proposed Miocene uplift in the Blue Ridge province is unknown, but several mechanisms have been suggested (Hack, 1982; Reinhardt, 1984; Matmon, 2003; Spotila et al. 2004; Gallen et al, 2013). It has been proposed that the lineaments formed from post-orogenic doming to accommodate upper-crustal extension (Dennison and Stewart, 2001), or they may be associated with Triassic rifting (Hatcher et al., 2005). During the Mesozoic the stress regime changed from one with the least compressive stress trajectories striking SE-NW to one where the least compressive direction are in a SW-NE direction, as it has remained to the present day (Garihan et al. 1993; Zoback, 1992). The Marietta-Tryon fault system contains fourteen major Mesozoic brittle faults in northwest South Carolina striking between N50E – N70E (Hatcher, 2005). The diabase dikes cut the brittle faults, but the brittle faults offset at least one of the dikes, leading to the interpretation that the faults and dikes are coeval (Garihan, et al., 1993). Hatcher (2005) attributed these faults and the Warwoman lineament to late Triassic-Jurassic extension and dike emplacement, and implied a connection between the Marietta-Tryon/Warwoman system of the Piedmont and the Swannanoa lineament of the Blue Ridge. The geometry of the Marietta-Tryon/Warwoman system is a large fault-bounded graben with a smaller inner graben. The faults in this system are more clustered, oriented differently, and less laterally extensive than the Swannanoa and Laurel Creek lineaments, neither of which is associated with an extensional graben system.

The Appalachian mountain belt inherited the sinuous pattern of promontories and embayments from the NE-trending rift segments and NW-trending transform faults of the Laurentian margin that formed after the Proterozoic break-up of Rodinia (Thomas, 2011). Thomas (2006) hypothesized that although most of the inherited structures are in the brittle, shallow crust, there may be a pervasive vertical fabric in the lithosphere that has affected the location of subsequent transform faults. Influence from buried transform faults may explain the origin of the NW-SE-trending topographic lineaments. These lineaments are parallel to proposed Iapetan transform faults produced during Rodinian rifting and parallel to Atlantic Ocean transform faults formed during the Mesozoic breakup of Pangea. The SE-NW set parallels proposed lateral ramps and may be surficial expressions of along-strike changes of regional décollements, also influenced by transform faults in the basement (Pohn, 1998).

Wooten et al. (2010) described the Mills Gap fault zone as a possible Mesozoic or younger fault zone striking ~295° cross-cutting Paleozoic fabrics. It parallels many local lineaments and larger NW-striking ones such as the Tuckasegee. This location contains strike-slip and oblique-normal faults that strike WNW-ESE and ENE-WSW interpreted to be associated with movement along younger, conjugate transtensional faults (Wooten et al., 2010; Chapman and Huffman, 2011). Further work needs to be done to constrain the age of these NW-SE striking lineaments and joints, if it is indeed only one event.

Gallen et al. (2013) speculated at a mechanism causing the 'transient' knickpoints of the Cullasaja River basin and broad uplift as the delamination of an eclogite root from under the Blue Ridge. The Cullasaja basin contains a high-relief, active landscape that is responding to uplift and a low-relief, relict landscape above the highest knickpoint. Based on these analyses, Gallen et al. (2013) determined that the relict landscape above the Cullasaja, which eventually drains into the Swannanoa lineament, has increased in relief by ~150% since the mid-Miocene (2013). Western North Carolina might owe its prominence to ~25-5 m.y. uplift that may have continued into modern time (Pazzaglia and Brandon, 1996; Stewart and Dennison, 2006; Galloway et al., 2011; Gallen et al., 2013).

Multiple catchments in western North Carolina contain streams with knickpoints around 1000 – 1300 m in elevation, some that correspond with lithologic boundaries and some that do not. It has been proposed that these knickpoints reflect a departure from equilibrium caused by uplift-related base level changes during the late Miocene. Gallen et al. (2013) offer an estimate of the age of the highest reaching knickpoints in the Cullasaja basin of ~8.5 Ma. The Cullasaja has the most pronounced knickpoints of the three areas studied in this paper, and this may be due to the cross-strike direction of the stream flow, or some of these features may be lithologic and not transient, or even possibly accentuated by the frequent debris flow and mass wasting events noted in the area (Wooten et al., 2008; Gallen et al., 2011). However, there are many knickpoints at similar elevations with some far from lithologic boundaries. Plus, the relict landscape above the Cullasaja knickpoints is much lower in relief than the active landscape below. The estimate of ~8.5 Ma is much younger than the ~20 Ma spike in sediment flux found in both the Atlantic Ocean (Pazzaglia and Brandon, 1996) and the Gulf of Mexico (Galloway et al., 2011). This temporal disparity may be explained if the uplift in the Cullasaja is younger than other phases of uplift in the Miocene that occurred in the Blue Ridge further to the west.

Sedimentary records of the US Atlantic coast (Poag and Sevon, 1989; Pazzaglia and Brandon, 1996) and the Gulf of Mexico (Galloway et al., 2011) document four main increases of sediment supply in the Appalachians since the Triassic. These signals do not match the global sediment records and therefore are not due to climate change and sealevel rise (Zachos et al., 2001). A Triassic erosional stage was caused by rifting and post-rift relaxation, followed by two stages in the Cretaceous related to asthenospheric flow and magmatism (Pazzaglia and Brandon, 1996). The least well understood and fourth increase in sediment supply was a pulse in the Miocene (~20 Ma; Pazzaglia and Brandon, 1996).

Based on cross-cutting relationships with the rest of the mountain chain, recent seismicity, and contrasting geometry from the regional rock fabric, these topographic lineaments must post-date the last major mountain-building event, possibly by tens or even hundreds of millions of years. Uplift and doming resulted in blocks of the crust separated by the lineaments moving vertically, possibly with the first block lifting the Smoky Mountains and the Black Mountains in the early Miocene; then another raising the area to the south of the Smoky Mountains during the mid-Miocene; followed by the most recently uplifted block, south of the Swannanoa lineament and east of the Franklin lineament by the late Miocene. Based on similarities in the stream profiles and relict landscapes upstream of knickpoints, the Watauga and New River catchments were likely uplifted coeval with the Cullasaja region.

This proposed sequence is based on the evolution of longitudinal stream profiles in western North Carolina showing varying degrees of equilibrium as reflected by the presence of transient knickpoints migrating in response to uplift-related base-level changes. The contrasts in the stream geometry of these areas may be due to rock strength and unequal erosion. It may be explained by different orientations of the stream networks and their interactions with the regional fabric of the Appalachians. Or, it is because of a temporal difference in the uplift of distinct blocks of the Blue Ridge separated by the major topographic lineaments. All three of these hypotheses offer insight into the contrasting relief and stream geometries of the areas on opposite sides of the lineaments and their links to rejuvenation of the Southern Appalachians. Obtaining uplift history from stream profiles in this fashion assumes much about original elevations, erosion rates, rock fabrics, etc., that any sequences suggested remain in need of much review and are only first order. Although there are many ways to form knickpoints and disentangling the mechanisms involved is difficult, a reasonable conclusion to be made from these stream profiles is that the different basins exhibit varying degrees of disequilibrium.

There are other lineaments dividing zones of varying topography that should be considered in greater detail when trying to synthesize a history of recent vertical movement in western North Carolina. This classification is not meant to imply that each zone moves cohesively or without internal deformation. Lineaments can be found at multitude of scales and these boundaries were drawn to represent major features. Some topographic lineaments separate different zones of topography but some do not. If a lineament formed from extension related to doming of the crust, the lineament may predate any differential uplift of the adjacent blocks, and there may be no reason the blocks move separately at all. The doming could continue after the formation of the lineament and the crust could rise evenly on either side of the lineament.

If the origin of the lineaments is related to uplift and rejuvenation of topography, the degree of evolution of the streams draining into the lineaments offers insight into the timing of that uplift. The fact that there is much heterogeneity in adjacent streams and the landscapes bounded by lineaments suggests that rather that broad, even uplift, the movement was temporally and spatially variable. This mechanism for the variation could be mantle heterogeneity, and the lineaments may owe their origin to lithosphere-scale forces.

Conclusions

The products of multiple Wilson Cycles and a rich tectonic history of deposition, magmatism, volcanism, metamorphism, faulting, and overprinting, the rocks at the surface in the southern Appalachians were once the crustal roots of Himalayan-scale mountains and have a unprecedented geologic past. In the absence of tectonic forces for over 200 m.y., the Blue Ridge province has experienced an enigmatic and atypical style of mountain building in the recent geologic past and possibly the present. Sometime in the Miocene, over 200 m.y. after the birth of the Atlantic Ocean, the Blue Ridge of western North Carolina was uplifted, likely not as a broad uniform section of the crust, but rather as blocks bounded by conjugate fracture zones that today form the Swannanoa, Laurel Creek, Franklin, and other unnamed lineaments. Some of the lineaments are seismically active fracture zones and others contain minor faults that may have played a role in separating zones of high and low relief and rejuvenating the rugged topography of the Blue Ridge.

Rejuvenation of the Blue Ridge province of western North Carolina may be connected to these previously recognized but poorly understood fracture zones containing minor dip-slip faults. I propose that the Blue Ridge province was not uplifted as a broad region, but rather in blocks or zones separated by the lineaments. This hypothesis is supported by the existence of high-relief drainages in equilibrium and high relief drainages out of equilibrium on opposite sides of the lineaments.

These topographic lineaments, the Swannanoa and the Laurel Creek, are primarily controlled by outcrop-scale fractures with minor faults, and are the largest and most evident east-west features cutting the landscape of western North Carolina without a known spatial or temporal link to Triassic or older geology. The streams draining into these low-lying trenches and others elsewhere in the Blue Ridge offer clues for synthesizing the relative sequence of zoned uplift and shed light on why an old mountain range could still have significant topographic relief long after the cessation of continental collision.

Appendix

Paleostress inversion algorithm

First, the data were added as strike, dip, and pitch. These angular measurements were converted to Cartesian coordinates for easier manipulation. A normal vector and a slip vector were described as follows:

φ = strike
δ = dip
λ = pitch

$$\left.\begin{array}{l} nx = -\sin\delta\sin\varphi \\ ny = \sin\delta\cos\varphi \\ nz = \cos\delta \end{array}\right\} \vec{\mathbf{n}}$$

$$\left.\begin{array}{l} sx = \sin\lambda\cos\delta\sin\varphi + \cos\lambda\cos\varphi \\ sy = -\sin\lambda\cos\delta\cos\varphi + \cos\lambda\sin\varphi \\ sz = \sin\lambda\sin\delta \end{array}\right\} \vec{\mathbf{s}}$$

The general stress tensor was described as:

$$\Sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{32} \end{bmatrix}$$

However, this stress tensor has nine degrees of freedom, so the stress tensor derived by Angelier (1990) with only four degrees of freedom was used for the inversion.

$$\Sigma = \begin{bmatrix} \cos\psi & \alpha & \gamma \\ \alpha & \cos(\psi + \frac{2\pi}{3}) & \beta \\ \gamma & \beta & \cos(\psi + \frac{4\pi}{3}) \end{bmatrix}$$

The variables $\psi, \alpha, \gamma, \text{and } \beta$ were randomly defined as twenty different initial sets of values. The optimization converged on the best-fit tensor regardless of initial input values. In this example, the engineering naming convention of principal stresses was used, where σ_3 is the greatest compressional stress, and σ_1 is the least compressional stress. Because there is no *a priori* knowledge of the absolute magnitudes of the stresses, only the *relative* magnitudes could be calculated. The stress-shape ratio was defined as follows:

$$\Phi = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3}$$

$$0 \leq \Phi \leq 1$$
$$\Phi = 1 \;\; when \;\; \sigma_2 = \sigma_3$$
$$\Phi = 0 \;\; when \;\; \sigma_1 = \sigma_2$$

The stress on the plane was given by:

$$\mathrm{T_n} = \Sigma^{\mathrm{T}}\mathrm{n}$$

The normal stress was caculated as:

$$\sigma_\mathrm{n} = (\mathrm{T_n} \cdot \mathrm{n})\mathrm{n}$$

The max shear stress was defined as:

$$\tau_{\mathrm{max}} = \mathrm{T_n} - \sigma_\mathrm{n} = \mathrm{T_n} - (\mathrm{T_n} \cdot \mathrm{n})\mathrm{n}$$

The best fit stress tensor had the minimum angle between *predicted* direction of τ_{max} and *observed* direction of the slickenlines. A difference function was defined as:

$$\mathrm{d} = \mathrm{s} - \frac{\tau_{\mathrm{max}}}{\sqrt{\sum_1^{\mathrm{n}} (\tau_{\mathrm{max}})^2}}$$

A residual function was defined as:

$$\mathrm{R} = \sqrt{\sum_1^{\mathrm{n}} (\mathrm{d_i} - \tau_{\mathrm{max}})^2}$$

The residual function was minimized to find the best-fit stress tensor using the Nelder-Mead method, a built in function that is part of the R package ‘stats.’

References:

Abbott, Richard N. (1984), Raymond, Loren A., The Ashe Metamorphic Suite, northwest North Carolina: Metamorphism and observations on geologic histories, American Journal of Science, v. 284, p. 350-375

Angelier, Jacques (1990), Inversion of field data in fault tectonics to obtain the regional stress – III, A new rapid direct inversion by analytical means, Geophysical Journal International, v. 103, p. 363-376

Brown, Phillip M. (1985), Parker, John M.,III, 1:500,000 Geologic Map of North Carolina, North Carolina Geologic Survey, plate 1

Davis, John C. (2002), Statistics and Data Analysis in Geology, 3rd Edition

Dennison, John M. (1997), Stewart, Kevin G., Roth, Emily A., Alcott, Allison E., Lowe, Ashley L., Vlahovic, Gordana, Post-orogenic linear fracture systems in the Great Smoky-Blue Ridge region of North Carolina, Tennessee, and Georgia; Geological Society of America Abstracts with Programs, Southeastern Section v. 29, no.3, p.13

Dennison, John M. (2001), Stewart, Kevin G., Regional structural and stratigraphic evidence for dating Cenozoic uplift of the southern Appalachian highlands; Geological Society of America Abstracts with Programs, Southeastern Section v.33, no.2, p.6

Dewey, J. F., (1988), Extensional collapse of orogens, Tectonics, v. 7, no. 6, p. 1123-1139

Duvall, Alison (2004), Kirby,Eric, Burbank, Douglas, Tectonic and lithologic controls on bedrock channel profiles and processes in coastal California, Journal of Geophysical Research, v. 109,

Erlanger, Erica C. (2012), Granger, Darryl E., Gibbon, Ryan J., Rock uplift rates in South Africa from isochron burial dating of fluvial and marine terraces, Geology, v. 40, no. 11, p. 1019-1022

Chapman, Martin (2005) , The August 25, 2005 Hot Springs, North Carolina earthquake: extensional faulting in the detached Alleghenian overthrust belt of the southern Appalachians, 77th Annual Meeting of the Eastern Section of the Seismological Society of America

Chapman, Melinda J. (2011), Huffman, Brad A., Geophysical logging data from the Mills Gap Road area near Asheville, North Carolina, U.S. Geological Survey Data Series 538

Farmer, G. Lang (2002), Glazner, Allen F, Manley, Curtis R., Did lithospheric delamination trigger late Cenozoic potassic volcanism in the southern Sierra Nevada, California?, GSA Bulletin, v.114, no. 6, p. 754 - 768

Garihan, John M. (1993), Preddy Mark S., Ranson, William A. Summary of mid-Mesozoic brittle faulting in the Inner Piedmont and nearby Charlotte Belt of the Carolinas, in Studies of Inner Piedmont Geology with a focus on the Columbus Promontory, eds., Hatcher, Robert D. Jr. and Davis, Timothy L, Carolina Geological Society Annual Field Trip 1993, p. 55-65

Gallen, Sean F. (2011), Wegmann, Karl W., Frankel, Kurt L., Hughes, Stephen, Lewis, Robert Q., Lyons, Nathan, Paris, Paul, Ross, Kristen, Bauer, Jennifer B., Witt, Anne C., Hillslope response to knickpoint migration in the Southern Appalachians: implications for the evolution of post-orogenic landscapes; Earth Surface Processes and Landforms v. 36, no. 9

Gallen, Sean F. (2012) and Wegmann, Karl, A Neogene to recent resurgence of topographic relief in the southern Appalachians: geomorphic evidence from the Cullasaja river basin, North Carolina, Geological Society of America Abstracts with Programs, Southeastern Section Vol. 44, No. 4, p. 78

Gallen, Sean F. (2013), Wegmann, Karl W., and Bohnenstiehl, DelWayne R., Miocene rejuvenation of topographic relief in the southern Appalachians, GSA Today, v. 23, p. 4-10

Galloway, William E. (2011), Whiteaker, Timothy L., Ganey-Curry, Patricia, History of Cenozoic North American drainage basin evolution, sediment yield, and accumulation in the Gulf of Mexico basin; Geosphere, v. 7; no. 4; p. 938–973

Gay, Parker S., Jr. (2000), Unmapped topographic alignments visible on 3D stereo terrain map of a 2 degrees X 2 degrees segment of the Southern Appalachians, Geological Society of America Abstracts with Programs, Southeastern Section v.32, no.2, p.19

Hack, John T. (1982), Physiographic divisions and differential uplift in the Piedmont and Blue Ridge; Geological Survey Professional Paper 1265

Hadley, Jarvis B. (1971), Nelson, Arthur, E., Geologic map of the Knoxville Quadrangle, North Carolina, Tennessee, and South Carolina; USGS Miscellaneous Geological Investigations Map

Hatcher, Robert D., Jr. (1974), Introduction to the Blue Ridge tectonic history of northeast Georgia; Georgia Geological Society of America Bulletin; v. 88, p. 1678-1688

Hatcher, Robert D., Jr. (1979) Butler, Robert J., Guidebook for southern Appalachian field trip in the Carolinas, Tennessee, and Northeastern Georgia; International Geological Correlation Program

Hatcher, Robert D., Jr. (2005), Merschat, A. J., and Thigpen, J. R., Blue Ridge Primer, in Hatcher, R. D., Jr., and Merschat, A. J., eds., Blue Ridge geology geotraverse East of the Great Smoky Mountains National Park, Western North Carolina: North Carolina Geological Survey, Carolina Geological Society Annual Field Trip Guidebook, p. 1-24.

Hatcher, Robert D., Jr. (2006), Merschat, A.J., and Raymond, L.A., 2006, Geotraverse: Geology of northeastern Tennessee and the Grandfather Mountain region, in Labotka, T.C., and Hatcher, R.D., Jr., eds., Geological Society of America 2006 Southeastern Section Meeting Field Trip Guidebook, p. 129–184.

King, Elizabeth R. (1978), Zietz, Isidore, The New York-Alabama lineament: Geophysical evidence for a major crustal break in the basement beneath the Appalachian basin, Geology v. 6, p. 312-318

Kirby, Eric (2001), Whipple, Kelin, Quantifying differential rock-uplift rates via stream profile analysis, Geology, v. 29, no. 5, p. 415-418

Kirby, Eric (2012), Whipple, Kelin, Expression of active tectonics in erosional landscapes, Journal of Structural Geology, v. 44, p. 54-75

Merschat, Carl E. (1988), Wiener, Leonard S., Geology of the Sandymush and Canton Quandrangles; North Carolina Geological Survey; Bulletin 90;

Merschat, Carl E., (1997), Geology of Yancey County, North Carolina Geological Survey-Division of Land Resources, Geologic Note no. 5

Miller, Brent V. (2006), Fetter, Allen H., Stewart, Kevin G., Plutonism in three orogenic pulses, Eastern Blue Ridge Province, southern Appalachians, GSA Bulletin, v. 118, no. ½, p. 171-184

Miller, Scott R. (2013), Sak, Peter B., Kirby, Eric, Bierman, Paul R., Neogene rejuvenation of central Appalachian topography: Evidence for differential rock uplift from stream profiles and erosion rates, Earth and Planetary Science Letters, 369- 370, p. 1-12

National Earthquake Information Center (2013): http://earthquake.usgs.gov/regional/neic/

NC Floodmaps Program (2013): http://www.ncfloodmaps.com/

Nelson, Kim J. Park (2007), Nelson, Frederick E., Walegur, Michael T., Periglacial Appalachia: Palaeoclimatic Significance of Blockfield Elevation Gradients, Eastern USA, Permafrost and Periglacial Processes, v.18: p. 61–73

Pazzaglia, Frank J. (1996), and Brandon, Mark T., Macrogeomorphic evolution of the post-Triassic Appalachian mountains determined by deconvolution of the offshore basin sedimentary record; Basin Research v. 8, no. 3, p. 255-278.

Pohn, Howard, A. (1998), Lateral ramps in the folded Appalachians and in overthrust belts worldwide - A fundamental element of thrust-belt architecture; USGS Bulletin 2163

Reinhardt, Juergen (1984), Prowell, David C., and Christopher, Raymond A., Evidence for Cenozoic Tectonism in the southwest Georgia Piedmont; Geological Society of America Bulletin, v. 95, p 1176-1187

Robinson, G.R. (1991), Jr, Lesure, F.G, Marlowe, J.I, II, Foley, N.K, and Clark, S.H, Bedrock Geology and Mineral Resources of the Knoxville 1x2 Quadrangle, Tennessee, North Carolina, and South Carolina; U.S. Geological Survey Bulletin 1979

Roy, Mousumi (2009), Jordan, Thomas H., Pederson, Joel, Colorado Plateau magmatism and uplift by warming of heterogeneous lithosphere, Nature v. 459 p. 978-984

Shake, Sally S. (1987), McHone, Gregory J., Topographic lineaments and their significance in central New England and adjacent New York; Northeastern Geology, v.9., no.3, p. 120-128

Spotila, James A. (2004), Bank, Greg C., Reiners, Peter W., Naeser, Charles W., Naeser, Nancy D., and Henika, Bill S., Origin of the Blue Ridge escarpment along the passive margin of Eastern North America; Basin Research, p. 41-63

Southworth, Scott (2012), Schultz, Art, Aleinikoff, John N., Merschat, Arthur J., Geologic map of the Great Smoky Mountains National Park region, Tennessee and North Carolina: Carolina: U.S. Geological Survey Scientific Investigations Map 2997, one sheet, scale 1:100,000, and 54-p. pamphlet. (Supersedes USGS Open-File Reports 03–381, 2004–1410, and 2005–1225.)

Stewart, Kevin G. (2006), Dennison, John M., Tertiary-to recent arching and the age and origin of fracture-controlled lineaments in the southern Appalachians, Geological Society of America Abstracts with Programs, Southeastern Section Vol. 38, No. 3, p. 27

Thomas, William. A., (1977), Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin: American Journal of Science, v. 277, p. 1233–1278

Thomas, William. A., (2006), Tectonic inheritance at a continental margin, GSA Today, v 16, no. 2

Thomas, William A., (2011), The Iapetan rifted margin of southern Laurentia; Geosphere, p 97-120

Wagner, Lara S. (2012), Stewart K., Metcalf, Kathryn, Crustal-scale shortening beneath the Blue Ridge Mountains, North Carolina, USA, Lithosphere

Wooten, R.M., (2008), Gillon KA, Witt AC, Latham RS, Douglas TJ, Bauer JB, Fuemmeler SJ, Lee LG. Geologic, geomorphic, and meteorological aspects of debris flows triggered by Hurricanes Frances and Ivan during September 2004 in the Southern Appalachian Mountains of Macon County, North Carolina (southeastern USA). Landslides v.5, p.31–44

Wooten, Richard M., (2010), Cattanach, Bart L., Gillon, Kenneth A., Bozdog, Nicholas, Geology of the Mills Gap Area, Buncombe County, North Carolina, North Carolina Geological Survey Report of Special Investigation

Zoback, Marie Lou (1992), Stress Field Constraints on Intraplate Seismicity in Eastern North America, Journal of Geophysical Research, vol. 97, no. B8, pp. 11,761-11,782

Zachos, James (2001), Pagani, Mark, Sloan, Lisa, Thomas, Ellen, Billups, Katharina, Trends, rhythms, and aberations in global climate 65 Ma to present, Science, v. 292, p. 686-693