Combining airborne Light Detecting and Ranging (LiDAR) and outcrop data to characterize m- to km-scale fracture networks in heterogeneous bedrock: Panthertown Valley and lower Hickory Nut Gorge, NC, USA

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1. Purpose and scope

Rock packages that experienced the same recent tectonic and uplift history can exhibit different fracture network geometries, which in turn may affect patterns of subsequent fracture propagation and interaction. Fracture patterns in sedimentary rock packages indicates heterogeneity often is related to "competency" contrast (e.g., rock type tensile strength) and/or anisotropy (e.g., lithological layering thickness). However, in regions where bedrock is largely comprised of ductilely deformed tectonites and intrusive igneous rocks, the scale(s) of, and geological characteristics linked to, fracture network heterogeneity is less well understood. Better understanding of fracture network heterogeneity in these regions would assist interpretation of fracture-influenced natural hazards, groundwater reservoirs, and landscape evolution.

The combination of public domain high-resolution LiDAR "bare earth" digital elevation models, 1:24,000 scale geologic maps, and targeted field work, offers an opportunity to characterize natural fracture networks at a range of scales and lithological packages. Combining these datasets are especially important in regions like western North Carolina where bedrock exposure is often poor. The following summarizes ongoing work using statewide LiDAR DEMs (NC QL2, 2019) in the Panthertown Valley and lower Hickory Nut Gorge areas of the southeastern Blue Ridge of western North Carolina (Fig. 1). These areas were selected for pilot studies because bedrock lithology and km-scale ductile structures are relatively simple, erosional levels expose ~300-600m of structural depth including the major lithologic contacts, and km-scale topographic features suggest influence by bedrock fracture patterns. Please find a summary of regional tectonic history and fracture sets, and related maps, in the conference field trip guidebook (Wooten et al., 2022).

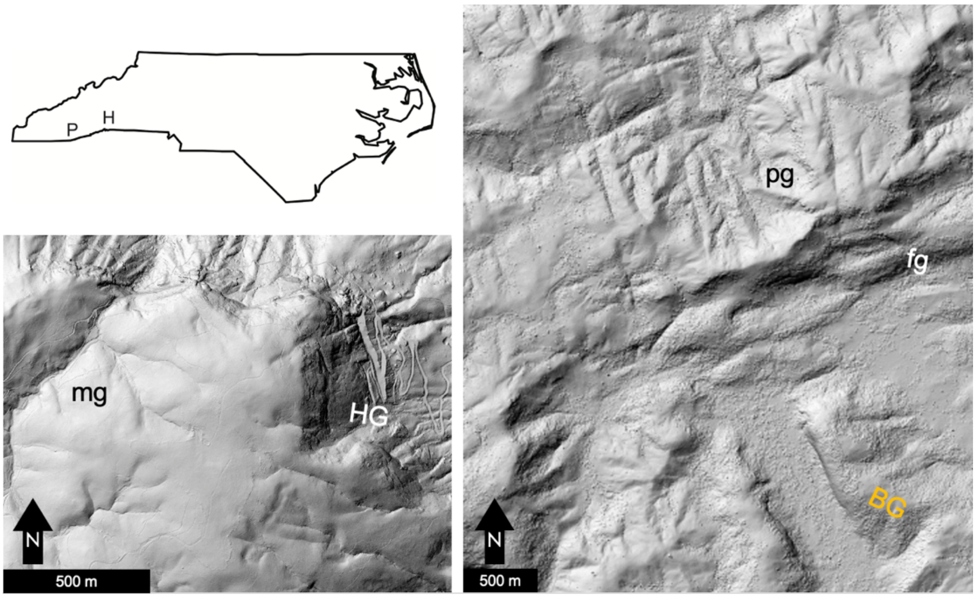

Figure 1. Top left: location of Panthertown Valley (P) and lower Hickory Nut Gorge (G) field areas in western North Carolina, USA. Lower left and right: Examples of shaded relief DEM perspectives from each field area. Left: Chimney Rock Mountain and southern side of lower Hickory Nut Gorge. Smoother LiDAR "texture" in mafic gneiss (mg) of the Poor Mountain map unit. Steeper cliffs and rougher "texture" in the Henderson Gneiss (HG). Right: W Panthertown Valley and highlands to N. Distributed NW lineaments in paragneiss unit (pg); NE-trending lower and NW-trending upper Panthertown Creek valley, and Big Green ridge (BG), in the felsic gneiss (fg).

2. Panthertown Valley

Bedrock in the Panthertown Valley area is comprised of a km-scale, open antiform of medium- to coarse-grained Neoproterozoic paragneiss with aluminous, mafic, and quartzofeldspathic lithological domains, which overlies medium-grained Ordovician two-mica felsic orthogneiss (Wickstrom, 1979; Stahr, 2008; this study). The felsic gneiss protolith intruded during or prior to penetrative granulite facies deformation (Wickstrom, 1979; Stahr, 2008; Keever et al., 2016; this study). The main lithological contact is gradational, retaining field and geochemical evidence of contact partial melting that mixed with the intruding felsic magma (Keever et al., 2016). Foliation intensity is also gradational across the contact. Near the contact, penetrative grain shape foliation is parallel to cm- to m-scale compositional layering in the paragneiss. Foliation weakens in the felsic gneiss inwards towards the fold axis.

The felsic gneiss is incised by steeply-sided, km-scale, linear valleys. The main valley lineament generally parallels the ENE-trending fold axis and the other, shorter, valley lineaments are nearly perpendicular (examples in Fig. 1, right). Prior work and for this study found no evidence of variation in mineral abundances, grain size distribution, or rock fabric, that correlates with these topographic lineaments (Wickstrom, 1979; Allen et al., 2016).

Most felsic gneiss exposure is in steep (>80°) valley walls and shallower dipping (<50°) exfoliation "shoulder" slopes leading upwards towards the transitional contact with the paragneiss. The valley wall fractures are ENE- and NW-oriented and up to 10m^2-scale. The larger surfaces are gently curved traces. Additional W, NW, and NNW steeply dipping fracture sets in the felsic gneiss are uncommon. Fractures in the paragneiss are common, dip steeply, NW-, NNW-, and E-oriented, and of <m scale height. Fractures are interpreted as extensional (joints or exfoliation).

Almost 800 lineaments in the ~80 km^2 field area, easily discernable from non-geologic features, have been manually identified in high resolution (0.5 m) "bare earth" DEMs derived from airborne LiDAR (NC QL2, 2019). Traces with >10 m length were prioritized to increase azimuth accuracy. Bedrock exposure, and fractures in exposures, are too widely distributed for meaningful comparison with LiDAR lineaments. However, the LiDAR lineaments are interpreted to represent steep bedrock fracture sets based on their orientations, lineaments remaining straight across elevation changes, and outcrop observations. Lineaments define NW, NE, and E sets and are twice as abundant in the paragneiss, consistent with outcrop observations (Fig. 2). Lineament orientation sets vary at the ~1 km scale (Fig. 2).

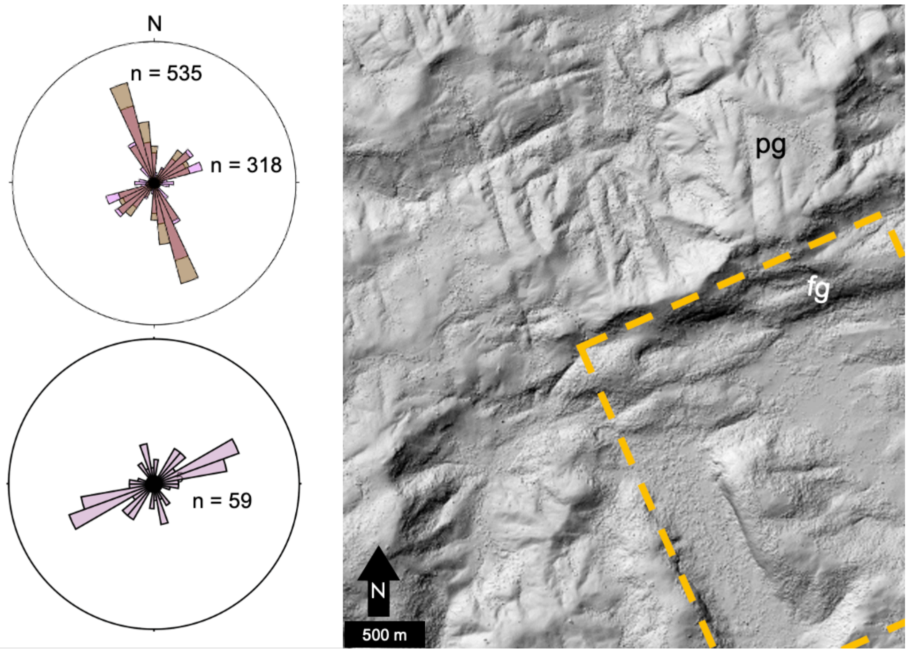

Figure 2. Examples of LiDAR lineament patterns in Panthertown valley. Top left: Lineament azimuth rose diagram from paragneiss (pg; brown) and felsic gneiss (fg, pink) from entire field area. Bottom left: Lineament azimuths from felsic gneiss only in area partly shown in yellow dashed box. Right: as in Fig. 1. Lineament azimuths shown in rose diagram bins of 10° and centered on 000; max petal radius 30%.

The above observations suggest the following. (1) The same fracture orientation sets developed in both the paragneiss and felsic gneiss. (2) Dominant fracture orientation sets and spacing patterns vary at 0.5 km scales. In particular, the NW and ENE fracture sets in the felsic gneiss localized into clustered zones indicated by the linear valleys, whereas these two fracture sets are more evenly distributed in the overlying paragneiss. (3) Steep fractures structurally lower in the felsic gneiss may have influenced development of lateral stress relief fractures, whereas the orientation of the major lithologic transitional contact may have influenced development of shallow exfoliation higher in the felsic gneiss nearer the paragneiss contact.

3. Lower Hickory Nut Gorge

Please find additional information about the lower Hickory Nut Gorge (HNG) area in the conference field trip guidebook (Wooten et al., 2022; Wooten and Waters-Tormey, 2022). Bedrock in the lower HNG area is comprised of gently SE-E dipping gneissic and mylonitic foliation within two Ordovician map units (Davis and Yanighara, 1993; this work). The lower unit (Henderson Gneiss) is dominantly porphyroclastic mylonitic gneiss, with lenses and layers of coarse-grained and fine-grained felsic gneiss migmatitic gneiss indicating a heterogeneous protolith. The main penetrative foliation is defined by aligned recrystallized wings of cm- to mm-scale, σ-type feldspar porphyroclasts and the grain shape preferred orientation of finer-grained quartz and biotite. Discontinuous biotite laminae spacing is controlled by porphyroclast size and distribution. An oblique foliation (“S” of “S-C”) is defined by unrecrystallized porphyroclast cores. In other textural zones, sigmoidal lenses of polycrystalline coarser-grained felsic domains, and felsic lenses and layers, help define similar fabrics. Ductile fabric intensity (e.g., straightness of grain shape and compositional foliation, parallelism of S-C foliations, overall grain size) varies at 1-10 m scales. Structurally above the Henderson Gneiss lies one of several lithotextural units of the Poor Mountain map unit. These are (1) fine-grained, mafic amphibolite gneiss typically exhibiting a cm-scale straight gneissic foliation; (2) fine-grained felsic gneiss in which foliation, and locally shear bands, are defined by grain shape fabric of biotite, feldspar, and quartz; (3) medium-grained muscovite foliated schist; and (4) volumetrically minor, thinner layers/lenses of fine grained biotite-hornblende gneiss enclosing 1-100 cm scale lenses of coarser grained felsic domains. Subparallel foliation and outcrop patterns suggest that these lithologies define a 1- to 10-m thickness scale compositional foliation.

Kinematically-consistent fabric domains, shear sense indicators, and stretching lineations occur throughout both units (Davis and Yanighara, 1993; ongoing work). These observations suggest that (at least locally) the original contact has been transposed along with km- to m-scale lithological domains. However, the top of the Henderson Gneiss can be constrained within a few meters of structural depth, even though different parts of the Poor Mountain unit lie above (map for Stop 3 in field trip guidebook, Wooten and Waters-Tormey, 2022).

At least two of W-, NW-, N-, and NE-oriented steep (most >75°) fracture sets occur in outcrops of both the Henderson Gneiss and Poor Mountain map units, although W, NW, and NE sets are most common. Most fractures are interpreted as extensional (joint) fractures. The number of fracture sets per m^2 is higher in outcrops nearer to the center of the lower gorge, suggesting a relationship with formation of the gorge, but exposure is poor.

Within the Henderson Gneiss, fracture height (i.e., at high angles to the shallowly dipping foliation) seems to be shorter where compositional domains are more abundant and aligned. Otherwise, fracture heights seem to be higher where (1) porphyroclast abundances and sizes are lower and spacing between the biotite folia is smaller, (2) compositional domains are more spaced, or (3) compositional domains form m-scale folded (sheath fold?) domains. Except where the felsic gneiss lithology is thicker, the Poor Mountain unit is characterized by 1cm–10 m-scale compositional foliation thicknesses, better developed and penetrative foliation-parallel fractures, and shorter cross-cutting fracture heights.

LiDAR DEM analysis and interpretation as described for Panthertown is underway in the lower HNG area. As in Panthertown, the major bedrock units have different “textures” in the DEM. All lithologies of the Poor Mountain unit appear smoother with spaced 100 m-length-scale lineaments (example in Fig. 1, left). The Henderson Gneiss, even when largely buried by colluvium and alluvium, has more abundant lineaments (Fig. 1, left; Fig. 3, right). Unlike in Panthertown, sufficient outcrop in much of the lower HNG area allows comparison of outcrop fracture and lineament orientations. For example, below the main cliffs of the north lower HNG, fractures define WNW, NW, and NE sets, whereas lineaments are dominated by a NE set (Fig. 3). This contrasts with the NW-oriented, gorge-parallel cliffs above.

The above observations and ongoing work suggest the following. (1) The same fracture orientation sets developed in both the Henderson Gneiss and compositionally layered Poor Mountain units. (2) dominant fracture orientation sets in outcrop and as indicated by LiDAR lineaments vary at 100m scales. (3) The degree of compositional layering in the Poor Mountain unit overall, and in more layered zones within the Henderson Gneiss, is inversely proportional to fracture height.

(3) Steep and tall fractures structurally lower in the Henderson gneiss may have influenced development of lateral stress relief fractures helping to create cliff sections.

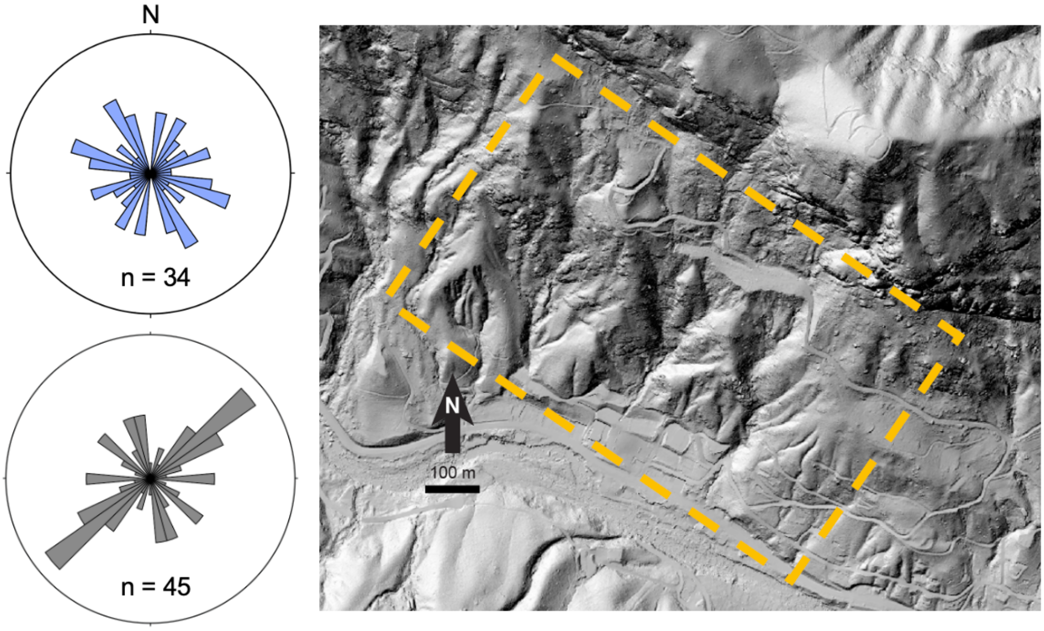

Figure 3. Example of outcrop fracture (top left) and LiDAR lineament patterns (bottom right) in lower HNG, below cliffs (yellow dashed box). Right: Shaded relief DEM of the northern side of gorge above the town of Chimney Rock, NC. Rose diagram bins of 10° and centered on 000; max petal radius 50%.

4. Summary

Geological mapping, outcrop-scale fracture morphology and geometry, and LiDAR DEMs provide different perspectives on bedrock fracture networks. In particular, the DEMs indicate fracture trace lengths and distribution patterns not discernable otherwise. In both field areas, field observations and LiDAR DEM “textures” suggest fracture network heterogeneity is related to overall lithology, but perhaps more strongly affected by compositional layering. Steep cliffs delineating linear topographic features may have formed where lateral stress relief fracturing was influenced by taller, vertical fracture sets in the bedrock.

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6. Acknowledgments

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