University of North Carolina at Asheville
Journal of Undergraduate Research
Asheville, North Carolina
May 2017

Kinematic and Deformation Temperature Constraints During Acadian Dextral Strike-Slip Faulting on the Burnsville Fault, Asheville, NC

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Abstract

The Appalachian Orogen records three mountain building events attributed to the creation of Pangaea; the Ordovician Taconic, Silurian-Devonian Acadian, and the late Paleozoic Alleghanian orogenies. In North Carolina, the rocks of the Ashe Metamorphic Suite were juxtaposed onto ~1 billion year old gneissic basement rocks during the Taconic. This contact near Asheville, NC was reactivated during the Acadian by the dextral strike-slip Burnsville shear zone, recognized by previous studies from Asheville north to Carvers Gap, NC. This study presents detailed field mapping and kinematic analysis of rocks collected along a transect through the Burnsville shear zone in Asheville, NC. Field observations and microstructural analysis of the rocks were combined with electron-backscattered diffraction (EBSD) analysis to quantify the amount of thinning, extension, and the depth of dextral shearing that occurred during the Acadian orogeny. Shear sense indicators seen in the field and microscopically supports dextral strike-slip shearing. EBSD and microstructural measurements were combined to calculate the vorticity (W_m; the ratio of flattening to shearing where 1 suggests shearing and 0 suggests flattening) and the strain ratio (R_{xz}; the ratio of the axes of flattening and shearing). Results indicate a W_m of 0.99 (minor flattening) and R_{xz} of 5.4, suggesting the rocks in one portion of the shear zone were shortened by 12.5% perpendicular to foliation and extended by 14.3% parallel to shear zone foliation. These data were collected from a sample with lower apparent strain, suggesting that the bulk extension and shearing across the shear zone is higher. Estimates of deformation temperatures from quartz lattice preferred orientations (LPO) collected from EBSD analysis as well as evaluation of quartz recrystallization suggest a temperature of ~500-600° C during Acadian dextral shearing, a depth of ~17-20 km. U-Pb ages from zircon in an undeformed granite dike that crosscuts the shear zone indicates that dextral shearing in this portion of the shear zone ended by ~330 Ma.

1. Introduction

The formation of Pangaea following the rifting of the supercontinent Rodinia occurred during the late Paleozoic as the result of three major orogenic events; the Ordovician Taconic, Silurian-Devonian Acadian, and Paleozoic Alleghanian (Hatcher 1987, 1989; Drake et al., 1989; Goldberg et al., 1989; Massey et al., 2005). The intricate geochronological history recorded in rocks of the Appalachian Mountains delineates these events, however, deformation and metamorphism during each event resulted in a complicated overprinting of these events in the rock record. In the southern Appalachians, this overprinting resulted in significantly less evidence of specific deformation events, such as the Acadian orogeny (Adams et al., 1995). Therefore, there is limited information about the Acadian orogeny in the southern Appalachians. The Burnsville shear zone in western North Carolina (Fig. 1) records Acadian deformation, and thus provides a unique opportunity to constrain the kinematics and temperatures recorded during the this event. This study constrains the kinematic and deformation temperatures recorded during the Acadian orogeny across a section of the Burnsville shear zone north of Asheville, NC. This study combined with others along this shear zone are imperative to understanding the crustal evolution of the fault during the Acadian orogeny in the southern Appalachians.

1.1. Geologic Setting

The Burnsville fault, located in western North Carolina in the Blue Ridge province of the southern Appalachians, establishes a portion of the boundary between the Mesoproterozoic Grenville basement rocks and the Ashe Metamorphic Suite (Fig. 1). The basement rocks consist of mainly gneiss and pegmatite and were present on the North American craton before the assembly of Pangaea, and the Ashe Metamorphic Suite consists of metasedimentary and metavolcanic rocks that sit atop the basement, including amphibolite, metagraywacke, and schist (Adams et al., 1995). The Burnsville fault was previously observed along this boundary from Asheville, NC north to Carvers Gap, NC (Adams et al., 1995; Cowan and Trupe, 2001; Trupe et al., 2003). The northern segment of the Burnsville fault, in the Grandfather Mountain vicinity, has been mapped as a fault reactivated during the Acadian orogeny as a strike-slip fault (Adams et al., 1995), similar to that recorded in Asheville. South of Asheville, however, the trace of the Burnsville fault is unconstrained and potentially correlates to the Chattahoochee-Dahlonega fault or the Hayesville fault (Fig. 1). However, neither of these faults have evidence for Acadian dextral strike-slip motion (e.g. Hatcher, 1989; Massey and Moecher, 2005).

The portion of the fault located near Asheville, NC was formerly mapped as the Holland Mountain thrust fault (Merchat and Wiener, 1988), however more recent studies have concluded the section records dextral strike-slip faulting that was active during the Acadian orogeny and likely overprints Taconic thrusting along this contact (Adams et al., 1995, Mallard et al., 1994, Cowan and Trupe, 2001; Trupe et al., 2003, Waters-Tormey et al., 2010). Adams et al. (1995) established the Burnsville fault as an Acadian fault through analysis of crosscutting relationships of Spruce Pine-type pegmatites and metamorphic grade of deformed minerals. Trupe et al. (2003) discuss further evidence of dextral shear sense along the Burnsville fault, including the presence of micro and mesoscale kinematic indicators. Additionally, Trupe et al. (2003) report deformation temperatures of ~550° C and an age from a deformed pegmatite within the shear zone, suggesting shearing took place 360-377 Ma, during the Acadian.

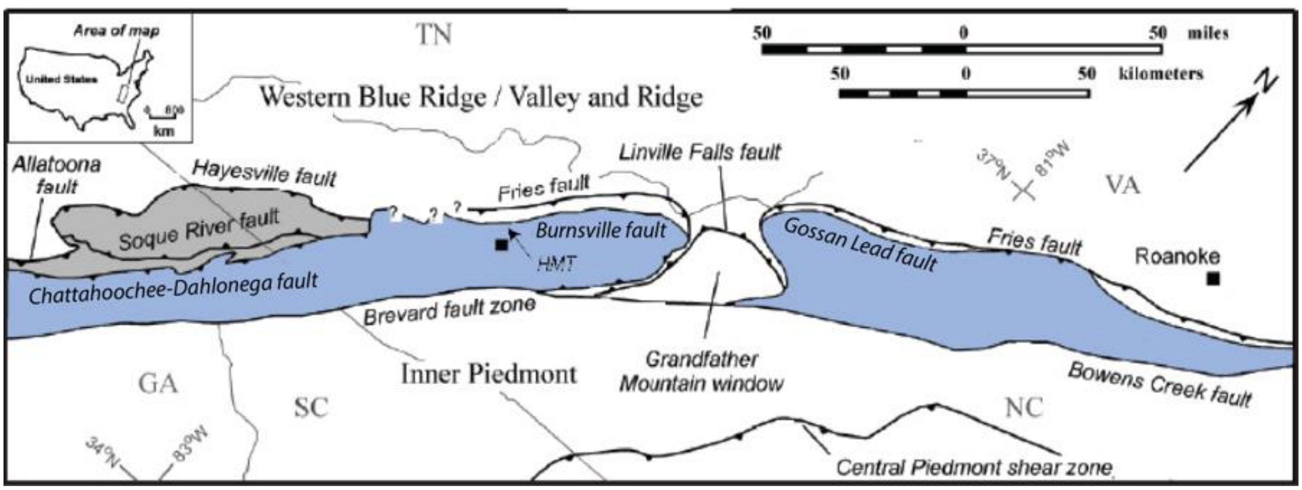

Figure 1. Simplified tectonic map of the southern Appalachians. Rocks belonging to the Grenville basement are north of the Burnsville fault. The Ashe Metamorphic Suite is colored as blue. Grey rocks have been mapped as Grenville basement. HMT notes where the Burnsville fault has been mapped as the Holland Mountain thrust. Modified from Trupe et al., 2003.

1.2. Objective

The objective of this study was to constrain the kinematic vorticity, strain ratio, and temperatures during deformation recorded during dextral strike-slip deformation through the Burnsville fault near Asheville, NC, which yields the percent shortening and extension experienced during deformation and the depth in the crust in which it occurred. Through analysis of microstructures in samples collected from the shear zone, as well as evaluations of visible kinematic indicators in the field, deformation temperatures and kinematic constraints were quantified in the attempt to address the degree and manner of deformation that occurred during the Acadian orogeny on this section of the fault.

Additional analysis of a granite dike cross-cutting the shear zone was utilized to further support the timing of deformation of Burnsville fault.

2. Methods

2.1. Field Mapping, Sample Collection and Preparation

Geologic mapping was completed along a transect through the Burnsville fault, north of Asheville (Figs. 1 and 2), previously mapped by Cowan and Trupe (2001). Samples were collected along this transect. The samples were selected both in North Buncombe Quarry and along Riverside Drive. Lineation, foliation, and geographical position were recorded for each stop, and notes were made of visible kinematic shear sense indicators. Additional foliation measurements along with geographical positioning were taken in North Buncombe Quarry in both the shear zone and unsheared basement rocks. This information was used for construction of a geologic map through this portion of the shear zone as well as lineation and foliation plotted on stereonets (Fig. 2). Hand samples were cut parallel to foliation and perpendicular to lineation, and cut into thin sections to be viewed with a transmitted light microscope and a scanning electron microscope (SEM) for microstructural analysis.

2.2. Deformation Temperature Constraints

Under the light microscope, thin sections were analysed utilizing transmitted light microscopy with plane and cross-polarized light. Observations were conducted of dynamic recrystallization of quartz grains located within the thin sections to constrain a deformation temperature. Quartz recrystallization occurs in three manners; bulging recrystallization (BLG), subgrain rotation (SGR), and grain boundary migration (GBM). Each means of quartz recrystallization develops at characteristic temperatures, 280-400° C, 400-500° C, and 500-650° C, respectively (Stipp et al., 2002a, 2002b; Passchier and Trouw, 2005).

In addition, deformed quartz was analyzed with Electron Backscattered Diffraction (EBSD). EBSD images represent patterns of backscattered electrons that are reflected from the quartz grains in a thin section under the SEM. The orientation of these minerals can be constrained from the backscatter patterns and plotted on a stereonet to produce a lattice-preferred orientation plot (LPO). The patterns exhibited on an LPO plot of quartz yield information about shear direction and deformation temperatures. When a cross-girdle arrangements is present, the opening angle can be used to calculate temperature during deformation (Lister and Hobbs, 1980; Law, 1990; Passchier and Trouw, 2005) (Fig 3). Quartz LPOs were obtained at the University of California, Santa Barbara, with a FEI Quanta 400 FEG SEM equipped with an HKL Nordlys 2 EBSD camera.

2.3. Kinematic Constraints

Observing the shear sense can be done in several manners. Shear sense indicators can be seen both microscopically in the lab and visually in the field. Visual kinematic indicators include rotated porphyroclasts (rigid grains), such as feldspar, quartz, and garnet, with tails of more easily sheared material signifying the direction of shearing. As quartz deforms during ductile shearing, the grains reorient parallel to an oblique fabric (S_B) relative to the main foliation (S_A) (Wallis et al., 1993; Wallis, 1995) (Fig. 4). Shear sense can be observed microscopically by analysis under the transmitted light microscope with cross-polarized light.

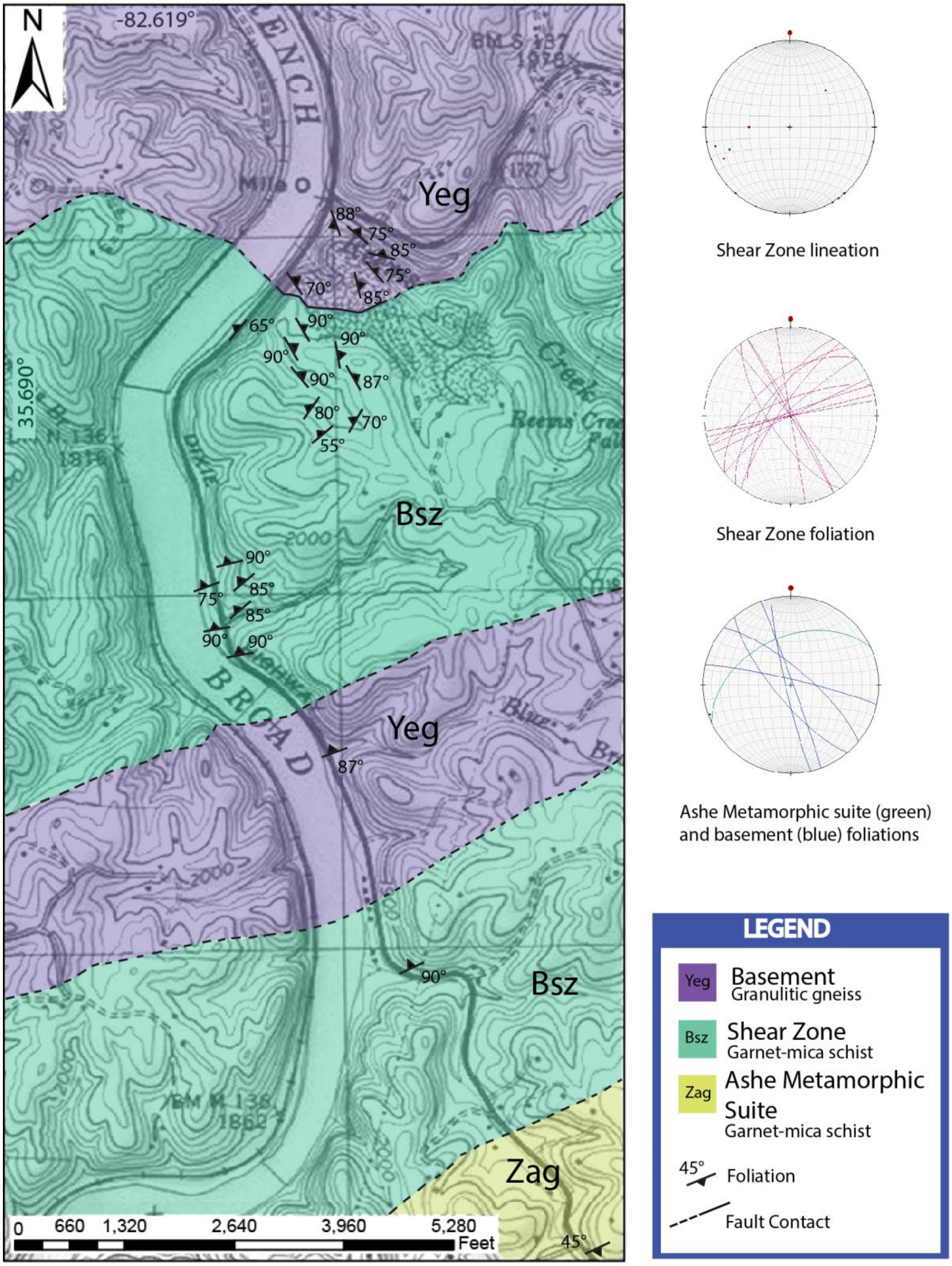

Figure 2. Geologic map of the area of study. Stereonets of the shear zone lineation and foliation as well as a stereonet of the Ashe/basement rocks show the orientation of measurements. Mapping was completed in this study with portions from Cowen and Trupe (2001). See text for explanation of stereonets.

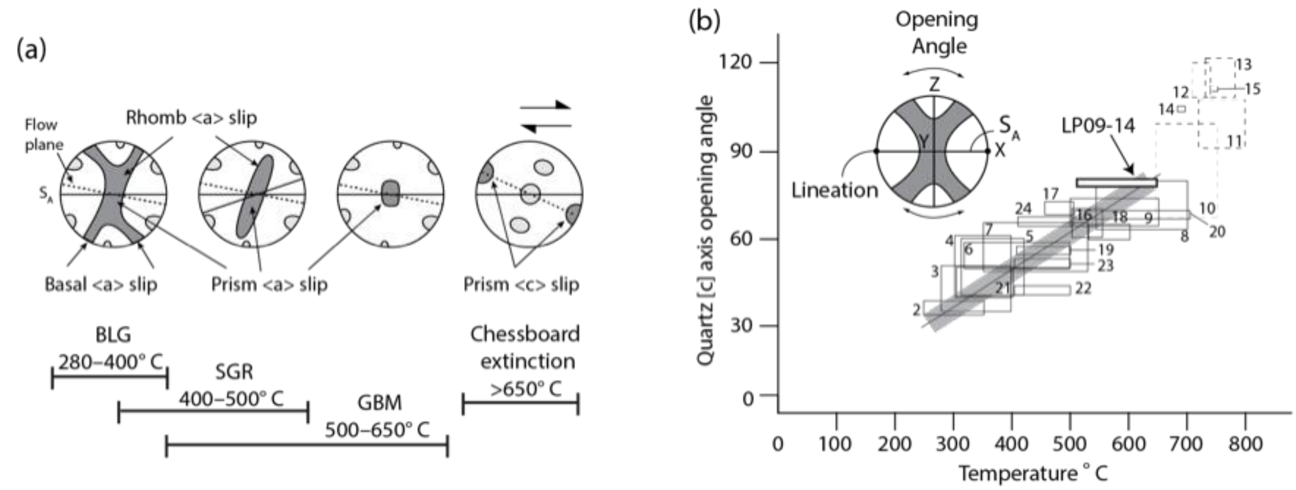

Figure 3. (A) Quartz [c] and <a> axis LPO patterns that indicate slip systems during plane strain deformation in relation to deformation temperature. Modified from Passchier and Trouw, 2005. (B) Correlation between opening angle of cross-girdled [c] axis LPOs and deformation temperature. Boxes 1-15: Kruhl, 1998; 16: Law et al., 1992; 17: Nyman et al., 1995; 18: Okudaira et al., 1995; 19-24 Langille et al., 2010; LP09-14: Langille et al. 2014. Modified from Law et al., 2004.

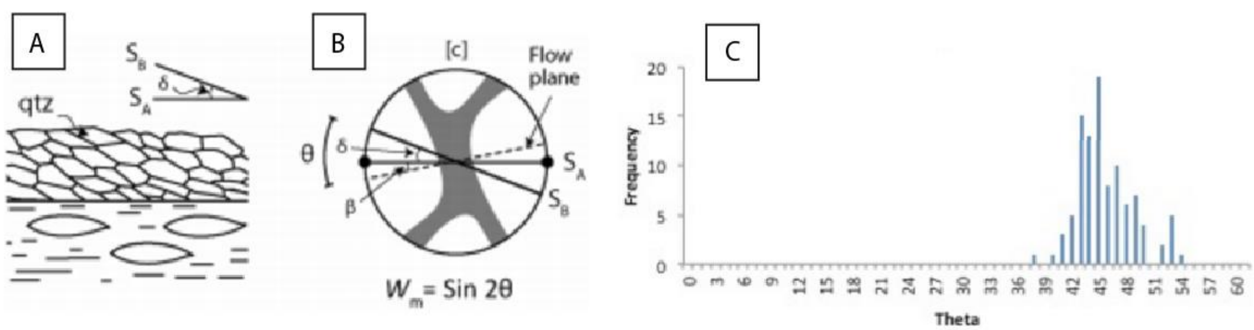

Figure 4. (A) Quartz oblique grain shape fabric where δ is the angle between the oblique grain shape foliation (S_B) and the main foliation (S_A) (from Langille et al., 2010). (B) Simplified image of quartz [c] axis LPO with the flow plane indicated (Xypolias, 2008). (C) Theta (Ө) angles measured from 100 quartz grains in sample BV13-02.

2.4. Vorticity and Strain Constraints

The percent of shearing and thinning that was experienced by a rock from a shear zone can be constrained by calculating the kinematic vorticity (W_m). W_m is calculated from the angle between the oblique quartz grain shape fabric and foliation (δ) and the angle between the foliation and the flow plane (β) (Fig. 4 A and B). Muscovite and biotite mica in this sample may also reoriented into a similar fabric as the quartz, so the orientations of both quartz and mica were measured.

W_m ranges in value from zero to one, where zero signifies pure shear (100% thinning) and one indicates simple shear (100% shearing). This method of determining vorticity from quartz fabrics requires that deformation occurred on a 2D plane (plane strain), and documents the most recent deformation the fault underwent (Wallis, 1995; Xypolias, 2009). Calculating the vorticity number follows this equation (Wallis, 1995), where a θ of 45 results in a W_m equal to 1:

$$W_m = \sin 2\theta = \sin 2\,(\beta + \delta) \qquad (1)$$

δ was measured from 100 quartz grains in sample BV13-02. The angle between the flow plane and the main foliation (β) was measured from the quartz [c] axis LPO plot of the same sample (Fig. 4). These two measurements, δ and β, were added together for θ, and a range of values was organized in a histogram. The value with highest frequency on the histogram were used in equation 1.

The kinematic vorticity number can be utilized in the calculation for strain ratio (R_{xz}) (Xypolias, 2009):

$$R_{xz} = \frac{1 - (\tan\theta\tan\beta)}{\tan^2\beta + (\tan\theta\tan\beta)} \qquad \text{where } \tan\theta = \cot\,[2\,(\beta + \delta)] = \frac{\sqrt{(1 - W_m^2)}}{W_m} \qquad (2)$$

Both the strain ratio and the kinematic vorticity number can further be utilized to constrain the percentage of shortening perpendicular to the shear zone and extension parallel to the shear zone that the sample underwent during deformation. Shortening occurs perpendicular to the shear zone foliation and is indicated by S, while extension occurs parallel to the shear zone foliation and is signified by S^{-1} (Wallis et al., 1993):

$$S = \{0.5\,(1 - W_m^2)^{0.5}\,[(R_{xz} + R_{xz}^{-1} + (2(1 + W_m^2) / (1 - W_m^2)))\ 0.5\ + (R_{xz} + R_{xz}^{-1} - 2)^{0.5}\ ]\}^{-1} \qquad (3)$$

2.5. U-Pb Zircon

An age for an undeformed granite dike cutting across the shear zone exposed in Hedrick Industries North Buncombe Quarry was obtained (Fig. 5). The age represents the time when the granite was injected and crystallized, and because it is undeformed, the age is post-deformation. Zircon crystals were separated from a sample collected from the dike. Ages were constrained using the U-Pb geochronometer. Zircon grains were separated and the U-Pb compositions were obtained in-situ from points across the zircon grains at the University of California Santa Barbara using laser ablation inductively coupled mass-spectrometer (LA-ICPMS). Analyses were obtained from the cores and rims of the zircon grains.

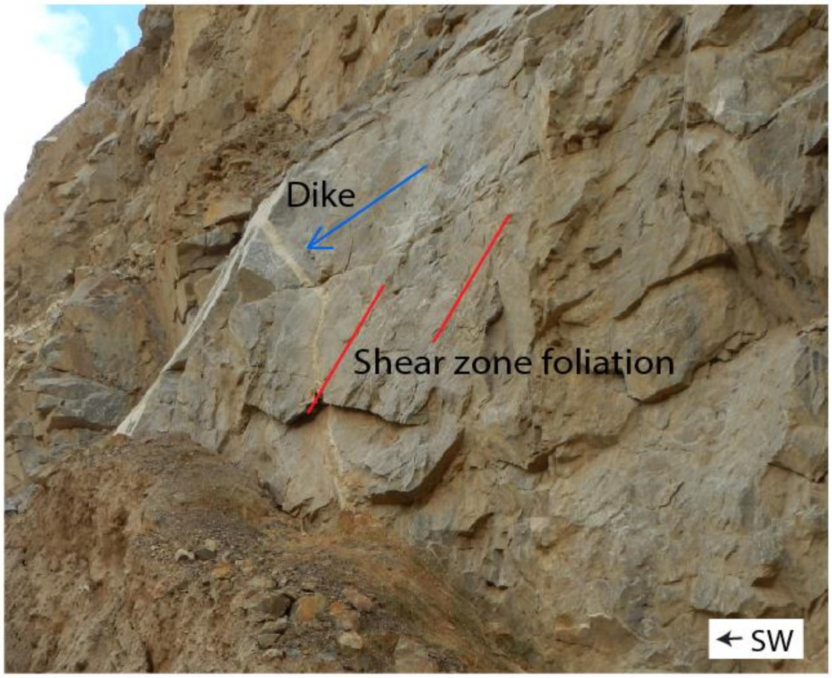

Fig 5. Photograph of the undeformed granite dike. The blue arrow indicates the granite dike. The red lines highlight the foliation of the shear zone.

3. Results

3.1. Field Observations

The stretching lineations documented from rocks within the shear zone were generally horizontal, in this case indicating strike-slip movement. However, some of the lineations were sub-horizontal suggesting some level of heterogeneous slip direction. Furthermore, in the field, the mylonites within the shear zone appeared to be variably strained with more strain south from the northernmost portion of the shear zone. Macroscopic indicators of shear direction included sheared porphyroclasts and shear folds, all supporting dextral strike-slip shearing. Quartz and feldspar mylonitic and ultra-mylonitic textures were also observed, and several strung out quartz veins were distinguished, another indication of high-strain (Fig. 6A, B).

The basement rocks north of the shear zone are folded and intruded by variably deformed trondhjemite dikes (Fig. 6C). The rocks within the shear zone generally strike NE-SW with near-horizontal stretching lineations, with the exception of the northern most portion of the shear zone which strikes NW-SE (see map and stereonets in Fig. 2). A stereonet of the Ashe Metamorphic Suite foliations paired with the basement rock foliations outside of the shear zone show that the rocks outside of the shear zone have different orientations than those within the shear zone. This shear zone is a widely distributed shear zone ~2 miles wide that occurs almost entirely within the Ashe Metamorphic Suite, with ~10-20 m of the northernmost contact sheared into basement rock (Fig. 6D).

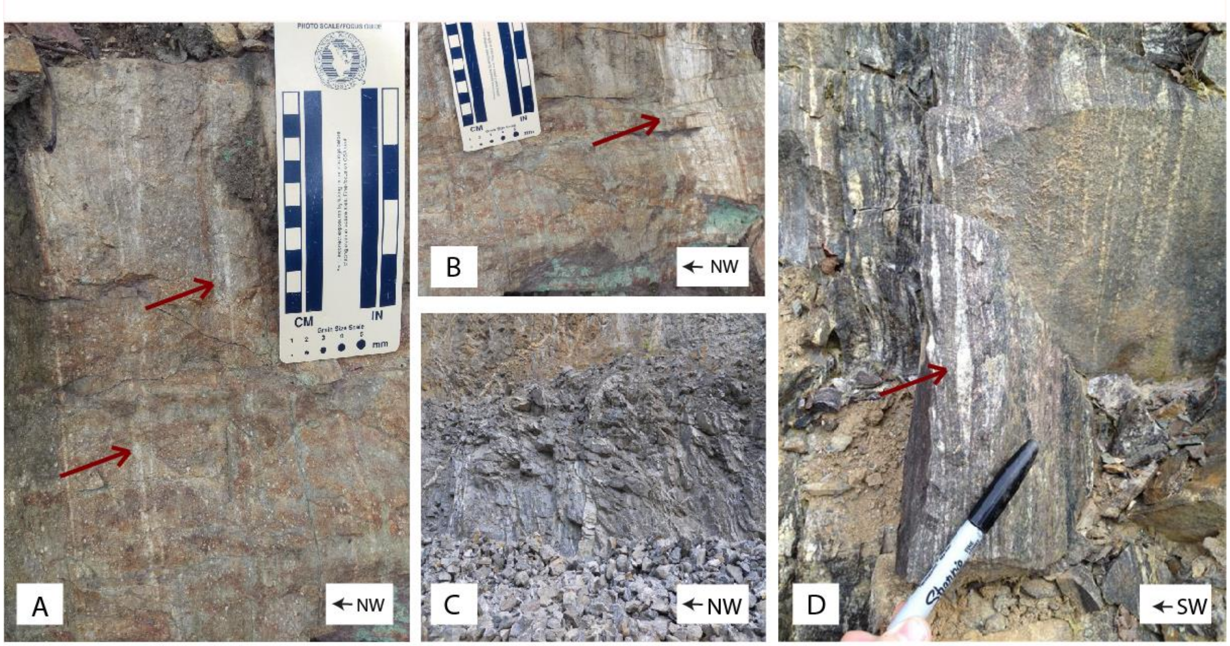

Figure 6. (A) Mylonite with porphyroclasts taken at sample RV16-01 (seen microscopically, Fig. 7). (B) Ribboned quartz taken at sample RV16-01. (C) Basement Gneiss outside of the shear zone intruded by trondjhemite dikes. (D) Mylonitic texture and boudins seen in rocks from the shear zone at the northernmost boundary of the shear zone.

3.2. Microscopy

Oblique-quartz orientations and mica foliations suggest dextral strike-slip direction (Fig. 7A, B). In addition to porphyroclasts seen in the field, porphyroclasts were observed under the transmitted light microscope. These quartz, feldspar, and garnet porphyroclasts contribute to evidence of dextral shearing along the Burnsville fault (Fig. 7C, D, E).

All of the samples from the shear zone exhibit grain boundary migration (GBM) with minimal subgrain rotation (SGR), suggesting temperatures during deformation of >500° C. Myrmekite was also documented, which records the reaction of potassium feldspar to quartz and plagioclase at temperatures >600° C (Fig. 7F). LPOs collected from EBSD in the SEM for two shear zone samples, BV13-01b and BV13-02, also display dextral shearing in their cross-girdled patterns (Fig. 8). These LPOs also indicated plane strain of the samples. The opening angles measured from the LPO of BV13-02 was a 70-75° angle and deformation temperature calculated from these angles was 550-600 ± 50° C as seen in Fig. 3B. The opening angle in sample BV13-01B was not used to calculate a temperature due to the loosely developed girdle (Fig. 8). The LPOs for BV13-02 and BV13-01B show dextral strike-slip shear. BV13-04 has a complicated pattern supporting that it is not extensively sheared and not part of the shear zone.

The angle (β) between the flow plane and the main foliation (S_A) was measured from sample BV13-02 at 20°. Combined with δ of 45° (Fig. 4C), this results in W_m of 0.99, essentially zero thinning perpendicular to the shear zone. These measurements suggest a strain ratio of 5.4, with 12.5% shortening perpendicular to the shear zone and 14.3% extension parallel to the shear zone.

3.3. U-Pb Zircon

U-Pb compositions from zircon from the undeformed granite dike that crosscuts the shear zone, range from the late Proterozoic to the mid-late Paleozoic. Excessive growth was shown to occur at ~450 Ma. A younger episode of zircon growth occurred at ~330 Ma, representing the age of the dike emplacement (Fig. 9).

4. Discussion

Field mapping through this transect of the shear zone supports that the Burnsville fault reactivated the contact between the basement rocks and the Ashe Metamorphic Suite. The majority of the shear zone is within the Ashe Metamorphic Suite and not the basement rocks. Within the shear zone, there is a block of weakly reoriented and sheared basement rock that likely represents a block of basement rock that was caught up in the shear zone and that strain was partitioned within the Ashe Metamorphic Suite around this block (Fig. 2).

The deformation temperature, vorticity, and strain measurements in this study are the first to be documented along this shear zone. BV13-02, a sample collected from the outskirts of the shear zone, records 12.5% shortening perpendicular to the shear zone and 14.3% extension parallel to the shear zone. This sample was collected from the northernmost portion of the shear zone. The foliation here trends NW-SE as opposed to NE-SW in the rest of the shear zone, suggesting that this portion of the shear zone was not sheared to an extent to completely transpose the foliation. Thus, higher strains are interpreted within the rest of the shear zone so the bulk shortening and extension is likely significantly higher.

The opening angle of the LPO collected from this sample was 70-75°, resulting in an associated deformation temperature of 550-600 ± 50° C. This temperature overlaps with the temperatures of >500° C recorded by GBM recrystallization of quartz. Myrmekite documents temperatures of >600° C. Assuming a typical geothermal gradient of 30° C per km, these deformation temperatures suggest that Acadian dextral strike-slip shearing on this fault occurred at depths between ~17-20 km. These temperatures are consistent with those of previous studies conducted about the Burnsville shear zone (Trupe et al., 2003; Adams, et al., 1995).

Trupe et al. (2003) distinguished several visible kinematic shear sense indicators, including porphyroclasts, boudins, and mica fish. They also determined a deformation temperature of various minerals, indicating temperatures of roughly 500-600° C. These studies presented evidence of GBM in feldspars and myrmekitic textures as well.

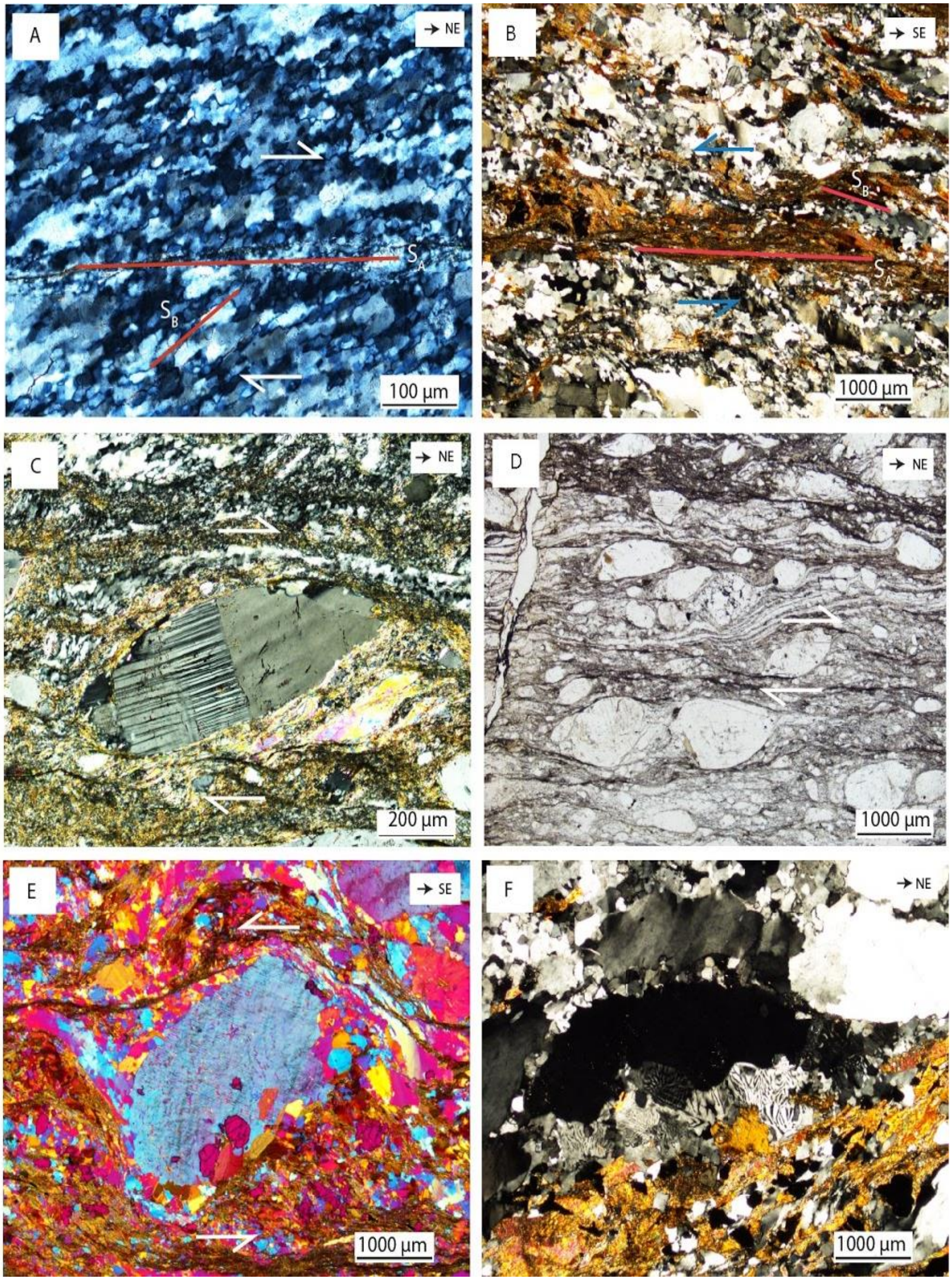

Figure 7. Micrographs of microscopic shear sense indicators viewed through a transmitted light microscope. (A) Quartz recrystallization indicating grain-boundary migration under cross polarized light (BV13-01). (B) Quartz oblique fabrics (S_B) relative to the main foliation (S_A) under cross polarized light (BV13-02). (C) Sheared porphyroclasts under cross polarized light (BV13-01). (D) Sheared porphyroclasts under plane light (BV13-01). (E)

Sheared porphyroclast under cross polarized light through a full wave plate (BV13-02). (F) Myrmekite (wormy intergrowth) seen under cross polarized light (BV13-01).

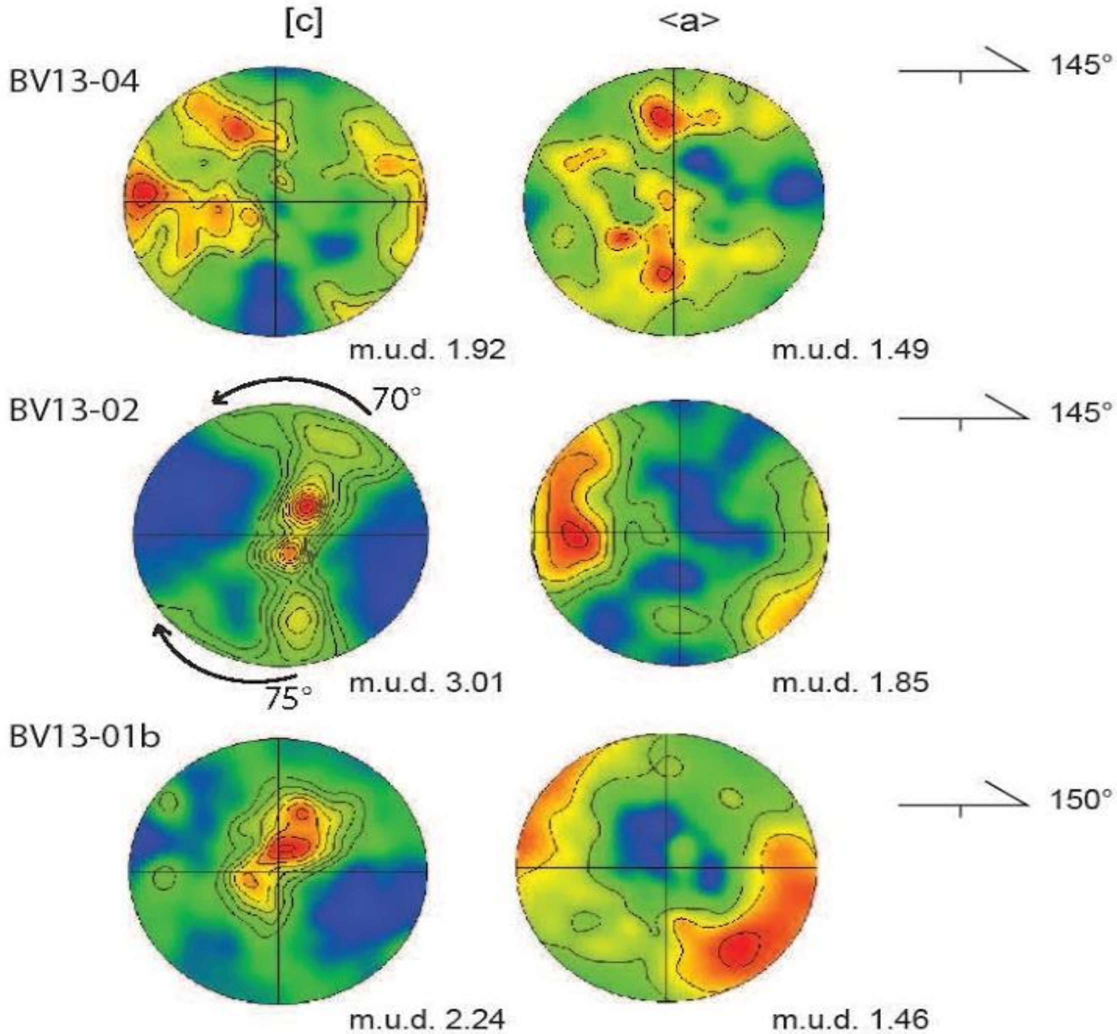

Figure 8. Lattice-preferred orientation patterns of quartz [c] axis. BV13-04 was collected from the basement rock outside of the shear zone. BV13-02 and BV13-01b were both collected from the northernmost portion of the shear zone. M.u.d. indicates the mean uniform density, where BV13-04 has n=2392, BV13-02 has n=4558, and BV13-01b has n=11357.

In addition to these constraints, an age from an undeformed granite that crosses the shear zone suggests that strike-slip shearing had ceased by ~330 Ma, consistent with Acadian deformation suggested by Trupe et al. (2003) for the fault near Burnsville, NC. It is unclear where Acadian dextral shearing of the Burnsville fault continues toward the south but this study supports that dextral shearing occurred during the Acadian and was a major structure lithologic structure that potentially produced significant offset.

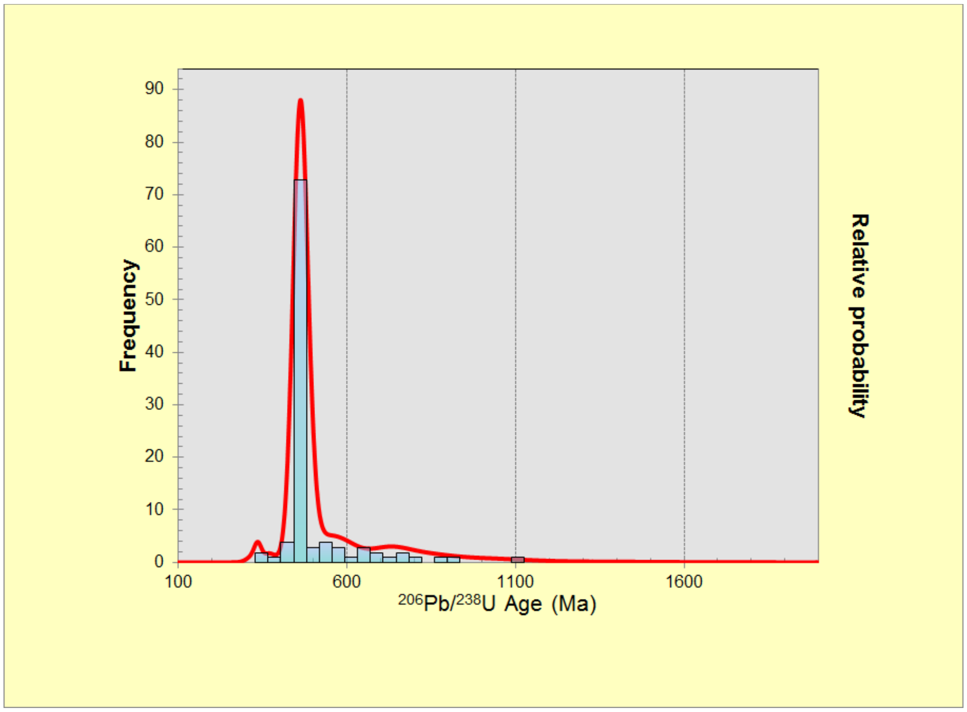

Figure 9. Frequency of U-Pb ages (Ma)

5. Conclusion

This study supports evidence for Acadian dextral strike-slip shearing along the Burnsville shear zone near Asheville, NC. While it is unclear how far this fault is exposed along the length of the southern Appalachians, this fault records dextral shearing at ~17-20 km depth and shortened by a minimum of 12.5% perpendicular to foliation and extended by 14.3% parallel to shear zone foliation. Field mapping shows that the Burnsville fault near Asheville is ~2 miles wide and is a major structure. Evidence for higher shearing suggests that this shear zone likely resulted in significant crustal thinning and extension.

6. Acknowledgements

Special thanks to Dr. J. M. Langille, University of North Carolina at Asheville. Funding was provided by the Geological Society of America awarded to J. Corradino. Zircon geochronology was provided by J. Cottle at the University of California Santa Barbara. EBSD analyses were conducted by G. Seward at the University of California Santa Barbara.

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