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Strain Analysis Across the Margins of the Elkahatchee and Coley Creek Plutons, Alabama Eastern Blue Ridge: Implications for the Alexander City Fault

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BY

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A Thesis Submitted in Partial Fulfillment of Requirements of the Honors College for Honors in the degree of Bachelor of Science in Earth and Space Science College of Letters & Sciences Columbus State University

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ABSTRACT

The Ashland-Wedowee-Emuckfaw belt of the eastern Blue Ridge of Alabama and Georgia consists of metamorphosed Neoproterozoic-Ordovician continental margin and Ordovician back-arc sedimentary/volcanic sequences intruded by Ordovician-Mississippian granitic plutons. Two of these plutons, the Elkahatchee Quartz Diorite and Coley Creek orthogneiss exhibit zones of high strain, evidenced by mylonitic fabrics, ductile deformation of feldspar grains, grain size reduction, and changes in mica content at their margins. Geologic mapping in the vicinity of the Coley Creek pluton shows no evidence for a ductile shear zone beyond its margins and thus, is unlikely to be associated with a major fault. More likely, this high strain zone is the result of differential shearing due to mechanical differences between schist of the adjacent Emuckfaw Group and quartzofeldspathic rocks of the Coley Creek orthogneiss, in conjunction with pervasive chemical alteration during metamorphic dewatering of adjacent pelites. Similar high strain zones observed along the margin of the Elkahatchee batholith have been attributed to a major ductile shear zone associated with the Alexander City fault. This ductile shear zone, along the southeastern margin of the batholith where it borders Wedowee Group graphitic schist, is projected by some workers to the AL-GA state line, in which case it would have significant implications for the local and regional geology. Other workers argue, however, that the regional geology does not support this interpretation, and that the ductile shear zone cannot be mapped beyond the Elkahatchee batholith. Importantly, shear zones observed along the southeastern margin of the Elkahatchee batholith are similar in nature to the shear zone observed along the margins of the Coley Creek pluton, where a major fault is not present. I utilize Rf-Φ analysis, along with mineralogical and grain size analysis, on 10

samples from regular intervals across the intrusive contacts of both plutons with their metasedimentary country rock towards the interiors of each pluton, to compare and contrast the mylonitic fabric observed along each margin. The work suggests the sheared margins of both are similar in nature and provides an alternative explanation for the ductile shear zone mapped as the Alexander City fault along the margin of the Elkahatchee batholith.

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I would like to thank Dr. Ticknor for being so incredibly helpful throughout my time in the Honors College and for initially encouraging me to start the research that led me to where I am today. And I would like to thank the Honors program of Columbus State University for supporting me in my research endeavors, including this project, and the projects leading up to this one.

And finally, I would like to thank the Department of Earth and Space Sciences for being such an outstanding department, thanks to the work of so many friendly, helpful, and hardworking professors and students.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

Ashland-Wedowee-Emuckfaw Belt

The field area lies within the Ashland-Wedowee-Emuckfaw belt (AWEB), which consists of three groups of metasedimentary units interspersed with metavolcanic units and intruded by silicic plutons of varying size and age, metamorphosed to mid-upper amphibolite facies. The belt is bounded to the northwest by the Hollins Line fault, which separates it from the structurally lower Talladega belt, and to the southeast by the Abanda fault, which separates it from the structurally higher Jacksons Gap Group of the Brevard Fault Zone.

Ashland Supergroup

The Ashland Supergroup forms the structural and stratigraphic base of the AWEB. The Higgins Ferry Group and Poe Bridge Mountain Group are correlative across the Millerville antiform, from the southwest to the northeast respectively and form the structural and stratigraphic base of the Ashland Supergroup. They are predominantly made up of biotite-rich schists of varying garnet, quartz, feldspar, and graphite content, with subordinate fine-grained paragneiss and graphitic quartzite. The presence of staurolite, sillimanite, and kyanite in the metapelitic rocks, in addition to pegmatitic units of muscovite, biotite, K-feldspar, plagioclase, and quartz, and migmatitic units indicate mid-upper amphibolite facies metamorphism (Allison and Morisani, 2002) These units grade upwards into the Hatchet Creek and Mad Indian Groups, respectively. The Hatchet Creek and Mad Indian Groups are dominated by muscovite biotite schists of varying garnet, feldspar, and quartz content, with subordinate fine-grained garnet biotite paragneiss, micaceous quartzite, calc-silicate, and graphitic schist. Again, migmatitic and pegmatitic units are present, as well as local kyanite and sillimanite.

Protoliths for Ashland Supergroup rocks are pelitic units interlayered with subordinate greywackes and mafic flows and/or sills. The interlaying of pelitic rocks with greywackes, suggestive of turbidite sequences, in conjunction with calc-silicate and orthoamphibolite showing intraplate basalt geochemical characteristics, indicates the lower Ashland Supergroup formed in a slope-rise setting off the Laurentian shelf (Barineau et al. 2015).

Wedowee Group

Structurally and stratigraphically above the Ashland Supergroup lies the Wedowee Group. Much of its boundary with the Ashland Supergroup is defined by the Goodwater-Enitachopco fault, but the boundary exists as a polydeformed stratigraphic contact southwest of Goodwater, where the Goodwater-Enitachopco fault tips out. Here the contact is gradational (Allison, 1992).

The rocks of the Wedowee Group are dominated by locally carbonaceous metapelitic units of varying garnet and graphite content, interlayered with subordinate quartzites and highly feldspathic schists to fine-grained biotite orthogneisses, interpreted to be metagreywackes. The presence of tourmaline, staurolite, kyanite, and sillimanite as accessory minerals again indicates middle-upper amphibolite facies metamorphism. Additionally, rocks of the Wedowee Group are interpreted to be early-mid Ordovician due to along-strike correlations with metavolcanic sequences in the Dahlonega gold belt, maximum deposition ages from detrital zircon, and intrusive pluton ages, and a U-Pb zircon age from a metavolcanic (metavolcaniclastic?) unit near its upper contact with the overlying Emuckfaw Group (Barineau et al., 2015; Sagul, 2016).

Emuckfaw Group

The structurally and stratigraphically highest unit of the AWEB is the Emuckfaw Group. It consists of interlayered variably graphitic, garnetiferous two mica schist, and subordinate fine-grained, variably garnetiferous biotite paragneiss, micaceous quartzite, and orthoamphibolite. The Ordovician-aged Kowaliga Gneiss (Sagul, 2016), provides an upper age constraint on the deposition of the Emuckfaw and Wedowee Groups. Across the eastern Blue Ridge of Alabama, the contact between the overlying Emuckfaw and the underlying Wedowee Groups is a gradational one marked by an increase in graphite across the boundary, from the graphitic Wedowee to the graphite poor to non-graphitic Emuckfaw. Detrital zircons from both the Wedowee and Emuckfaw Groups loosely constrain deposition to Early-Middle Ordovician or younger, while intruding plutons (e.g. ca. 472Ma Zana Granite and ca. 462 Kowaliga Gneiss; Sagul, 2016) restrict the minimum depositional age to ca. 472 Ma. Detrital and intrusive age constraints, as well as inferred along-strike correlations with the metavolcanic units of the Dahlonega gold belt, indicate formation of Wedowee and Emuckfaw Group metasedimenary rocks and interlayered metavolcanics during the Early-Middle Ordovician.

Alexander City Fault

Interpretation 1: Through Going Thrust Fault Projected to GA Line

The Alexander City fault (summarized in Tull and Campbell, 2012) was first defined by Bentley and Neathery (1970), who described it as running along the southeastern margin of the

Elkahatchee Quartz Diorite south of Alexander City and characterized "by intense shearing of schist units adjacent to the fault zone…Within the fault zones 'button' schist or mylonite schist are the most characteristic lithologies…." Bentley and Neathery (1970) interpreted the Alexander City fault as a thrust between the Elkahatchee batholith to the northwest and the Wedowee Group to the southeast, tracing the fault through the Wedowee Group to the Wedowee/Emuckfaw contact. Because of infolding along this same boundary, however, Muangnoicharoen (1975) interpreted the Wedowee/Emuckfaw contact to be a metamorphosed stratigraphic contact and not the location of the Alexander City fault. Bieler and Deininger (1987) observed minimal structural discordance across the Emuckfaw/Wedowee contact, but no measurable displacement, also interpreting the boundary between the two units as a metamorphosed stratigraphic contact. Drummond (1986) and Drummond et al. (1994;1997), similar to earlier interpretations by Bentley and Neathery (1970), placed the Alexander City fault along the southeastern margin of the Elkahatchee Quartz Diorite, but argued it was a high angle (70-90° dip), late stage, brittle fault displaying predominantly normal displacement. Guthrie (1995) interpreted the Alexander City fault as an early thrust emplacing the Emuckfaw Group structurally above the Wedowee Group, which was later overprinted by oblique dextral slip displacement (Fig. 1).

Figure 1. State geologic map of Alabama showing interpretation of the Alexander City fault as an extensive thrust fault at the structural top of the Elkahatchee Quartz Diorite along its contact with the overlying Wedowee Group, before cutting up section to become the boundary between the Wedowee Group and overlying Emuckfaw Group northeast of the Elkahatchee batholith. Adapted from Szabo et al. 1988.

Interpretation 2: Fault Tips Out South of Alexander City

Recent interpretations by Tull and Campbell (2012), taking into account the notable linear trace and similarity to the Abanda fault (e.g. steep dip and similar trace, normal displacement), suggest the Alexander City fault tips out along the margin of the Elkahatchee batholith south of Alexander City. There it transitions into a relay ramp (Fig. 3 and 4), marked by silicified breccia, that crosses the Wedowee and Emuckfaw Groups and links to the Abanda fault (Fig. 2).

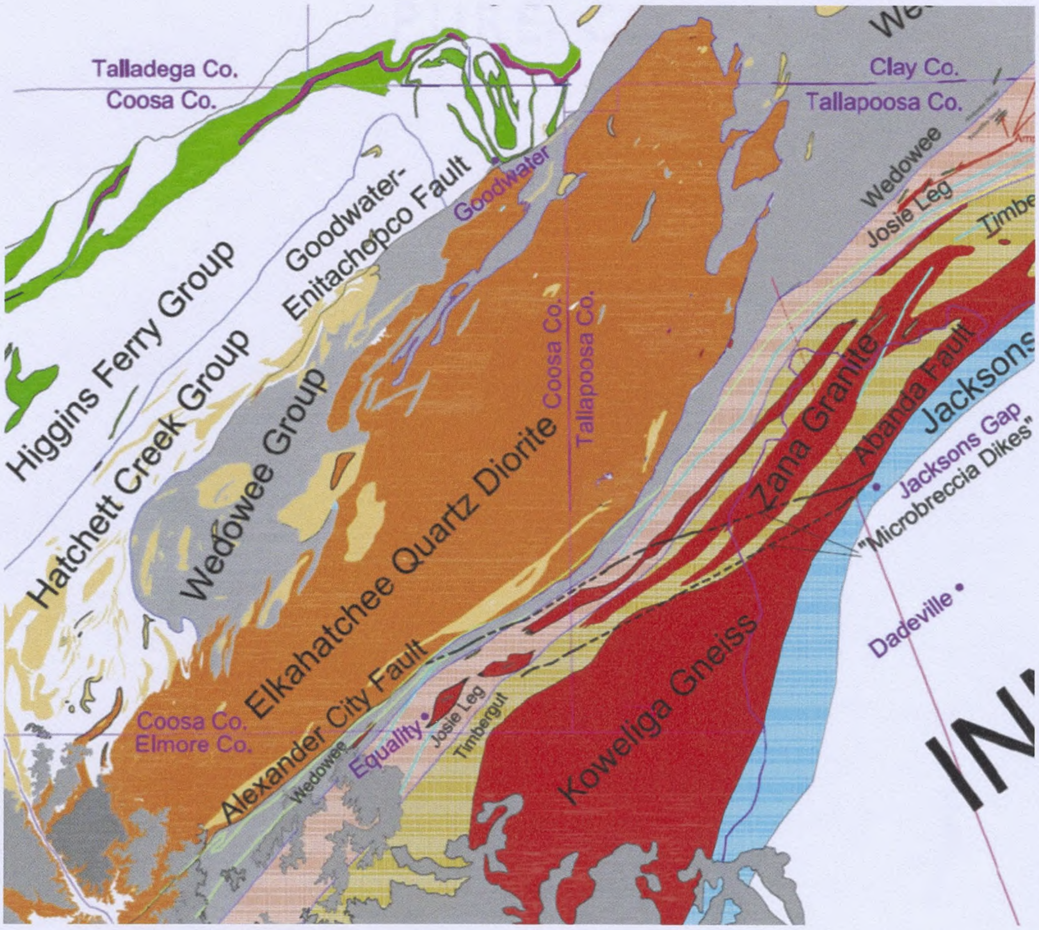


Figure 2. Geologic map from Tull and Campbell (2012) depicting the Alexander City fault as a late stage, brittle, predominantly normal displacement structure with a fault tip south of Alexander City on the margins of the Elkahatchee batholith. In this interpretation, the Alexander City fault connects to the Abanda fault at the northwestern margin of the Brevard Fault Zone across a broad relay ramp.

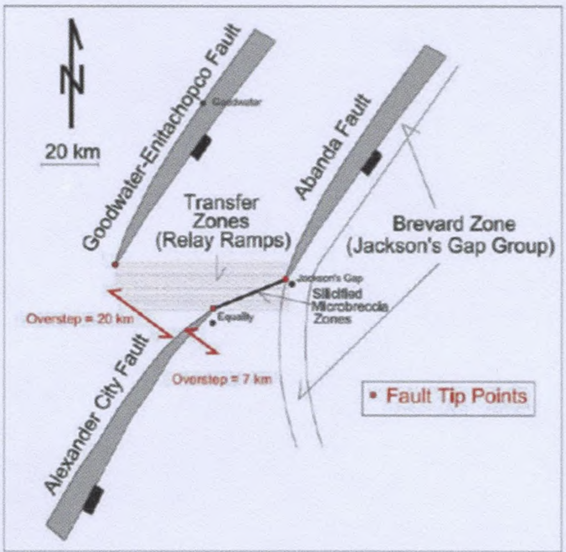


Figure 3. Hypothesized transfer zone via relay ramps from the tip points of the Alexander City and Abanda faults across the Emuckfaw Group. Highly brecciated cataclastic “dikes” with minimal offset mark the location of this relay ramp. From Tull and Campbell, 2012.

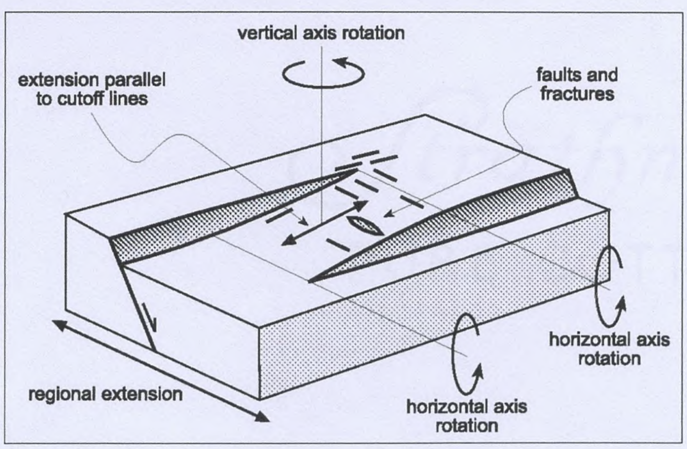


Figure 4. Diagrammatic model for a relay ramp between two fault zones with normal displacement, similar to interpretations of the Alexander City and the Abanda faults (Tull and Campbell, 2012). Brecciated zones between the fault tips in the diagram are marked by cataclastic dikes between the Alexander City and Abanda faults in the Ashland-Wedowee-Emuckfaw belt. Adapted from Bucci et al., 2006.

Interpretation 3: Wide, Through Going Ductile Shear Zone

Steltenpohl et al. (2013) argues the Alexander City fault is a "dextral strike-slip fault rather than a west-vergent thrust fault, as was previously thought." Here, he proposes the Alexander City fault, in conjunction with the Goodwater-Enitachopco fault, is part of an Alleghenian dextral right slip system across the entire eastern Blue Ridge of Alabama and western Georgia (Fig. 5). Differing spatial and kinematic interpretations for the Alexander City fault affect interpretations of the geologic history of the region, particularly the relationship between stratigraphic units and subsequent interpretations of geologic setting for these rocks. For example, a fault of potentially significant offset between the Wedowee and Emuckfaw Groups, which are interpreted as stratigraphically contiguous and part of the same Laurentian margin back-arc basin (Tull et al., 2014; Barineau et al., 2015), would suggest that no correlation exists, and these units are potentially not genetically related to one another. Therefore, resolving the location, timing and kinematics of the Alexander City fault is important for understanding the larger geologic history of the eastern Blue Ridge of the southern Appalachians.

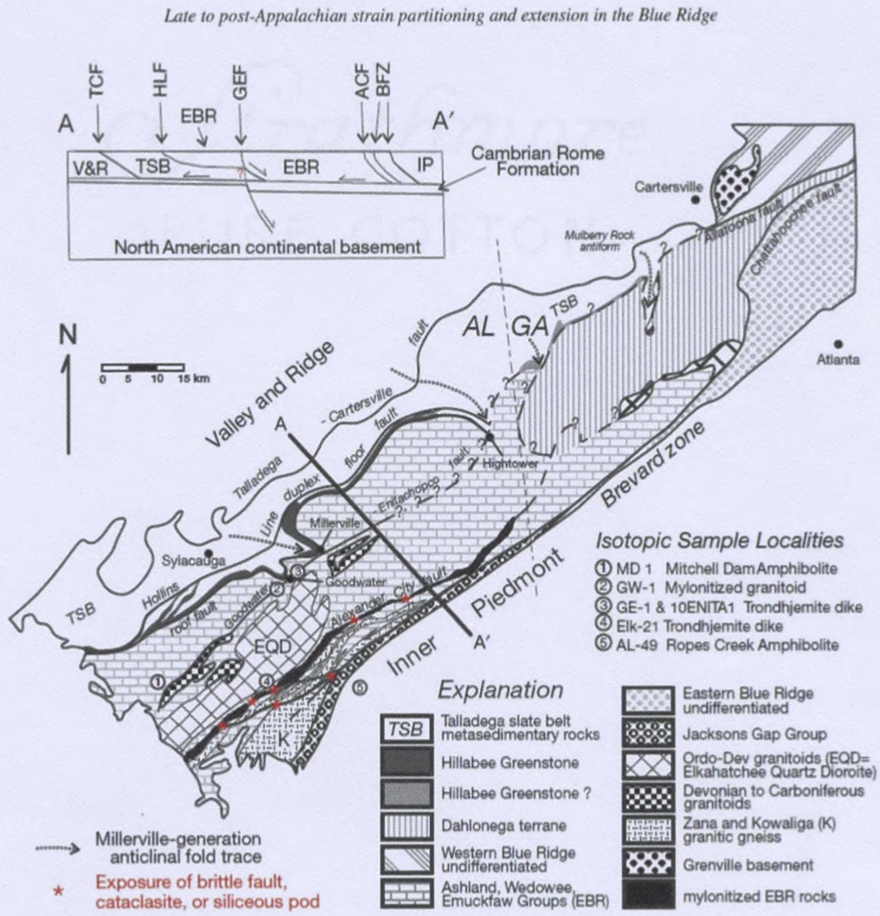


Figure 5. Geologic map from Steltenpohl et al. (2013) depicting the Alexander City fault as a broad pre to syn-metamorphic ductile shear zone separating the structurally lower Elkahatchee Quartz Diorite and overlying Wedowee Group from the structurally higher Emuckfaw Group across the entire eastern Blue Ridge of Alabama.

Prior Work on Field Area

The field site I used to examine the possibility of a pre to synmetamorphic ductile shear zone phase of the Alexander City fault is located several kilometers south of Alexander City (Fig. 1), on the margin of the Elkahatchee Quartz Diorite, where it contacts the Wedowee Group. Harstad (2015) found the contact between the two units consisted of a 150m transitional zone of interlayered, mylonitized granodiorites and metapelites. Both outcrop scale and thin section scale analysis failed to show definitive signs of cataclasis, indicating the brittle phase of the

Alexander City fault tipped out south west of the location. Rocks across the transition show signs of ductile shear, including an "S-C "button" fabric in metapelitic units and sigmoidal feldspar porphyroclasts in metaigneous rocks, as well as isoclinal folding of quartz ribbons in both units" (Harstad 2015), while shear sense indicators show dextral shearing under pressure-temperature conditions capable of producing feldspar plasticity.

METHODOLOGY

Comparing the Coley Creek and Elkahatchee Margins

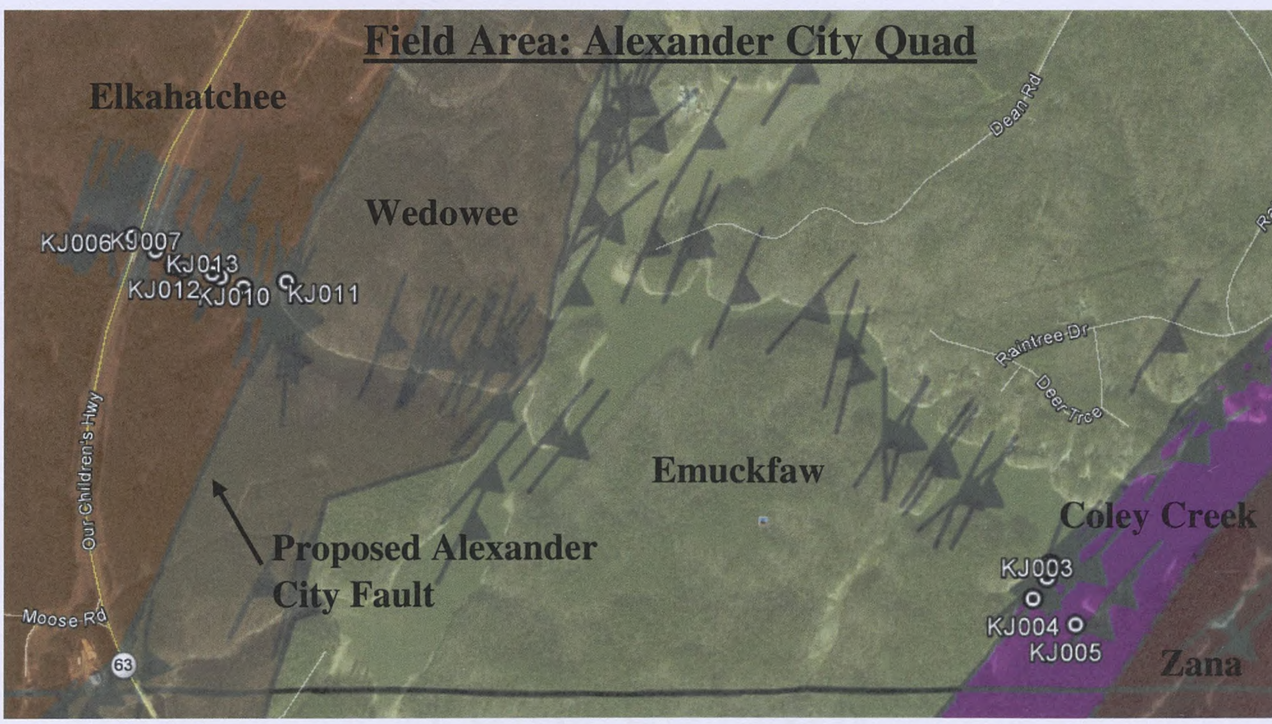


Figure 6. Field area, including the location of the proposed Alexander City Fault, the Coley Creek orthogneiss, and relevant geologic units. See figure 1. For location within regional context. Credit, Google Earth imagery, geologic map adapted from (Carpenter, 2015).

Evidence for ductile shearing was noted along the margins of the Elkahatchee Quartz Diorite and Coley Creek orthogneiss (Fig. 6) in the Ashland-Wedowee-Emuckfaw belt during field mapping. These ductile shear zones shared common features, most notably the presence of mylonitic fabrics in orthogneiss lithologies and phyllonitic textures in metapelitic (schist) lithologies, across the contacts between these units. Although deformation in this region has resulted in macroscopic and megascopic isoclinal folding of stratigraphy, it is clear from regional map relationships that the Coley Creek orthogneiss intrudes stratigraphy of the Ordovician-aged Emuckfaw Group. Preliminary isotopic ages on the Coley Creek suggest a Middle Ordovician crystallization age, similar to magmatic ages of the Zana Granite and Kowaliga Gneiss (Sagul et al., 2015). Importantly, the highly strained zones on the margins of the Coley Creek orthogneiss are not mappable beyond the margins of this contact and are not associated with a fault zone of significant magnitude.

We hypothesize that these areas of high strain along the margins of the Coley Creek where it borders the Emuckfaw Group, approximately 1.4 kilometers southeast of the proposed ductile shear zone along the Elkahatchee Quartz Diorite margin, are due to contrasting mechanical competency between the pluton and the adjacent schist during peak kinematic conditions. Additionally, it is likely that dehydration of pelitic units during metamorphism concentrated fluid flow along the margins of the Coley Creek orthogneiss, which, coupled with the rheological contrasts, provides the conditions necessary to create concentrated zones of high strain during Carboniferous (ca. 330 Ma) amphibolite facies metamorphism. In this study, I compare and contrast the ductile shearing observed by Steltenpohl et al. (2013) and others along the “ductile” Alexander City fault with ductile shearing along the margins of the Coley Creek pluton in an attempt to assess both zones as potentially resulting from mechanical differences and fluid flow between the pluton and surrounding schist bodies during metamorphism, rather than as a through-going ductile shear zone with significant offset. This research compares strain gradients across the margins of the Elkahatchee Quartz Diorite at Elkahatchee Creek, where right-slip ductile shearing is observed and attributed to the Alexander City fault, to the highly strained margins of the Coley Creek orthogneiss, where ductile shearing is attributed to localized shearing along an intrusive contact.

Figure 7. Rock samples were cut parallel to the mean stretching lineation and perpendicular to foliation, then photographed. Identifiable feldspar grains on each photograph were outlined by free-hand tracing their boundaries in PowerPoint.

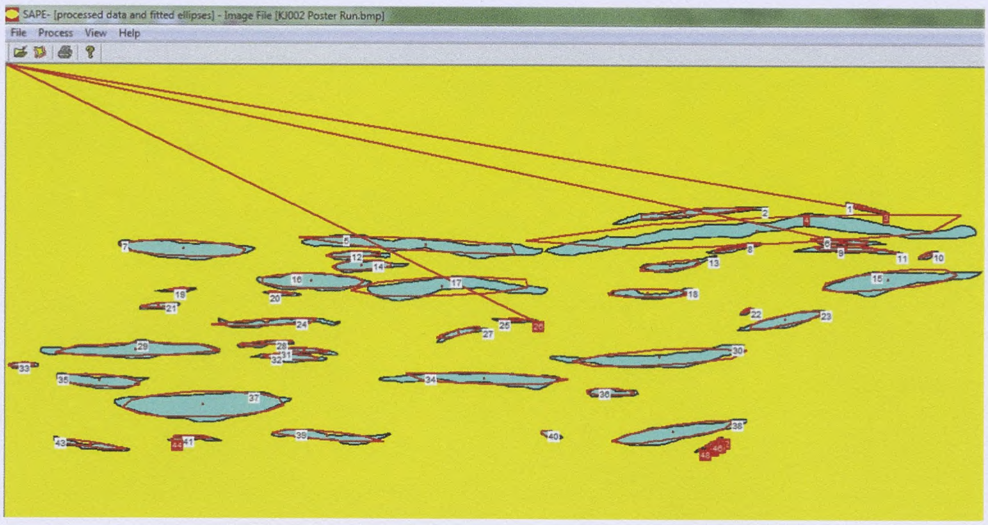
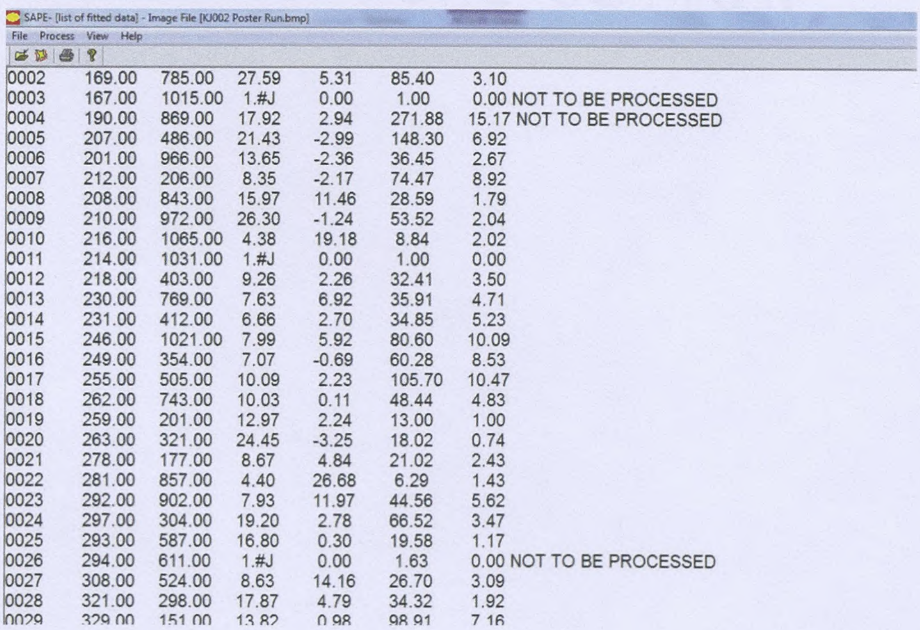


Figure 8. The background photo was then deleted, leaving the grain outlines, which were imported into SAPE for analysis (Mulchrome et al. 2005). SAPE calculated best fit ellipses for all grain outlines. The smallest high aspect ratio grains were occasionally misread by the program, which produced observably incorrect best fit ellipses for them. These grains were excluded from the exported data.


SAPE- [list of fitted data] - Image File [KJ002 Poster Run.bmp]
File Process View Help

0002	169.00	785.00	27.59	5.31	85.40	3.10	
0003	167.00	1015.00	1.#J	0.00	1.00	0.00	NOT TO BE PROCESSED
0004	190.00	869.00	17.92	2.94	271.88	15.17	NOT TO BE PROCESSED
0005	207.00	486.00	21.43	-2.99	148.30	6.92	
0006	201.00	966.00	13.65	-2.36	36.45	2.67	
0007	212.00	206.00	8.35	-2.17	74.47	8.92	
0008	208.00	843.00	15.97	11.46	28.59	1.79	
0009	210.00	972.00	26.30	-1.24	53.52	2.04	
0010	216.00	1065.00	4.38	19.18	8.84	2.02	
0011	214.00	1031.00	1.#J	0.00	1.00	0.00	
0012	218.00	403.00	9.26	2.26	32.41	3.50	
0013	230.00	769.00	7.63	6.92	35.91	4.71	
0014	231.00	412.00	6.66	2.70	34.85	5.23	
0015	246.00	1021.00	7.99	5.92	80.60	10.09	
0016	249.00	354.00	7.07	-0.69	60.28	8.53	
0017	255.00	505.00	10.09	2.23	105.70	10.47	
0018	262.00	743.00	10.03	0.11	48.44	4.83	
0019	259.00	201.00	12.97	2.24	13.00	1.00	
0020	263.00	321.00	24.45	-3.25	18.02	0.74	
0021	278.00	177.00	8.67	4.84	21.02	2.43	
0022	281.00	857.00	4.40	26.68	6.29	1.43	
0023	292.00	902.00	7.93	11.97	44.56	5.62	
0024	297.00	304.00	19.20	2.78	66.52	3.47	
0025	293.00	587.00	16.80	0.30	19.58	1.17	
0026	294.00	611.00	1.#J	0.00	1.63	0.00	NOT TO BE PROCESSED
0027	308.00	524.00	8.63	14.16	26.70	3.09	
0028	321.00	298.00	17.87	4.79	34.32	1.92	
0029	329.00	151.00	13.82	0.98	98.91	7.16	

Figure 9. Raw data, including long and short axes of the best fit ellipses and Φ values, as shown above, were then exported to a .txt file. Rows labeled “NOT TO BE PROCESSED” were automatically omitted when the data is exported. From there the data was copied into a CHEW Excel Spreadsheet capable of performing Rf-Φ analysis and calculating bulk strain (Chew 2003). Using the methods outlined in Chew (2003), the data was plotted and bulk strain (Rs) values were calculated for each sample.

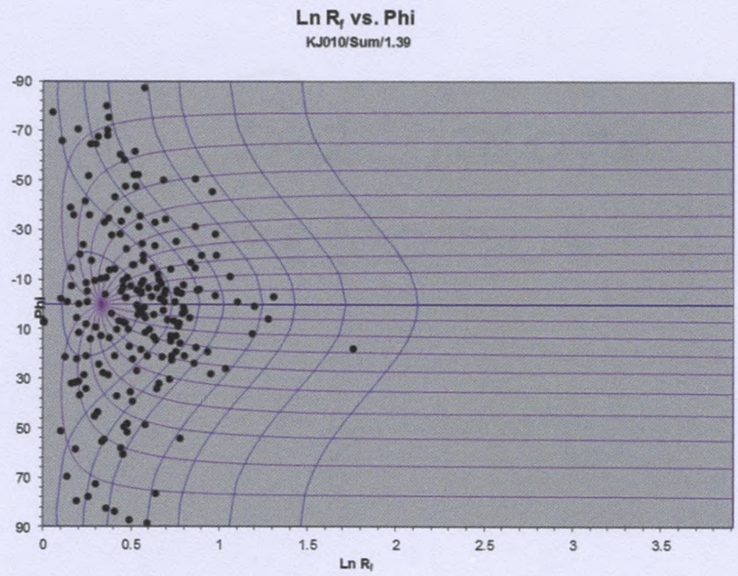


Figure 10. Ln Rf VS. Phi for sample KJ010 plotted using CHEW Excel Spreadsheet. Plot shows aspect ratio vs orientation of feldspar grains. Bulk strain values for this sample (Elkahatchee) are approximately 1, the minimum for all samples in this study.

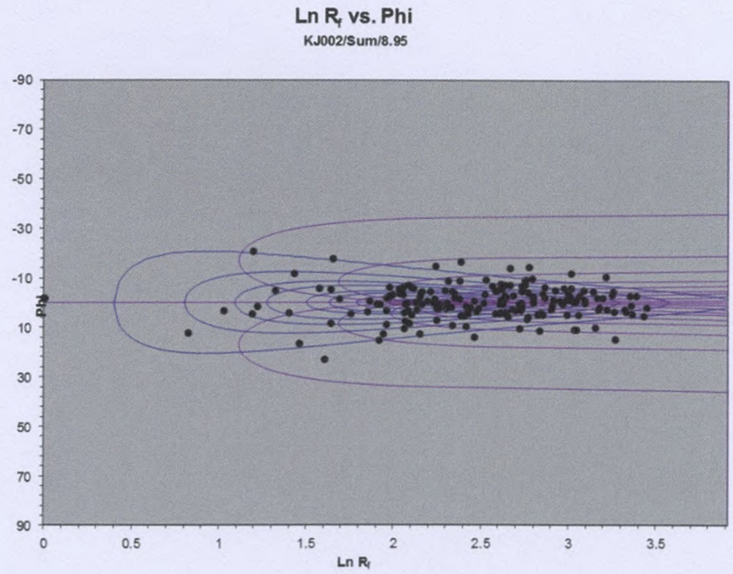


Figure 11. Ln Rf VS. Phi for sample KJ002 plotted using CHEW Excel Spreadsheet. Plot shows aspect ratio vs orientation of feldspar grains. Bulk strain values for this sample (Coley Creek) are approximately 9, the maximum for all samples in this study.

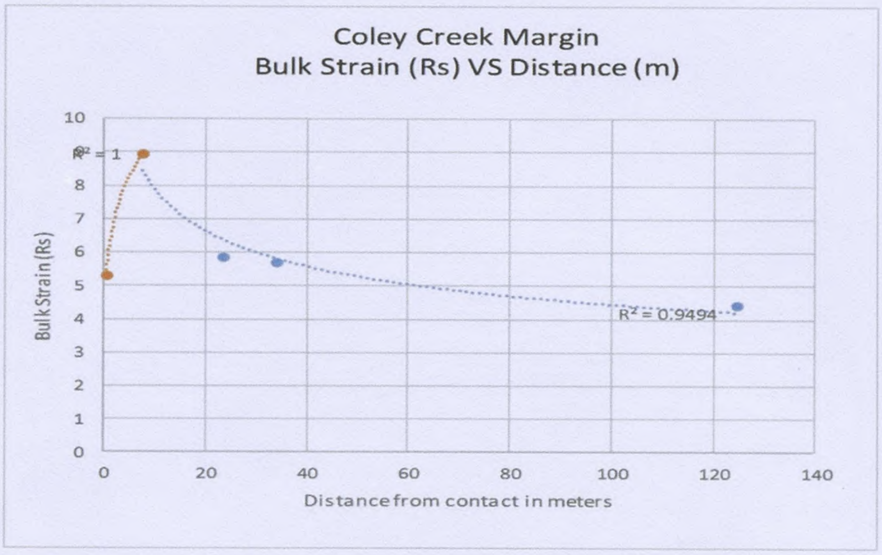


Figure 12. The strain gradient across the Coley Creek margin is significantly more intense than that of the Elkahatchee. Rs values for each sample range from just under 4.4 to nearly 8.95, decreasing from the contact into the Coley Creek, with the exception of the sample at the contact (see interpretation). Higher bulk strain values calculated for the Coley Creek, proximal to its contact with schist of the Emuckfaw Group, are consistent with observations of mylonitic fabrics present in hand samples.

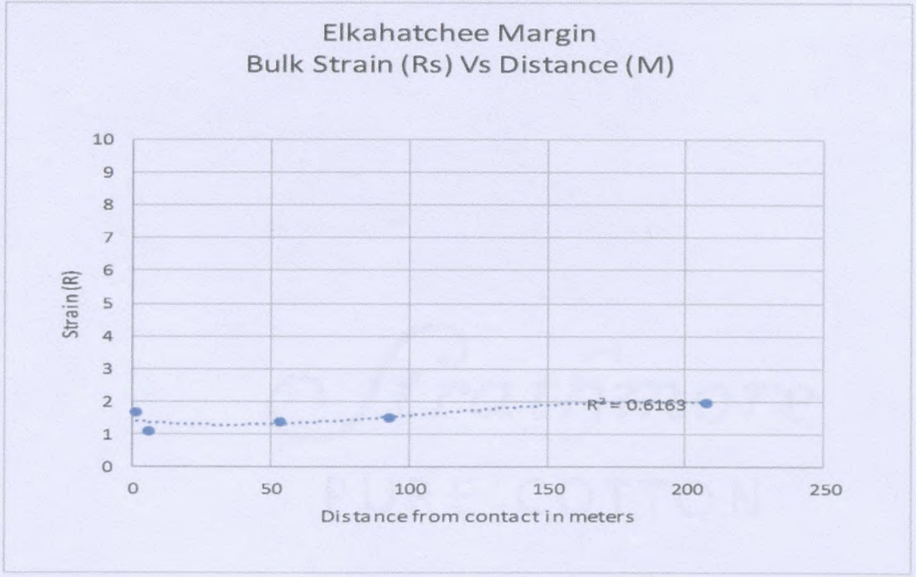


Figure 13. After calculating the Rs values for each sample, we plotted bulk strain data against distance from the contact (calculated true thickness). The strain gradient across the margin of the Elkahatchee at Elkahatchee Creek is significantly lower than that observed along the margins of the Coley Creek pluton. Additionally, Rs values for Elkahatchee samples are lower than those of the Coley Creek.

RESULTS

From my analysis, we see that the margin of the Coley Creek pluton, which is not associated with a major fault, records significantly higher Rs values and a higher strain gradient (Fig. 12), than the margin of the Elkahatchee batholith (Fig. 13), where a ductile shear zone has been proposed (Steltenpohl et al., 2013). Qualitative mineralogical and grain size analysis of the samples (Figs. 14-17) shows mylonitization of feldspar megacrysts along the margins of the Coley Creek orthogneiss, but no major changes in mineralogy (Figs. 14-15). Along the margins of the Elkahatchee batholith, no change in mineralogy and only minimal grain size reduction, as compared to less strained portions of the Elkahatchee where grains were presumably closer to their original size, was observed in our samples, despite the presence of mylonitic fabrics (Figs. 16-17).

Discussion

There are, however, a number of pitfalls associated with this research. With progressive mylonitization, it is possible that grain size reduction accompanied by decreases in aspect ratio (Rf value) could cause a highly strained rock to have low calculated bulk strain values using this method. Therefore, it is possible that Rs values associated with mylonitic fabrics at the margins of the Elkahatchee batholith (Fig. 16) might not represent the true bulk strain of these rocks. However, in the field, we were not able to observe the types of strain gradients seen along the margins of the Coley Creek pluton, which we would expect to occupy the transition zone between less sheared portions of the Elkahatchee and more highly strained, mylonitic rocks within the proposed Alexander City fault “ductile” shear zone (Fig. 13). Further and more quantitative mineralogical and grain size analysis may reveal more about the similarities and differences between these margins, but my initial investigation suggests, aside from mylonitization of feldspar megacrysts on the margin of the Coley Creek pluton, major changes in grain size or mineralogy are not present along the margins of either body.

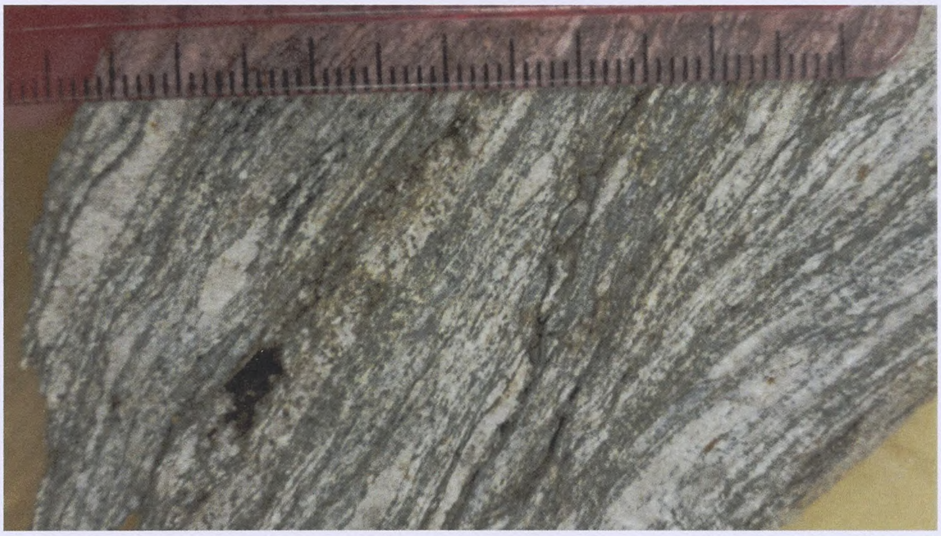


Figure 14. KJ001, collected 0.5m from the Coley Creek/Emuckfaw contact, clearly shows high strain.

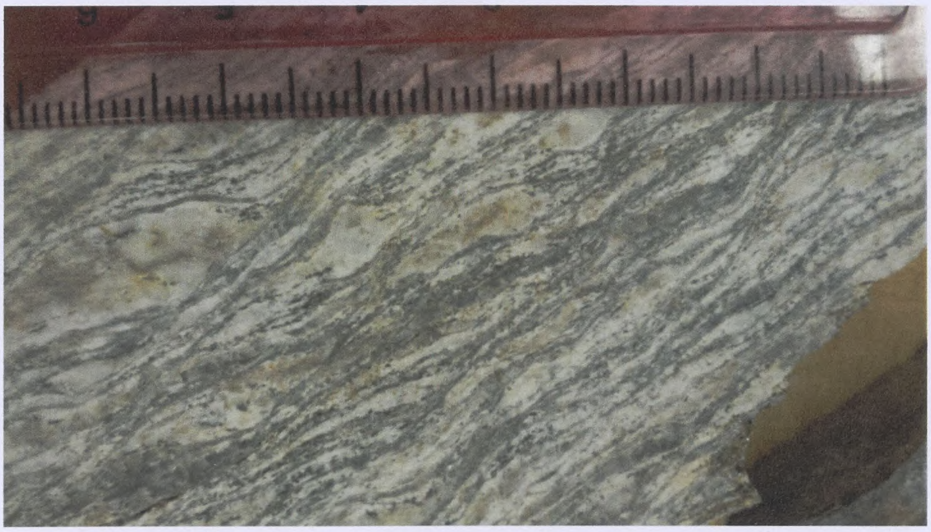


Figure 15. KJ005, collected 136m structurally above the Coley Creek/Emuckfaw contact, shows little to no mineralogical change, although a lower aspect ratio of feldspars is evident, suggesting lower bulk strain values relative to the margins of the pluton.

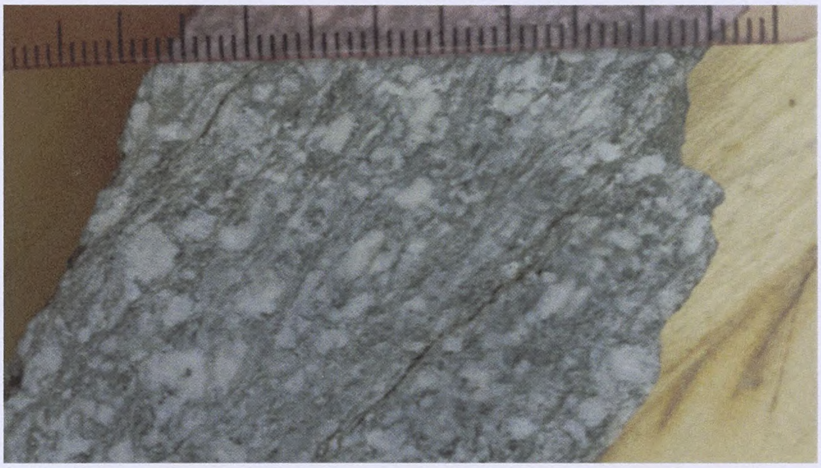


Figure 16. KJ011, collected 2m from the Elkahatchee/Wedowee Contact, depicts development of a mylonitic fabric, however grain size in this sample is similar to that in less strained Elkahatchee.

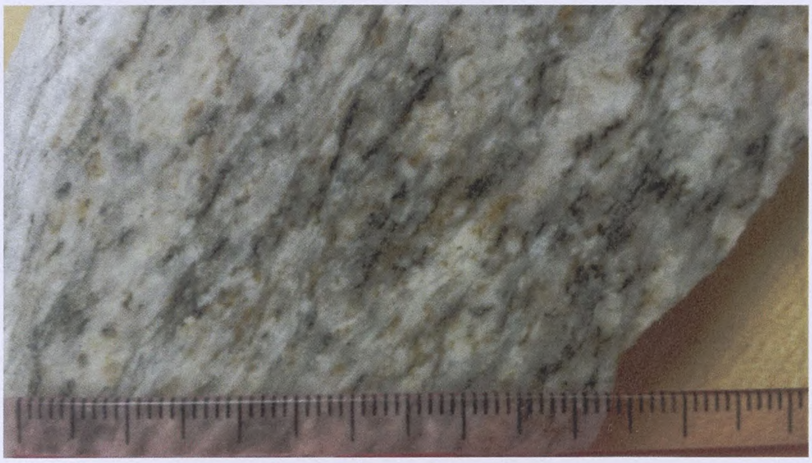


Figure 17. KJ007, collected 281m from the Elkahatchee/Wedowee contact.

CONCLUSIONS

The data suggests it is possible to interpret the shearing on the margins of the Elkahatchee batholith in terms of mechanical difference and fluid flow during metamorphism, rather than a major tectonic boundary with significant displacement. More detailed strain mapping of the plutons in question, as well as more quantitative grain size and mineralogical analysis of samples could provide more definitive results.

Due to the logistics of Rf-Φ analysis, we were unable to map the strain gradient 4.5km into the Elkahatchee Quartz Diorite, as proposed by Steltenpohl et al. (2013). It is possible, therefore, that the low bulk strain values observed across the Elkahatchee-Wedowee contact could still be associated with significant dextral offset if it were argued that the shear zone ("ductile Alexander City fault") was very wide (>3km). However, it should be noted that this interpretation still centers on the observed high strain zones along the margins of the Elkahatchee, which we have shown to be explainable by other means. Additionally, interpretations of a kilometers-wide shear zone is partially based on the presence of a sheared trondjhemite dike internal to the batholith, but ~4.5km away from the Elkahatchee-Wedowee contact. The nearly identical ages, however, between the dike and the Elkahatchee batholith (ca. 370 Ma) suggests this sheared dike was being deformed while the Elkahatchee host rock was still crystallizing (Tull and Campbell, 2012; Barineau et al., 2015).

Discussion

This work suggests it is possible to interpret the strain observed along the margins of the Elkahatchee Quartz Diorite, in the Elkahatchee Creek area, several kilometers north of where the brittle Alexander City fault is proposed to tip out (Tull and Campbell, 2012; Harstad, 2015), as simply the result of mechanical differences between the Elkahatchee Quartz Diorite and the adjacent Wedowee Group in addition to penetration of chemically active fluids from the Wedowee Group during peak metamorphism, which occurred after the intrusion of the Elkahatchee Quartz Diorite and Coley Creek Gneiss, rather than as a ductile shear zone with potentially significant offset between two bodies otherwise considered to be stratigraphically connected.

There are, however, a number of caveats on interpretations presented herein. If the shear zone really is ~4km wide, as presented in Steltenpohl et al. (2013), this research covered only a small area of it, and a wider study would be needed to see if it yielded similar results. However, logistical issues associated with taking a statistically significant number of samples across the proposed 4km shear zone and analyzing them requires a large scale project far beyond the scope of this exploratory exercise.

Additionally, because Rf-phi analysis cannot accurately quantify strain in rocks that have suffered significant grain size reductions coupled with decreases in aspect ratio, samples with very-fine grain sizes were specifically avoided during sampling. If these zones accommodated significant strain, it is probable that this analysis would have underestimated their bulk strain values.

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