Appendix I

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Microstructural and Geochronologic Constraints at the Duke Energy Lee Nuclear Power Station

Shear Zone Fabric Description

The shear zones contain an early ductile fabric that is composed primarily of elongated "polygonalized" polycrystalline quartz aggregates indicative of dynamic recrystallization and annealing recovery mechanisms (Nicolas and Poirier, 1976). These quartz aggregates occur in a foliated matrix of white mica and sometimes biotite. Potassium feldspar and plagioclase porphyroclasts are reported and this fabric is described as mylonitic. The feldspar fraction is highly altered to white mica and epidote. Iron staining of the shear planes is ubiquitous. Biotite in the protolith is reported to be "olive green" in color. In contrast, biotite reported in association with the shear zones is almost always reported to be "brown."

The early ductile fabric is overprinted by a brittle fabric that contains fractured and broken plagioclase, quartz and quartz aggregates in a finer grained matrix of smaller clasts and fine-grained material. This fine-grained matrix is overgrown by undeformed white mica (Figure 1). This white mica occasionally stitches the boundary between larger clasts and the fine-grained matrix. In addition, the matrix contains randomly oriented chlorite plates and masses, along with epidote, calcite and pyrite.

Veins containing quartz, calcite, epidote, white mica, chlorite, pyrite and a low birefringent material identified as K-feldspar (probably adularia; C.E. Weaver report, Fugro Consultants (2011a)) cut the ductile and brittle fabrics (Figure 2). Veins also occur that contain various mixtures of these minerals. These veins are in various states of deformation ranging from undeformed, to slightly deformed, to folded and bent. In addition, stringers of the vein material are reported sub-parallel to the dominant foliation (FSAR Subsection 2.5.1.2.5.4 and Figure 2.5.1-230). This indicates that these veins are both late-syn- and post-kinematic with respect to both the ductile and brittle phases of deformation.

Geochronology and Kinematic Constraints

The geochronologic database for the Cherokee site consists primarily of K-Ar ages with a few Rubidium – Strontium ages. K–Ar ages in slowly cooled settings (regional metamorphism) are typically interpreted in the context of closure temperature intervals; that is the temperature intervals in which minerals become closed systems to argon volume diffusion (Hodges, 1991; McDougall and Harrison, 1999). There are several potassium containing minerals in which the closure temperature intervals are well

characterized either experimentally or empirically (Hodges, 1991; McDougall and Harrison, 1999), including hornblende, muscovite, biotite and K-feldspar (Figure 3). There are two important corollaries to the interpretation of K-Ar ages in the context of closure temperature intervals. One is that the K-Ar age records the time (date) at which a mineral passed through the closure interval as it cooled and therefore dates a temperature. The second is that the K-Ar age is the minimum age for the mineral to have crystalized. In order to have confidence in the validity of these corollaries it is necessary that the K-Ar age is from a monomineralogic sample for which the K-Ar thermal systematics are well known (Figure 3). This excludes whole rock samples in slowly cooling settings and minerals with little or no potassium in their composition. In addition, this precludes the use of minerals whose structural state is unknown such as highly deformed, weathered, and/or altered samples or minerals that may have incorporated significant amounts of non-radigenic ^{40}Ar from the environment.

The geochronologic database for the Cherokee site contains several samples that meet the above criteria. Sample B-28, 106 ft. contains undeformed hornblende (closure to argon loss of about 500°C; Figure 3) with a K-Ar age of 290±9 Ma. Sample BP-7, 59 ft. contains an undeformed biotite (closure to argon loss at about 300°C; Figure 3) with a K-Ar age of 296±7 Ma. These ages are essentially the same and would indicate relatively rapid cooling of the terrain following emplacement of Late Paleozoic late- to post kinematic granitic intrusions nearby. Also the K-Ar age reported for potassium feldspar from an undeformed dilational vein that cross cuts one of the shear zones constrains the minimum age for the shear-breccia zones. This sample gives a mineral age of 219 ± 1 Ma (sample GTP-7). This result is significant in two respects: (1) because the feldspar is undeformed and cross-cuts the shear zone, the feldspar is older than 219 Ma cooling age, the timing of deformation related to shear zone formation is older than 219 Ma; (2) the temperature for closure to argon loss for potassium feldspar is about 250°C (but has an interval as large as ±100^{0}C; (Hodges, 1991)). The data are indicating that the thermal environment at the site has probably not been sufficient to produce greenschist facies metamorphic effects (muscovite and biotite growth) since at least 219 Ma. The overgrowths of muscovite and biotite on both the ductile and brittle fabric components (Figure 1) indicate that the fabric elements are significantly older than indicated by the potassium feldspar age since muscovite and biotite require thermal conditions above most of the closure interval of K-feldspar to grow. The K-Ar biotite age discussed above indicate that these structural fabrics are 300 Ma or older. This conclusion is supported by the Rubidium-Strontium age (Rb–Sr;) on biotite from sample B-51, 76 ft. of 291 ± 10 Ma providing a minimum age constraint on biotite by an independent geochronologic technique. These data indicate the site has not experienced tectonic deformation since the Mesozoic, and possibly not since 219 Ma to 300 Ma.

In summary the K-Ar geochronologic data indicate that the Cherokee site cooled through the closure intervals for both hornblende and biotite (500°C and 300°C respectively) following regional heating probably from the intrusion of nearby Late Paleozoic granitic plutons at about 300 Ma. The similar ages for both hornblende and biotite indicate that

cooling through this temperature interval was relatively rapid. The K-Ar age for the K-feldspar of 219 Ma indicates that the Cherokee site cooled through about 250°C in the Triassic and provides a minimum age constraint on the shear – breccia zones, although based on overprinting biotite and muscovite these zones are older. The Cherokee site age dates are consistent with those documented regionally in other studies (Evans and Bartholomew, 2010; Figure 4).

The heavy line on figure 4 shows the regional cooling and depressuration path for the southeastern Piedmont as established by Evans and Bartholomew (2010) based on geochronology and fluid inclusion data. The cooling path shows cooling following intrusion of Late Paleozoic plutons through the closure interval of hornblende at 295±3 Ma which is within error of the hornblende ages obtained for the Cherokee site. The muscovite closure interval on Figure 4 is dated at 275±3 Ma, which is younger than the 297±6 Ma age for biotite from the Cherokee site. This muscovite is from the Augusta, Georgia area and may reflect slightly slower regional cooling at this location, the Kiokee terrane, relative to the Charlotte terrane.

Following regional cooling in the Late Paleozoic, the path shows a large negative pressure gradient in the Triassic at or slightly before 220 Ma based on K-feldspar alteration (Figure 4). This depressuration event resulted from Triassic crustal extension and unroofing during the formation of the Atlantic Ocean basin. The age of this event is identical to the K-feldspar age of 219±1 Ma obtained at the Cherokee site. This indicates that the K-feldspar K-Ar ages at the Cherokee site also reflect cooling following regional unroofing related to Triassic crustal extension.

In summary, although the Late Paleozoic cooling rates may have differed for different geologic terranes in the southeast US, the general pressure-temperature history for the southestern Piedmont (the rapid cooling following crustal extension and rifting in the Triassic) is applicable to the Cherokee site.

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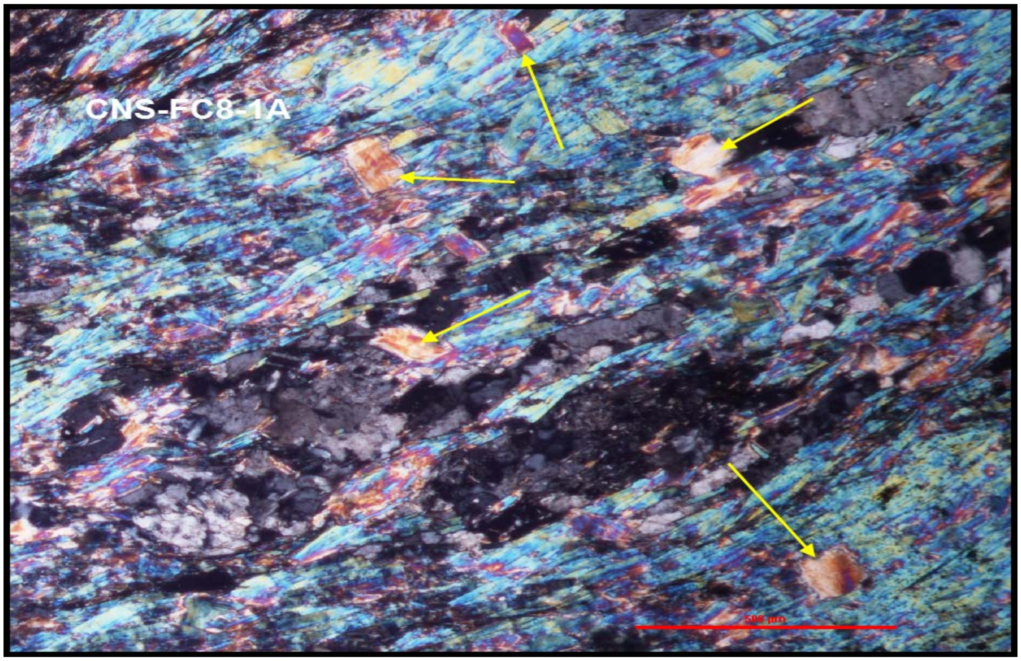
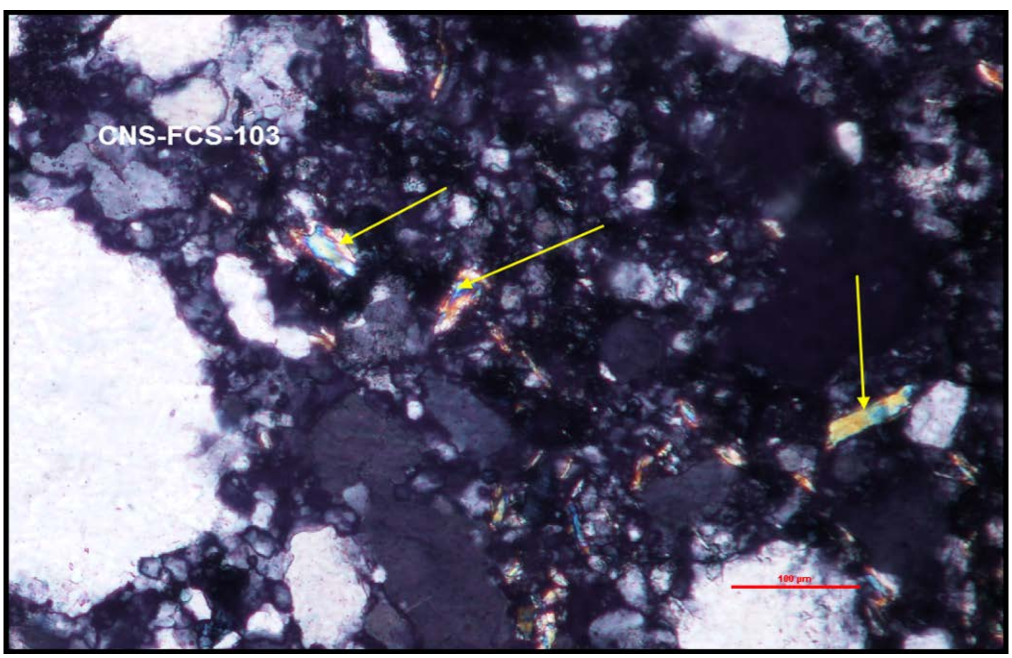


a.



b.

Figure1. Late- to post-kinematic white mica (denoted by yellow arrows) overgrowing ductile fabric (**a**) and brittle fabric (**b**).

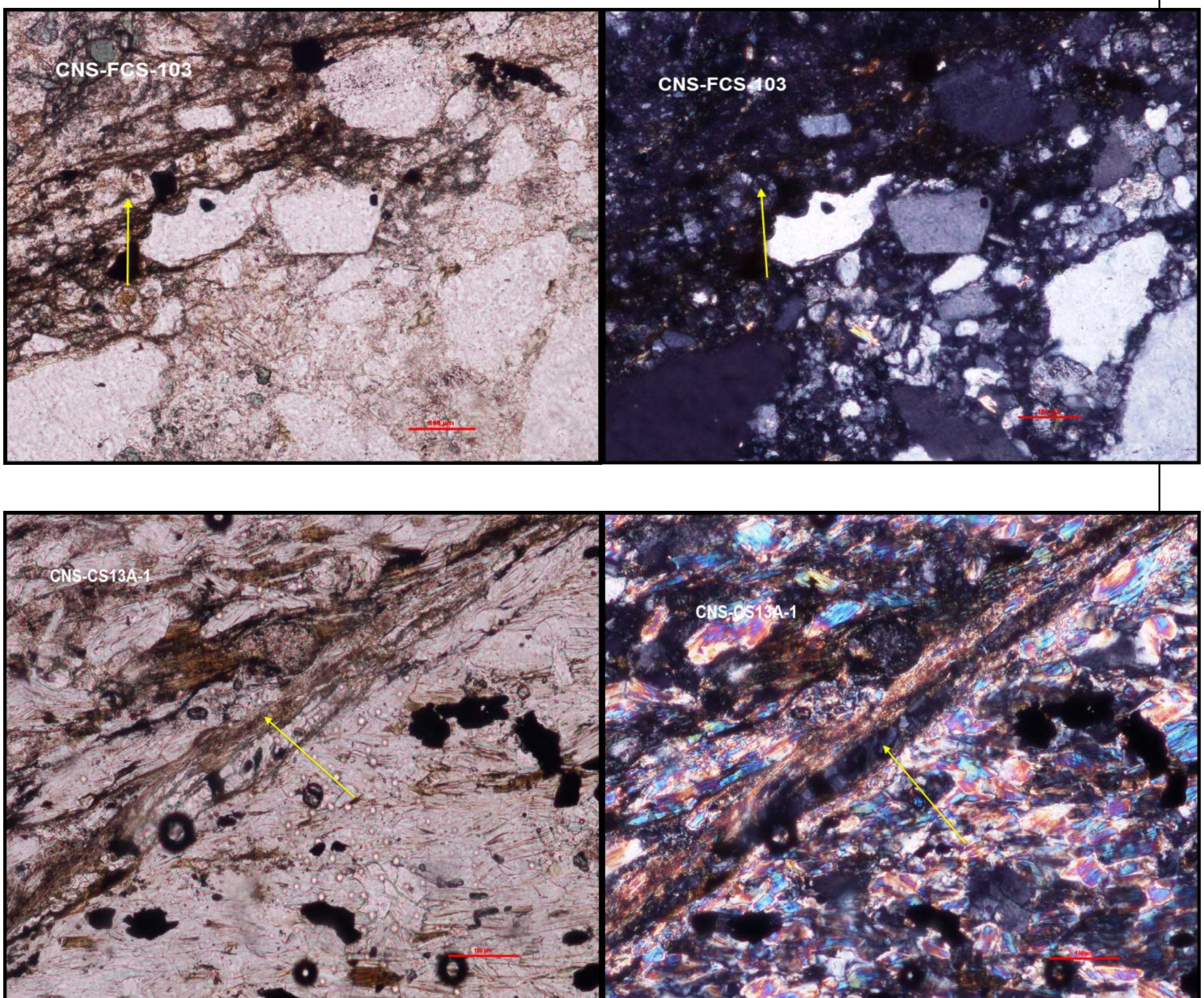


Figure 2. Examples of low birefrengent material (K-feldspar) in veins cross cutting Structural fabric (left -plain light, right – crossed polarized light).

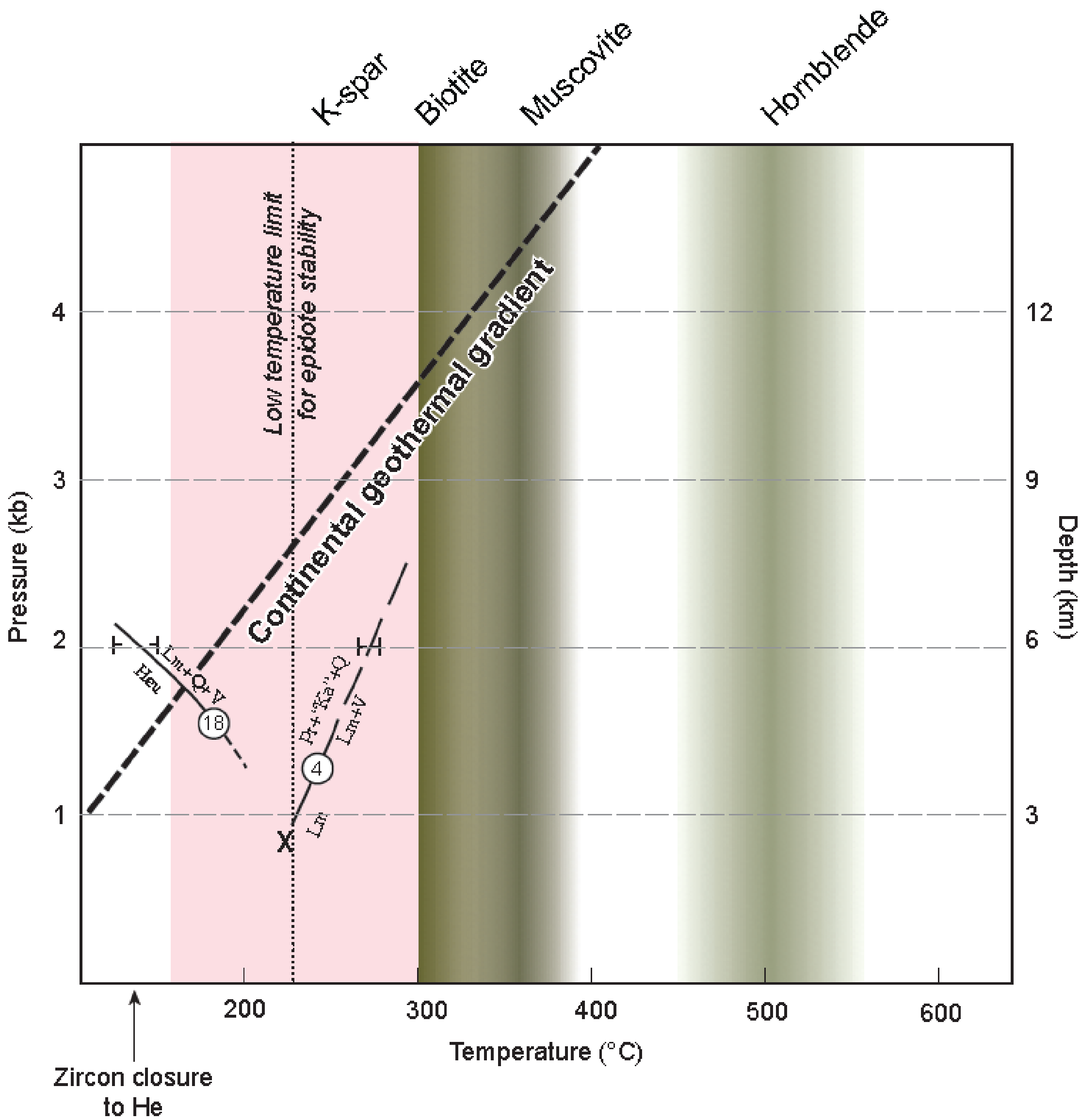


Figure 3. Modified after Thompson (1971). Thermodynamic stability fields for laumontite (Lm) and associated reaction products along with the closure intervals of selected mineral phases shown at top of figure. Important constraining reactions are reaction number 18 that indicates that laumontite (La) + quartz (Q) + vapor (V) breaks down at lower temperatures and pressures to Heulandite (Heu) and reaction 4 which indicates that laumontite (Lm) + vapor (V) breaks down to prenhite (Pr) + clay (Ka) + quartz (Q) at low temperatures.

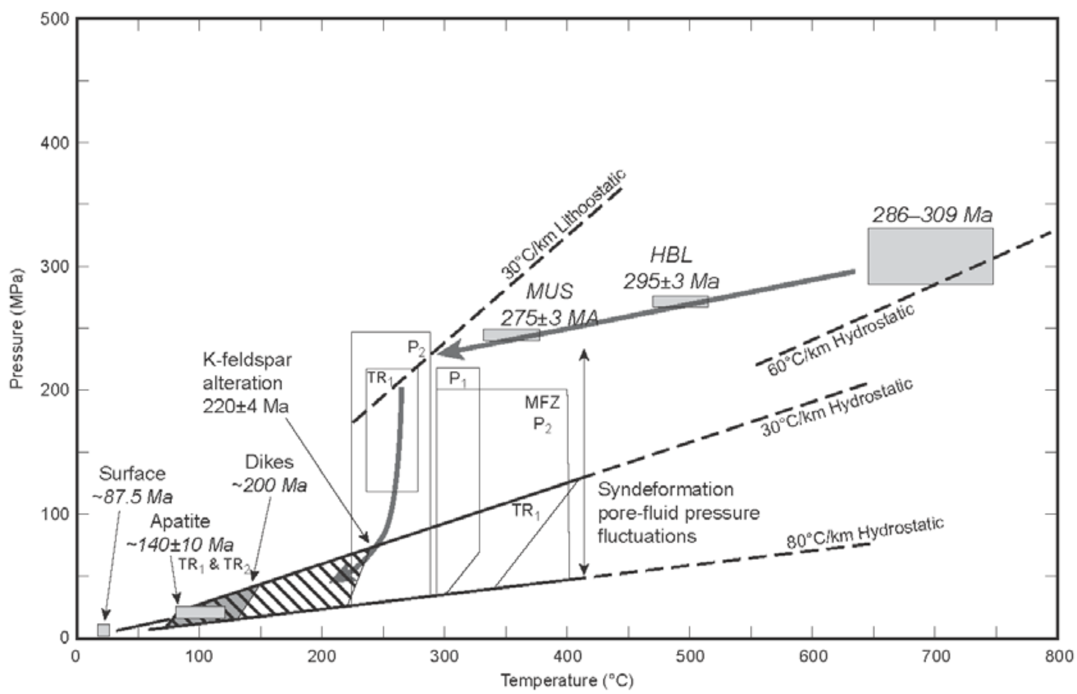


Figure 4. Pressure – Temperature evolution for the southeastern Piedmont (from Evans and Bartholomew, 2010). Key features referred to in text: Large grey rectangle= Intrusion of Late Paleozoic late- to post-kinematic granites at 286 – 309 Ma; Small grey rectangles= closure to argon diffusion of hornblende (HBL) and muscovite (MUS); Heavy line with arrows= cooling and decompression path.