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DEFORMATION TEMPERATURE AND KINEMATICS OF THE DAKOTA TECTONIC ZONE WITHIN THE LITTLE ELK GRANITE IN THE BLACK HILLS, SOUTH DAKOTA, NEAR NEMO, SOUTH DAKOTA

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ABSTRACT

Precambrian rocks in the Black Hills record multiple tectonic processes, including suturing of the Wyoming and Superior cratons from ca. 1.740-1.715 Ga. One of these structures active during this time is the Dakota Tectonic Zone (DTZ), which is a strike-slip shear zone. We examined intracrystalline deformation and associated microstructures in oriented thin sections of the Little Elk Granite (2.560 Ga gneiss) within the DTZ to further document how the strike-slip deformation fits into the Precambrian structural evolution of the Black Hills. At the outcrop scale, the Little Elk Granite contains two types of fabrics. Fabric type 1 is an augen gneiss fabric characterized by alignment of ~1-5 cm K-feldspar crystals that is interpreted to have formed during emplacement of the Little Elk Granite. Fabric type 2 cross-cuts the augen gneiss fabric and is characterized by comminution of the large K-feldspar grains within mylonitic shear zones. Whereas the type 1 fabric is folded throughout the field area, the type 2 shear fabric is consistently oriented at ~150/70°SW and contains a down-dip stretching lineation. Oriented thin sections cut perpendicular to foliation and parallel to lineation contain broken feldspar crystals that in some cases also exhibit undulose extinction. Domains between paired fragments of broken feldspar crystals are filled in with equant polycrystalline quartz aggregates and are regularly oriented at a high angle (>45°) to the shear foliation. Quartz-rich domains in the type 2 fabric generally display undulose extinction and dynamic recrystallization textures. Kinematic indicators from asymmetric strain shadows associated with feldspar porphyroclasts and asymmetrically folded micas yield dominantly top-to-the-right shear sense, but top-to-the-left shear sense is also common. These data from the Little Elk Granite suggests that the DTZ is an upper greenschist facies (~300-450°C) right-lateral pure shear dominated transpression zone that likely formed late in the suturing of the Wyoming and Superior cratons.

INTRODUCTION

The metamorphic core of the Black Hills uplift exposes poly-deformed Precambrian metamorphic rocks (Redden and DeWitt, 2008) (Fig. 1). Multiple folding events have been identified in the Precambrian core of the Black Hills; two of these folding events are thought to be associated with the suturing of the Wyoming and Superior cratons from ca. 1.740-1.715 Ga (Norwood, Brown, and Hawkins, 2013; Allard and Portis, 2013). These folding events show shortening deformation in F1 and F2 recumbent folds associated with thrust faults. A third deformation event, D3/F3, is characterized by vertically plunging isoclinal folds, which deform D2/F2 features and thus likely form late in the suturing process (Redden and DeWitt, 2008; Allard and Portis, 2013). The F3 folds are spatially associated with strike-slip shear zones, and the deformation zone along the northeastern boundary of the metamorphic core has collectively been called the Dakota Tectonic Zone (DTZ) (Allard and Portis, 2013) (Fig. 1B).

Previous research on the DTZ has focused on the kinematics of deformation at various locations throughout the Black Hills. This research builds upon the previous work by using oriented samples

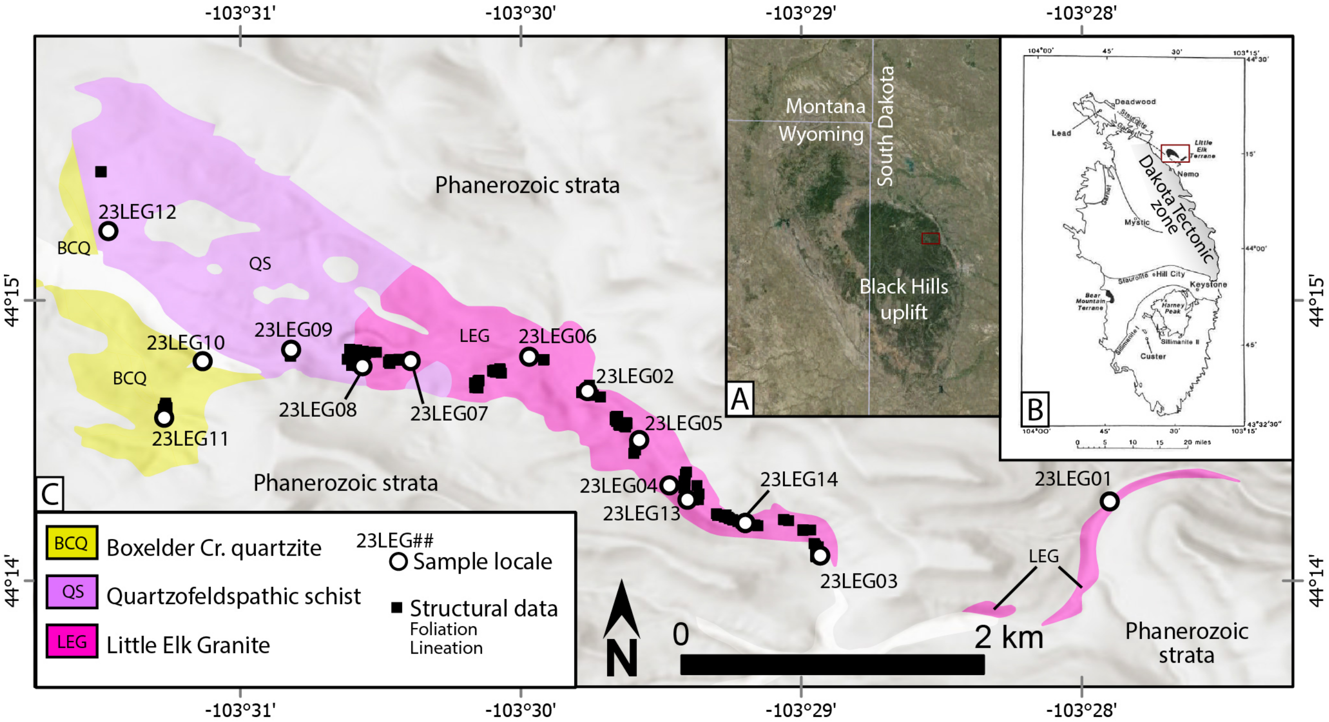

Figure 1. A) Google Earth image showing the location of the Black Hills (dark green region) relative to political borders. The Little Elk Creek area is outline by the red rectangle. B) Metamorphic isograd map of the Black Hills Precambrian core from Gosselin et al. (1988). Black shaded regions represent Archean rocks. The Little Elk Creek area is outline by the red rectangle. C) Geologic map of the Little Elk Creek area showing sample and structural data locations. Modified from Redden and DeWitt (2008).

to document microstructures along Little Elk Creek in a systematic transect across the shear zone. The results from this analysis bear on the kinematics and temperature of DTZ deformation in the northeastern Black Hills.

GEOLOGIC SETTING

The oldest rocks in the Black Hills are in the Little Elk (Fig. 1) and Bear Mountain terranes, which are dated at 2559 ± 6 Ma and 2596 ± 11 Ma, respectively (McCombs et al., 2004) (Fig. 1B). Other Precambrian rocks in the Black Hills consist of Paleoproterozoic metasedimentary rocks that are interpreted as deposited on top of the Archean rocks (Redden and DeWitt, 2008). This includes the Nemo Group, which is a package of quartzite, metaconglomerate, and iron formation exposed in a thrust sheet near Nemo, SD (Allard and Portis, 2013). These Paleoproterozoic rocks are generally interpreted to have been deposited within a continental rift that stretched between the Black Hills and Sudbury, Ontario, Canada (Dahl et al., 2006).

Deformation of Precambrain rocks in the Black Hills records four folding events that are interpreted to have formed during convergence between the Wyoming craton to the west and other cratonic blocks to the south and east (e.g., Norton and Redden, 1990; Redden et al., 1990; Terry and Friberg, 1990; Helms and Labotka, 1991; Dahl et al., 1999, 2005a, 2005b; Nabelek et al., 1999, 2006; Redden et al., 2008). D1, the earliest folding event, is thin-skinned, nappe-style, deformation that produced north-vergent recumbent folds that affected all rocks older than 2480 Ma (Redden et al., 1990, 2008). D1 had an associated folding event, F1, that is represented by local east-northeast-trending, tight-to-isoclinal folds in bedding, S0, and axial planes that dip shallowly to the south-southeast (Redden et al., 1990, 2008). The F2 folds, that are associated with D2, refold the F1 structures into upright, north-northwest-trending isoclinal synforms and antiforms with subhorizontal hinge lines (Redden et al., 1990, 2008). F2 folds are associated with an axial-planar cleavage fabric, S2, that is north-northwest-striking and subvertical (Redden et al., 1990, 2008). D3 is associated with “cross folds”, F3, that refold the S2 fabric from D2 into upright, vertically plunging folds (Dahl et al., 1999; Redden et al., 1990, 2008). The DTZ (D3) is associated with F3, which can be distinguished from S2 near F3 fold hinges where it cross-cuts the S2 fabric (Redden et al., 1990, 2008). D4 occurred after the DTZ and is characterized by recumbent folding along the margins of the the Harney Peak Granite in the southern Black Hills (Fig. 1B) and is interpreted to record vertical flattening following intrusion at ca. 1715 Ma (Dahl et al., 1999; Redden et al., 1990).

MATERIALS AND METHODS

Fieldwork was done in the Nemo, SD, area, looking at outcrops of the Little Elk Granite. The fieldwork consisted of going to the outcrops and using the FieldMove application on an Apple iPad to measure strike and dip of the shear foliation and the trend and plunge of the stretching lineation. A Brunton compass was used when the outcrop surface was too small for the iPad. Notes were taken in a notebook about the outcrop characteristics, such as outcrop scale deformation features. Pictures of all the outcrops were taken using the FieldMove app and annotated to record the observations. A rock hammer and chisels were used to collect seven oriented samples, about 10cm to 15cm in diameter. Because the Little Elk Granite is primarily an augen gneiss with K-feldspar crystals up to 3 cm in diameter, the samples were selected to have crystals smaller than the thin section glass slide so the section would contain more than a single crystal.

After the fieldwork was completed, the samples were brought to the Mineral Industries building on the South Dakota School of Mines and Technology campus to be cut into billets using a rock saw. The samples were cut into billets 0.5 x 2.7 x 4.6 cm proportions. The billets were cut perpendicular to the foliation and parallel to the lineation, and oriented with a notch in the down-plunge direction. After this process was complete, the billets were sent to Wagner Petrographic to be made into thin sections.

When thin sections were returned petrography was performed using a Nikon Eclipse LV100 POL model microscope. The thin sections have allowed for the identification of grain boundaries, undulatory extinction, strain shadows, and other microstructures. Structures that recorded the shear zone kinematics were documented and tallied.

RESULTS

At outcrop scale, the Little Elk Granite has two different fabrics (Fig. 2). Fabric type 1 is an augen gneiss fabric characterized by alignment of ~1-5 cm K-feldspar crystals that is interpreted to have formed during emplacement of the Little Elk Granite. Fabric type 2 cross-cuts the type 1 augen gneiss fabric and is characterized by comminution of the large K-feldspar grains within mylonitic shear zones. The type 1 fabric is folded throughout the field area, whereas the type 2 shear fabric is consistently oriented at ~150/70°SW and contains a steeply plunging lineation with a rake of ~70°. The microstructural analysis focused on the type 2 fabric.

In the thin section reference frame (cut parallel to the steeply plunging lineation), both top-right and top-left shear sense indicators are present. These structures are recorded by asymmetric pressure shadows associated with feldspar porphyoclasts and simple shear folding (Fig. 3). The quantity of microstructures showing each shear sense is similar, with 14 structures exhibiting top away from the notch and 12 structures exhibiting top towards the notch among all analyzed samples. The subtle predominance of top-away-from-notch

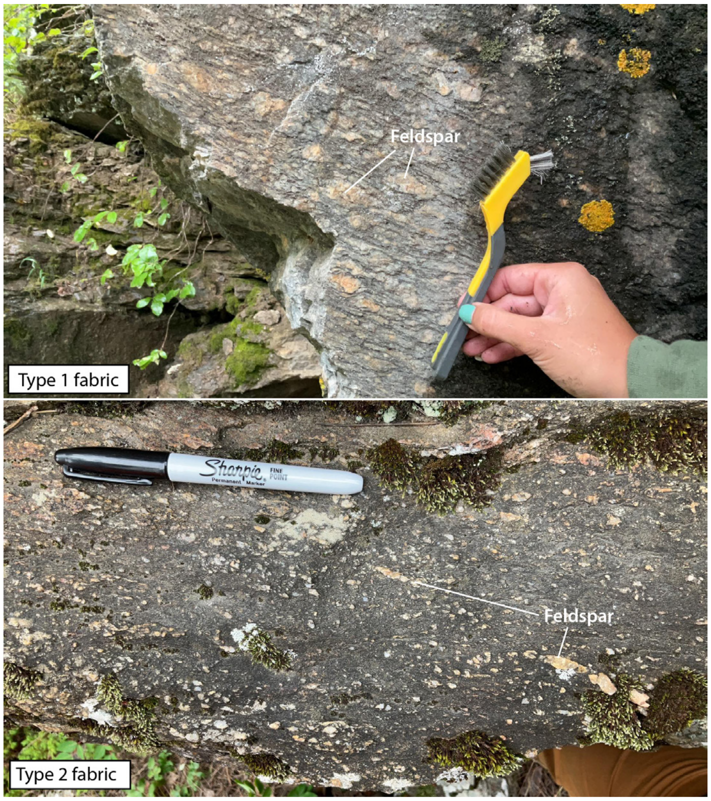

Figure 2. Field photographs of the the two fabric types in the Little Elk granite.

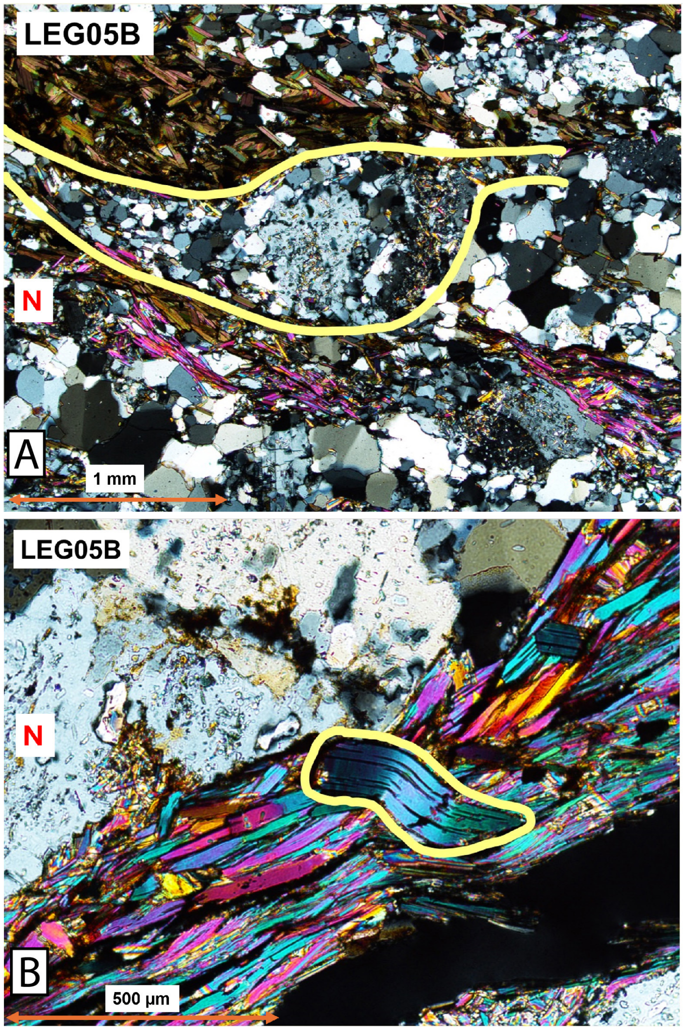

Figure 3. A) Photomicrograph showing top-to-the-right asymmetric pressure shadow on feldspar porhyroclast. B) Asymmetric fold in mica grain giving top-to-the-left shear sense. N–notch.

shear sense corresponds to oblique thrust-dextral shear sense in the geographic reference frame. Other characteristics that were exhibited in the thin sections are indicated in Table 1.

Most thin sections contain large (~1 mm) broken feldspar grains with polygonal quartz in the spaces in between feldspar fragments (Fig. 4). These fractures are regularly oriented at a high angle (>45°) to the shear foliation. Some thin sections contain isolated K-feldspar porphyroclasts with no obvious paired fragments. All thin sections contain quartz grains with undulose extinction. Some thin sections also have feldspar and mica grains with undulose extinction. Many thin sections have dynamic recrystallization textures, which are indicated by both quartz and feldspar grains having sinuous boundaries (Fig. 4). In some instances, the feldspar grains with sinuous boundaries follow the sinuous grain boundaries of the quartz.

DISCUSSION

Deformation Kinematics

The transect through the Little Elk Granite along Little Elk Creek offers the opportunity to walk across the DTZ with nearly continuous outcrop. These outcrops show both left- and right-lateral kinematics, which are also recorded at the thin section scale (Fig. 3). Based on the data collected here, the two types of structures are almost equal in population, which suggests that the rotation direction of the mineral grain during deformation is controlled by the orientation of the long crystallographic axis prior to deformation (Fossen and Tikoff, 1993). This process is common in deformation conditions where the incremental shortening axis is

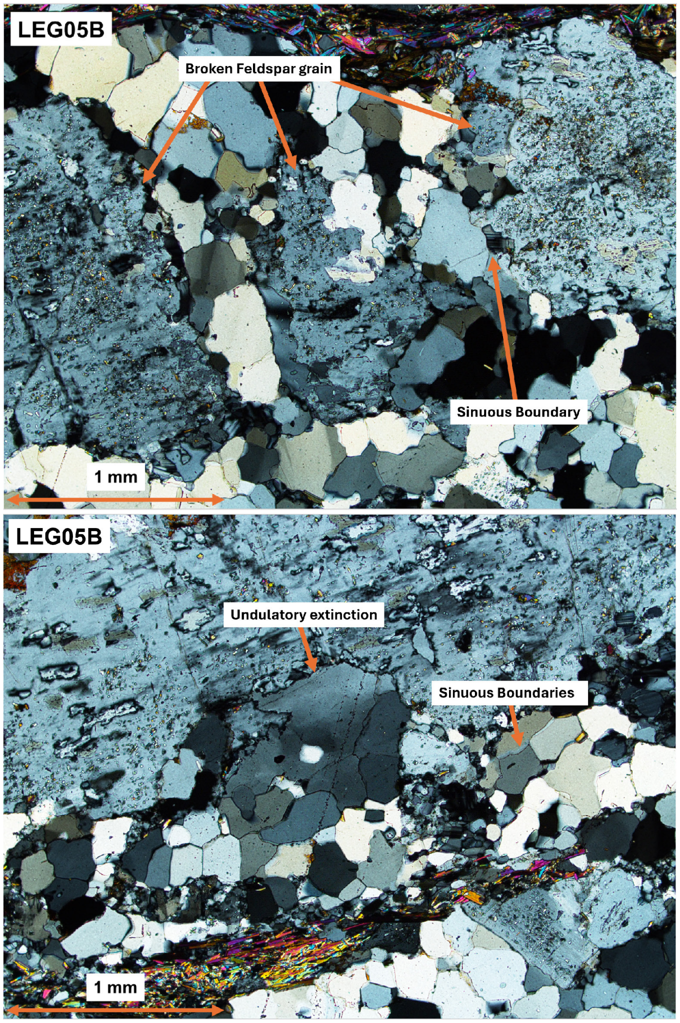

Figure 4. Photomicrographs illustrating deformation textures in quartz and feldspar grains including: broken feldspar, undulose extinction, and high surface area grain boundaries.

Table 1: Thin section observations

	Sample number								
Feature/ Structure	23LEG02A	23LEG02B	23LEG05A	23LEG05B	23LEG07A	23LEG07B	23LEG10A	23LEG12A	23LEG12B
Majority right-lateral	X					X		X	X
Majority left-lateral				X					
Equal right and left lateral							X		
Broken fsp	X		X	X	X		X		
Polygonal qz in cracks	X		X	X	X		X		
Undulos fsp	X		X		X		X		
Undulos qz	X	X	X	X	X	X	X	X	X
Sinuous qz boundaries	X	X	X		X	X	X	X	X
Sinuous fsp boundaries		X							
Polygonal qz	X	X	X	X	X	X	X	X	X
Polygonal fsp									
Twinning fsp	X	X	X	X					
Very Small grains (<200μm)	X	X	X	X	X	X	X	X	X
Small grains (201μm-600μm)	X	X	X	X	X	X	X	X	X
Medium grains (601μm - 1,000μm)	X		X	X	X	X	X		
Large grains (>1,000μm)			X	X	X		X		

oriented at a high (>45°) angle to the fabric, such as pure shear (Fossen and Tikoff, 1993). At the outcrop scale, the evidence of pure shear deformation is significant with a strong foliation and stretching lineation. Evidence for simple shear in outcrop consists of asymmetric pressure shadows associated with feldspar prophyroclasts, and local S-C-C' fabrics (Allard and Portis, 2013). Together, these data imply that the bulk deformation involved components of both pure shear and simple shear. The slight predominance of top-up-plunge shear sense indicators in thin section and the obliquity of the stretching lineation in outcrop suggest that oblique dextral-reverse kinematics predominate for DTZ deformation at this location. The combination of strike-slip shear sense observed in map view, conflicting shear sense indicators, and nearly down-dip stretching together suggest that the bulk deformation fits a pure shear dominated transpression model (Fossen and Tikoff, 1993; Twiss and Moores, 2007). This interpretation is consistent with other studies of the DTZ; however, the slight predominance of right-lateral shear observed here contrasts with previous work emphasizing left-lateral shear (e.g., Allard and Portis, 2013).

Deformation Temperature

The contrasting quartz and feldspar microstructures allow for an estimation of the DTZ deformation temperature. At typical crustal strain rates, feldspar deforms by plastic deformation mechanisms at temperatures above 450°C, and quartz deforms by plastic deformation mechanisms at temperatures above 300°C (Fossen and Cavalcante, 2017). At temperatures below 300°C, both the feldspar and quartz grains would deform by brittle mechanism, whereas if the deformation temperature was above 450°C, then both minerals would deform by crystal-plastic deformation mechanisms. In the DTZ at Little Elk Creek, large feldspar grains are broken, forming cracks between the broken pieces that are filled with polygonal quartz (Fig. 4). Quartz grains exhibiting undulatory extinction indicate deformation by crystal-plastic processes. Quartz, and sometimes feldspar, grains commonly display sinuous grain boundaries that interact with the grains around them, which records grain boundary migration by plastic deformation mechanisms (Passchier and Truow, 2005) (Fig. 4). These observations together suggest that the quartz was deforming by plastic deformation while the feldspar was deforming by brittle deformation, which together bracket the deformation temperature to 300-450°C. This interpretation is supported by samples from gabbroic dikes within the Little Elk Granite that display reaction rims of syn-kinematic actinolite pseudomorphing hornblende in thin section. These observations collectively indicate that the DTZ at the location of the Little Elk Creek deformed at upper greenschist facies temperatures.

The interpretation of greenschist facies deformation within the DTZ at the Little Elk Creek contrasts with observations of the DTZ farther south in the Black Hills where it is documented to be a higher-grade shear zone (e.g., Hill, 2006). This along-strike change in deformation temperature could be explained by the DTZ in the Little Elk Creek being a preserved higher crustal level of the shear zone or the heat source of the metemorphisim being in the southern area of the hills. If the DTZ along Little Elk Creek is a preserved higher crustal level of the shear zone, it could indicate that the Precambrian basement of the Black Hills has been tilted to the north, allowing for preservation of the higher crustal in the north. If the heat source of the metamorphism in the hills was in the south, this could indicate that deformation in the DTZ overlapped in time with the emplacement of the Harney Peak Granite.

CONCLUSION

The DTZ is part of the D3 event recorded in the Precambrian basement of the Black Hills. This event is associated with flattening and strike-slip shear that is primarily focused along the eastern side of the Black Hills metamorphic core. This deformation is shown clearly in the Little Elk Granite through quartz and feldspar grains. The quartz and feldspar grains show both left- and right-lateral shear sense at outcrop and thin-section scales, with right-lateral structures marginally dominating both. This opposing shear sense, along with steeply plunging stretching lineation, suggests that the DTZ is a pure-shear-dominated transpression zone. Feldspar grains within the shear zone deformed by brittle mechanisms while quartz deformed by cystal-plastic mechanisms. This relationship indicates that the DTZ at the location of Little Elk Creek is an upper greenschist facies shear zone.

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