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KINEMATIC ANALYSIS OF SHEAR ZONES IN THE LITTLE ELK GRANITE, BLACK HILLS, SOUTH DAKOTA

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ABSTRACT

The Black Hills of western South Dakota and eastern Wyoming were uplifted as a result of the Laramide orogeny occupying the suture between the Wyoming and Superior cratons. Two exposures of Archean orthogneiss, the Bear Mountain Terrane and the Little Elk Granite (LEG), represent the oldest rocks exposed in the Precambrian core of the Black Hills and offer the opportunity to study tectonic processes involved in forming the Laurentian craton. This study presents new structural field data (orientation of foliation planes, stretching lineations, and cross cutting relations; n=270 measurements) along a ~5 km transect that record the deformation history of the LEG. Two dominant fabric types were found in outcrop: augen gneiss (type 1) and mylonitized granite (type 2). The type 1 fabric is characterized by 1-5 cm K-feldspar crystals aligned to give top-down or "normal" sense of shear, small-scale folding of the fabric, and is cross-cut by aplite dikes at multiple sites. The type 2 mylonitic fabric overprints the type 1 fabric and intensifies from east to west along the transect, resulting in a loss of the type 1 fabric. The stretching lineation in the type 2 fabric plunges down dip with shear sense indicators observable in outcrop. Both fabrics display a southeast-striking and ~70°SW dipping foliation at every site. Yet, subtle folding of the type 1 fabric at some sites causes it to be crosscut by the type 2 fabric. Based on the high-temperature deformation features in the type 1 fabric and the cross-cutting relationship with aplite dikes, we interpret that the type 1 fabric formed during emplacement of the granite. Assuming the LEG has not experienced significant tilting since emplacement, the top-down shear sense recorded by alignment of K-feldspar may suggest emplacement of the LEG into an extensional setting. Our observations of the type 2 fabric, including down-plunge stretching lineations and opposing shear sense indicators support previous interpretations of transpressional deformation within the LEG and metasedimentary rocks sheared along its western margin. With the new data describing shear zone kinematics in the LEG, we interpret that the type 1 fabric formed prior to suturing of the Wyoming and Superior Cratons and the type 2 fabric formed during craton suturing.

INTRODUCTION

Precambrian rocks present in the Black Hills, South Dakota form a domal core due to regional uplift during the Laramide Orogeny (Redden et al., 1990). The Archean Little Elk Granite (LEG) and Bear Mountain Granite (BMG) are present on the edges of the exposed Precambrian core (Fig. 1), which was metamorphosed and deformed during the Early Proterozoic (Redden et al., 1990). Laying in the southeastern portion of the Wyoming Craton, Paleoproterozoic and Neoarchean rocks of the Black Hills underwent multiple tectonic events affiliated to the collision of the Wyoming and Superior Cratons (Dahl et al., 2006). In association with large-scale folds, Paleoproterozoic, north-northwest-trending, axial planar foliation was found preserved in east-northeast-trending fold nappes within the Black Hills (Dahl et al., 2006). These structures can be seen as a result accretion of the norther Yavapai island-arc terrane and more importantly the approximate east-west shortening associated with the suturing of the Wyoming and Superior crtatons (Dahl et al., 2006). These events formed a northwest-southeast-striking foliation in the Precambrian rocks throughout the Black Hills (Redden et al., 1990).

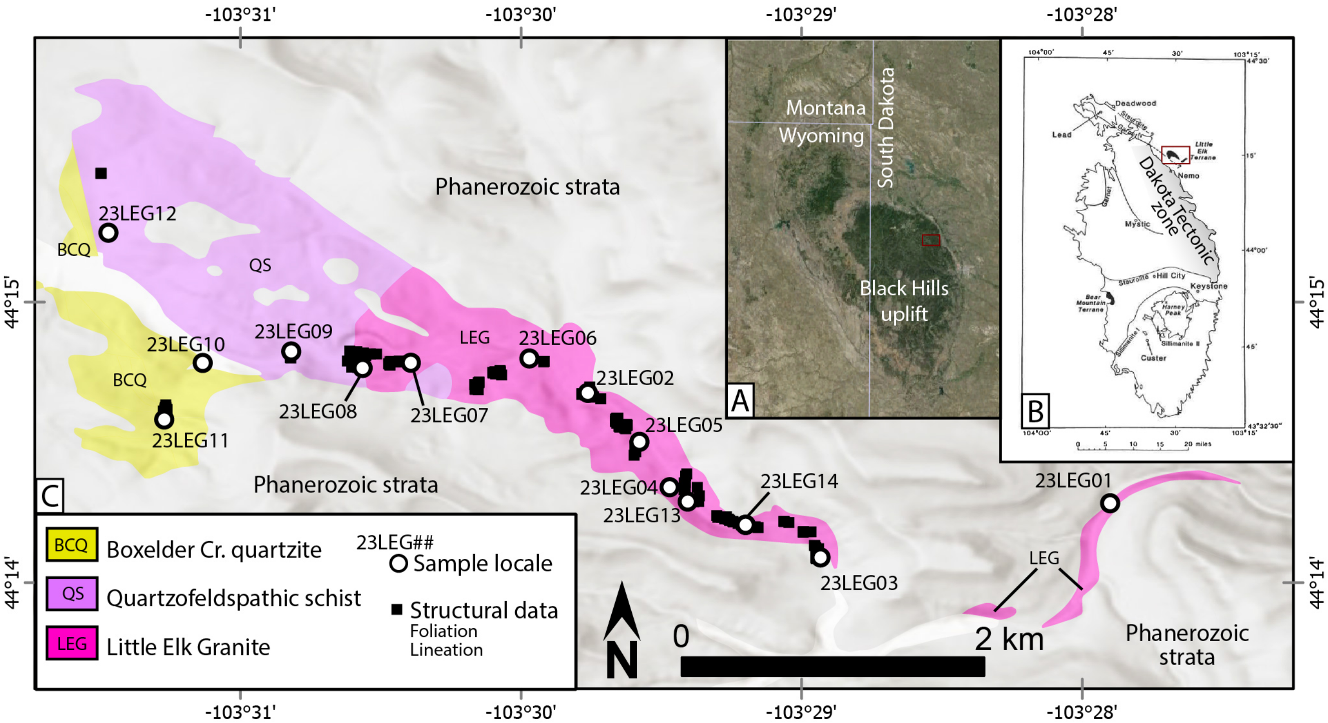

Figure 1. A) Google Earth image showing the location of the Black Hills (dark green region) relative to political borders. The Little Elk Creek area is outline by the red rectangle. B) Metamorphic isograd map of the Black Hills Precambrian core from Gosselin et al. (1988). Black shaded regions represent 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).

Exposure of the LEG is limited to two windows in the Paleozoic sedimentary rocks over an area of ~2 square miles (Zartman & Stern, 1967) (Fig. 1). The LEG is feldspathic, displaying a dominant porphyritic, coarse grained texture with well-developed augen structure (Redden et al., 1990). The gneissic LEG occupying the valley of Little Elk Creek is well banded consisting of mica flakes parallel to well-defined layers between quartz and feldspar bands (Runner, 1934). Thin section analysis from Runner (1934) displays a composition of microcline, orthoclase, and albite feldspar, 60%; quartz 25%; biotite and muscovite, 15%; along with minor content of apatite, tourmaline, zircon, and pyrite. Large fractured quartz and feldspar grains were among the first essential minerals to form in the Little Elk gneissic granite. Subsequent of initial crystallization of these minerals is formation of mylonitic zones, micaceous layers, and veinlets. These developed along fractures in the quartz and feldspar grains (Taylor, 1935). Aplite dikes are seen to frequently cut through the main mass along with small quartz-rich veins. Cross cutting features intrude along and across structural planes of the main granite, but they do not display some of the same metamorphic characteristics of the granite. Previously observed in Runner (1934), the folding in this region consists of a doubly plunging isoclinal antiform that is overturned toward the northeast.

The aims of this study are to assess the kinematics and deformation history of the LEG. Through the assessment of field measurements, kinematic analysis of LEG shear zones can assist in further interpretation of metamorphism of the Archean basement and the LEG.

METHODS

The LEG was observed during August 2023, which involved structural-kinematic analysis in the field and sampling for analytical work. Ten days were spent in the field collecting structural measurements and field samples of exposed outcrops of the LEG. Outcrops were observed and analyzed along a transect along Dalton Lake Road (Fig. 1). Site observation started east of Dalton Campground with site 23LEG01 and continued west to 23LEG12 (Fig. 1). An application on iPad Mini, FieldMove, was utilized to measure strike and dip of foliation planes, contact planes of dikes, localized shear zones, and fault planes. Trend and plunge of mineral lineation were measured using the same instrumentation. With the use of Allmendinger's Stereonet 11 program, field measurements were plotted on stereonets and a map of the studied area to assess patterns in the orientations among the sites.

RESULTS

Fabric observations

Two fabric types are present in LEG outcrops as: an augen gneiss fabric (type 1) and a mylonitized granite fabric (type 2). Cross-cutting aplite dikes display different deformation characteristics visible in each fabric. Preservation of type 1 fabric to decreases to the west as the type 2 fabrics intensifies. West of site 23LEG08 (Fig. 1), type 1 fabric is not preserved. East of 23LEG14 (Fig. 1), type 2 fabric is not present.

Type 1, augen gneiss

Type 1 fabric consists of deformed feldspar augens up to ~5 cm in diameter (Fig. 2a). Throughout the transect, augens in type 1 fabric predominately display top-down, or hanging wall-down shear sense along a dipping fabric, recorded by asymmetric pressure shadows associated with the augens (Fig. 2a inset). Aplite dikes are observed to crosscut the type 1 fabric, and do not experience any deformation associated with the type 1 fabric (Fig. 2b).

Type 2, mylonitic fabric

The type 2 fabric lacks the large feldspar augens that characterize the type 1 fabric (Fig. 3a). Based on outcrop scale deformation textures, feldspar in the type 2 fabric deforms by fracturing of augens from the type 1 fabric. In the type 2 fabric, rotation of fractured grains, asymmetric pressure shadows, and local S-C fabrics record both dextral and sinistral shear sense (Fig. 3a, b). Aplite dikes that crosscut the type 1 fabric are deformed along with the type 2 fabric (Fig. 3c).

Stereonet observations

Foliation plane, lineation, joint, and fold axis measurements were collected at a total of 16 sites along the transect. Table 1 displays the number and type of measurements taken at each site. A threshold of ≥5 measurements was used to determine notable sites. The sites that were deemed notable to use for further analysis are: 23LEG – 02, 03, 05, 06, 07, 08, 10, and 13 (Fig. 4). Sites that contain the type 1 fabric have a relatively consistent trend of southeast-striking and southwest-dipping foliation (Fig. 4). Sites that contain the type 2 fabric display similar trends in orientation to those with type 1 fabric of a generally southeast-striking and southwest dipping fabric. Among the notable sites, 23LEG13 is the sole location in which the general orientation of the foliation planes differs. Type 1 fabric at LEG13 is consistent with the type 1 fabrics at other sites, but the type 2 foliation planes at this site are strike north-south and have variable dip direction (Fig. 4). All lineations corresponding to both fabrics display a plunge moderately to the southwest, congruent with a down dip relationship to the foliation planes with little variation.

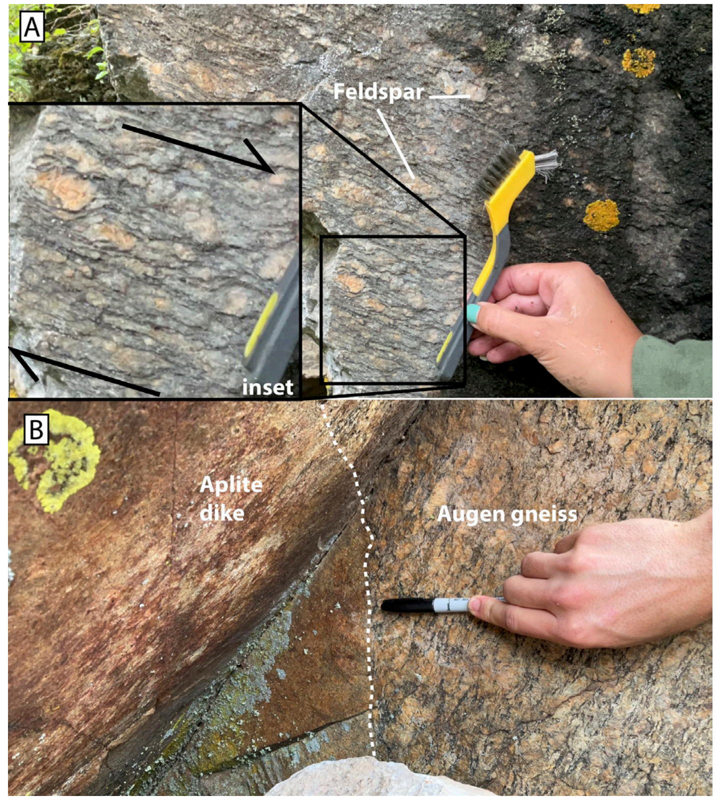

Figure 2. A) Outcrop photo of type 1 fabric (augen gneiss) foliation plane at site 23LEG03. Inset: Asymmetric shear on large, orange-pink, feldspathic augens indicate top-down shear sense. B) Augen gneiss fabric crosscut by undeformed aplite dike at 23LEG02.

DISCUSSION

The identification of two different fabric types provides insight to the deformation history of the LEG. The presence of large feldspar augens in the

Figure 3. A) Outcrop photo of well-developed type 2 fabric (mylonitic granite) indicating top-to-the-left shear sense. B) S-C structure in type 2 fabric indicating top-to-the-right shear sense. C) Aplite dike stretched within the type 2 fabric. D) incipient development of the type 2 fabric overprinting and localized within the type 1 augen gneiss fabric.

type 1 fabric may indicate a metamorphic process that was hotter, resulting in plastic deformation of the feldspar grains (Fig. 2). The type 2 fabric, however, is characterized by smaller feldspar grains that display brittle deformation features, indicating a colder metamorphic process during deformation. The type 2 fabric is observed to develop along the type 1 fabric (Fig. 3d) and deform aplite dikes that crosscut the type 1 fabric (Fig. 3c). Moreover, the westward intensification of type 2 fabric in combination with loss of type 1 fabric suggests that shearing related to the type 2 fabric resulted in the lithologic boundary along the western margin of the LEG (Fig. 1) (Allard and Portis, 2013). These data together indicate that the deformation features observed in the LEG record an evolution from higher temperature to lower temperature, wherein the higher temperature fabrics predate the intrusion of aplite dikes. Although one sample of undeformed aplite dike (sampled from

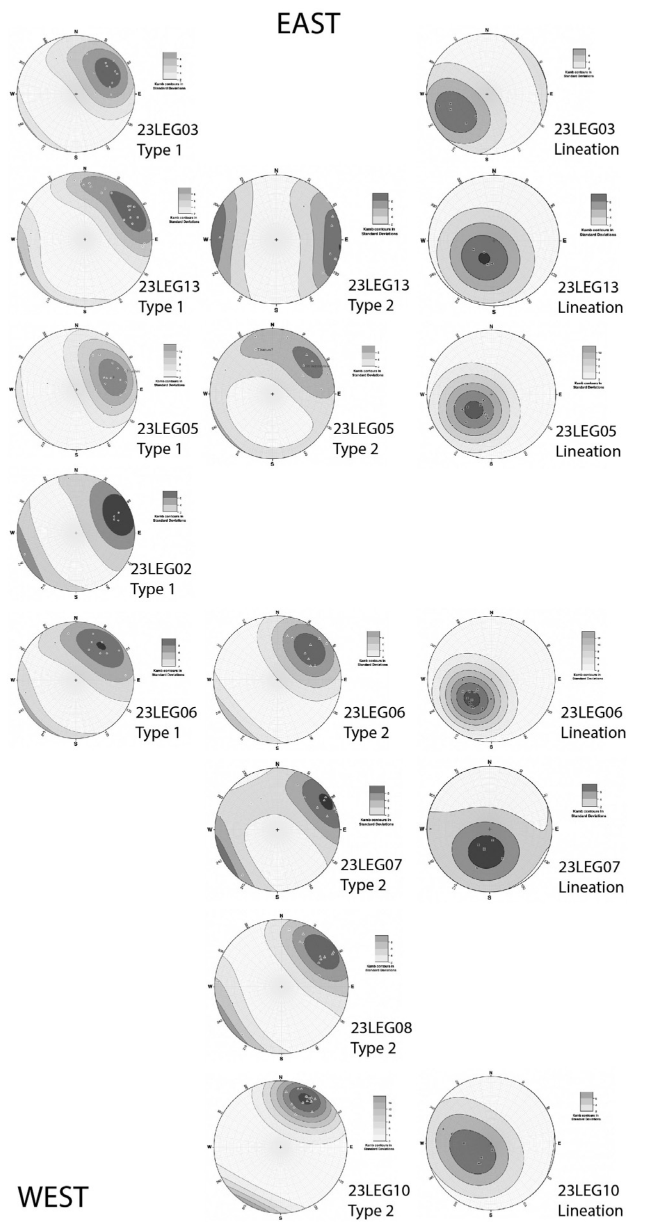

Figure 4. Structural data for notable sites organized from east to west along the transect. Planar data (fabric types 1 and 2) are plotted as poles to the foliation. Kamb contours in standard deviation are associated with the data to aid in visualization.

Table 1. Little Elk Granite Structural data

Station ID	Type 1	Type 2	Dike margin	Stretching Lineation	Fold axis
23LEG01	4	0	0	3	0
23LEG03	16	0	0	5	1
23LEG14	3	1	0	1	0
23LEG13	22	10	0	4	0
23LEG04	1	0	0	0	0
23LEG05	20	12	7	12	0
23LEG02	6	1	4	1	0
23LEG06	12	9	5	13	0
23LEG07	2	12	0	6	5
23LEG08	0	15	3	2	0
23LEG09	0	3	0	1	0
23LEG10	0	16	0	7	0
23LEG15	7	2	0	1	0
23LEG16	7	7	0	0	0

Fig. 2b) did not yield zircon for dating, the common interpretation that aplite dikes form late in the emplacement history of igneous bodies and the high temperature implied by the plastic deformation of feldspar in the type 1 fabric together suggest that the type 1 fabric may have formed during emplacement of the LEG.

Both similarities and difference appear by incorporating the deformation textures with the orientation and kinematic information of each fabric type. Although the orientation of the type 1 fabric is modified by overprinting (Fig. 4), sites that preserve the type 1 fabric commonly display top-down shear sense in asymmetric augen porphyroclasts along a moderately-steeply southwest dipping foliation (Figs 2a, 4). The top-down shear sense is accompanied by a moderately developed stretching lineation that plunges nearly down dip (Fig. 4). The type 2 fabric displays spatially variable development of opposing strike-slip shear sense indicators (Fig. 3a, b, d) combined with a stretching lineation that plunges nearly down dip. Strike-slip shear zones with opposing shear sense and a steeply plunging stretching lineation have been widely documented and are generally thought to form by a combination of pure shear and simple shear deformation in a strain regime called "transpression" (Fossen and Tikoff, 1993).

Incorporating the deformation textures, structural geometries, and kinematic information together yields insight to the deformation history of the LEG and the processes that led to deformation. Interpreting the type 1 high temperature augen gneiss fabric to have formed during emplacement of the LEG implies that emplacement took place in an active tectonic setting. Although there is little/no information to test whether the type 1 fabric is presently in the orientation at which it formed, the current geometric-kinematic information suggests that the fabric formed in an extensional environment. Interestingly, the age of the LEG (2559 ± 6 Ma: McCombs et al., 2004) was closely followed by the breakup of supercontinent Kenorland (Bekker and Eriksson, 2003). Thus, the interpretation of the type 1 fabric forming in an extensional environment is permissible with the present data. The transpressional features displayed by the type 2 fabric have been documented elsewhere in the Black Hills and are interpreted to represent a left-lateral transpression zone called the "Dakota Tectonic Zone" that formed late in the suturing of the Wyoming and Superior cratons along the Trans-Hudson Orogeny (Allard and Portis, 2013). The timing of Dakota Tectonic zone deformation is not well bracketed, but is interpreted to precede, or slightly overlap with emplacement of the Harney Peak granite at ca. 1715 Ma (Redden et al., 1990; Allard and Portis, 2013).

CONCLUSIONS

Through observing shear zones of the LEG, some of the most notable discoveries are the differing fabrics and their foliation and lineation orientations. The LEG contains two fabrics: an older, high temperature augen gneiss fabric (type 1), and a younger low-temperature mylonitic fabric (type 2). The type 2 fabric formed subparallel to the type 1 fabric and locally crosscuts it. Synthesizing kinematic information from each fabric with the regional geologic framework suggests that the type 1 fabric formed in an extensional environment after ca. 2560 Ma and that the type 2 fabric formed in a transpressional environment prior to 1715 Ma.

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