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Constrains on vorticity and non-coaxial shear direction in Neoarchean L-S tectonites, an example from northern Minnesota, USA

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ABSTRACT

We present a detailed kinematic study of seven Neoarchean L-S tectonite samples in order to constrain vorticity and non-coaxial shear direction relative to foliation and elongation lineation. Samples are L-S tectonites from the Wawa Subprovince of the Archean Superior Province, more specifically the Vermilion District of NE Minnesota, a NE-trending belt of greenschist grade supracrustal rocks and granitoid bodies. Supracrustal rocks host multiple L-S tectonite packages with a well-developed sub-vertical metamorphic foliation and elongation lineation; elongation lineation generally plunges steeply to gently, although zones of shallow plunge occur locally. The Wawa Subprovince is widely interpreted as a transpressional plate margin with shear zones recording unidirectional dextral strike-slip, an interpretation held up as fundamental evidence for Archean plate-tectonic processes. However, vorticity and shear direction within Vermilion District L-S tectonites remain unconstrained. We compare data from thin-sections, X-ray computed tomography, and quartz crystallographic fabric analysis to monoclinic shear models to constrain vorticity and better understand the geometric relationships between vorticity, non-coaxial shear direction, foliation, and elongation lineation. Kinematic indicators in thin-section and image slices from X-ray computed tomography consistently record asymmetric microstructural fabrics in foliation-normal/lineation-parallel planes, whereas planes normal to foliation and elongation lineation display dominantly symmetric microstructural fabrics. Mantled porphyroclast 3D-shapes and star-volume distribution analyses indicate that porphyroclast short-axes are normal to foliation and long-axes parallel elongation lineation. Quartz crystallographic preferred orientation data show *a*-axes maxima sub-parallel to foliation-normal/lineation-parallel planes. Kinematic data consistently show a vorticity vector within the foliation plane and normal to elongation lineation; thus non-coaxial shear direction is sub-parallel to elongation lineation. Data are inconsistent with shear models in which non-coaxial shear direction is normal to lineation, or in which the vorticity vector is normal to foliation. Rather, kinematic data indicate that tectonites record non-coaxial shear broadly parallel to elongation lineation regardless of the geographic orientation of lineation.

1. Introduction

There is no consensus about the thermomechanical processes responsible for the assembly of Archean crust. The North American Superior Province is widely interpreted as a series of accreted terranes with subprovinces representing individual terranes (Talbot, 1973; Goodwin and Ridler, 1970; Langford and Morin, 1976; Dimroth et al., 1983a,b; Ludden et al., 1986; Sylvester et al., 1987). The Neoarchean (2.7–2.5 Ga) Wawa Subprovince forms a NE-trending belt of sub-greenschist- to greenschist-facies supracrustal rocks cut by multiple L-S tectonite packages marked by a well-developed metamorphic foliation (Fm) and elongation lineation (Le) (Fig. 1). The Wawa Subprovince has been further interpreted as a transpressional plate-margin recording dextral strike-slip shear (Hudleston et al., 1988; Schultz-Ela and Hudleston, 1991; Jirsa et al., 1992). This interpretation is highlighted as evidence for Archean plate-tectonic processes based on plate-tectonic models that require extensive strike-slip shear zones, with length ≥1200 km (Sleep, 1992). Despite apparent

Abbreviations: Fm, metamorphic foliation; Le, elongation lineation; SLSZ, Shagawa Lake shear zone; KSZ, Kawishiwi shear zone; XRCT, X-ray computed tomography; VNS, vorticity normal section; SVD, star-volume distribution; CPO, crystallographic preferred orientation.

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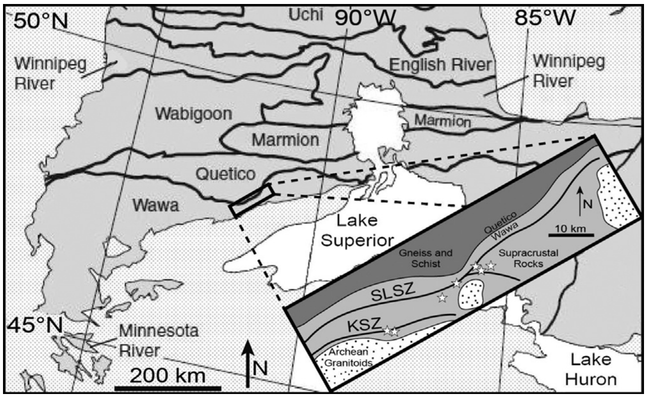

Fig. 1. Selected subprovinces of the Superior Province, including the Wawa Subprovince. Inset: Generalized geologic map of a portion of the Vermilion District showing the location of the Shagawa Lake shear zone (SLSZ) and Kawishiwi shear zone (KSZ) near the boundary of the Wawa and Quetico Subprovinces. Stars mark the locations of samples used in this study. Sample coordinates located in Table 1. Modified from Thurston et al. (2008).

broad acceptance of this interpretation, the nature of L-S tectonite formation within the Wawa Subprovince remains poorly constrained.

Within L-S tectonites, shear direction and magnitude is genetically linked to vorticity, defined by the vorticity-normal-section (VNS) and vorticity vector (pole to VNS) (Truesdell, 1953; Means et al., 1980). However, geometric relationships between shear direction and macroscopic structures, such as Fm and Le, can vary depending on the mechanism governing L-S tectonite formation (Passchier, 1998). Le can occur parallel, perpendicular, or oblique to shear direction during L-S tectonite formation. Therefore, the geometric relationship between the VNS, vorticity vector, Fm, and Le requires careful consideration before interpretation of shear direction. The constrainment of the vorticity vector and characterization of the geometric relations between VNS, Fm, and Le can allow for the use of Fm and Le as an indicator of non-coaxial shear direction during L-S tectonite formation.

In this contribution, we place constraints on the orientation of the VNS and vorticity vector orientations, within a sample-dictated coordinate system, for seven samples of Neoarchean Vermilion District L-S tectonite (Fig. 1). We employed a combination of petrographic microstructural, quartz crystallographic preferred orientation (CPO) data, and 3-D X-ray computed tomography (XRCT) analysis. To our knowledge, this work presents the first quartz CPO analyses (including *c*- and *a*-axes) and the first XRCT analyses of Vermilion District L-S tectonites. These data indicate that the VNS lies within, or close to, the Fm-normal/Le-parallel plane and that the displacement direction is sub-parallel to Le for all seven samples. Regional Le orientation varies within the Wawa Subprovince, ranging from steep to moderate plunge, with rare local zones of shallow plunge (Hudleston, 1976; Hudleston et al., 1988; Bauer and Bidwell, 1990; Jirsa et al., 1992; Goodman, 2008; Erickson, 2008, 2010; Johnson, 2009; Karberg, 2009). We conclude that non-coaxial shear direction is sub-parallel to Le regardless of Le geographic orientation.

2. Background

2.1. Geologic setting

The Vermilion District of NE Minnesota is a NE-trending belt of greenschist-facies metavolcanic and metasedimentary rocks with granitoid bodies scattered throughout (Fig. 1). The Vermilion District includes, from north to south: the Vermilion Granitic Complex, greenschist-facies metavolcanic and metasedimentary sequences, and quartz monzonite of the Giant's Range Batholith (Sims, 1976). Granite, granite-rich and biotite-rich migmatites, biotite and amphibolite schists, metagabbro, metabasalt, and trondhjemite characterize the Vermilion Granitic Complex. Greenschist-facies metavolcanic and metasedimentary sequences, which include protoliths of basalt, diabase, pyroxenite, basalt flows, felsic to intermediate volcanic tuff, felsic volcanic rocks, conglomerate, greywacke, shale, and banded iron formation, are cut by ovoid granitoid bodies (Sims, 1976). Volcanic and plutonic rocks within the Vermilion District range in age from 2.75 to 2.69 Ga and from 2.74 to 2.65 Ga, respectively (Card, 1990 and references therein). To the SE, Proterozoic plutonic rocks intrude the Vermilion District (Gruner, 1941; Jirsa and Miller, 2004).

The Vermilion District volcano-sedimentary sequence hosts several NE-striking subvertical L-S tectonite packages which extend up to ~70 km long and 7–10 km wide, although L-S tectonite boundaries are diffuse. Vermilion District L-S tectonites contain a well-developed anastomosing Fm with an orientation of 065, 90 ± 15 (Bauer and Bidwell, 1990; Erickson, 2008, 2010; Wolf, 2006; Goodman, 2008). Bedding marked by compositional layering commonly parallels Fm. Within the Fm plane is a variably developed Le, marked either by striations or elongated mineral grains. Le orientation varies within and between individual L-S tectonite packages; however, Le pitch ranges from moderate- to high-angle, with rare cases of low-angle pitch (Hudleston, 1976; Hudleston et al., 1988; Bauer and Bidwell, 1990; Jirsa et al., 1992; Goodman, 2008; Erickson, 2008, 2010; Johnson, 2009; Karberg, 2009).

2.2. Vorticity within L-S tectonites

An understanding of sample vorticity is fundamental to understanding of sense of shear and shear direction within naturally occurring L-S tectonites. Kinematic vorticity is mathematically expressed as a vector that has both direction and magnitude, the vorticity vector. This vector describes the internal instantaneous curl component of the flow within the larger velocity gradient tensor that describes the whole deformation (Truesdell, 1953; Means et al., 1980). The vorticity-normal section (VNS) is commonly defined as the plane perpendicular to the vorticity vector. In strict simple shear, the transport direction across the deforming zone is normal to the vorticity vector. In the classic Ramsay and Graham (1970) shear-zone model wherein Fm, Le, and other fabric elements are directly controlled by a simple-shear kinematic framework, the VNS is the Fm-normal, Le-parallel section. Many strain models and some studies of naturally deformed rocks indicate that the vorticity vector may not be directly related to any fabric elements in more complex (triclinic) kinematic geometries (Lin et al., 1998; Jones and Holdsworth, 1998; Iacopini et al., 2007; Forte and Bailey, 2007; Fernández and Díaz-Azpiroz, 2009). No strict criteria exists to distinguish monoclinic from triclinic shear zones (Jiang and Williams, 1998; Passchier and Coelho, 2006). However, it is commonly assumed that the VNS is the plane containing the maximum fabric asymmetry visible in a sample. A number of studies have used this assumption to infer the orientation of the vorticity vector (e.g., Passchier, 1987; Sullivan and Law, 2007; Sullivan et al., 2011). In this contribution we make the assumption that the plane containing the maximum asymmetric fabric is the VNS. Therefore, identification of the VNS should define shear direction relative to Fm and Le. It is not the goal of this study to define the vorticity vector, but rather to place constraints on the orientation of this vector, and to place constraints on the non-coaxial shear direction relative to Fm and Le. In short, given that we are studying a natural shear zone system with complex flow given the range of composition, grain size, and functional rheology of clasts and matrix (to say nothing of the type of shear) we are attempting