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L tectonites

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ABSTRACT

Rocks with a pure linear fabric, or L tectonites, often indicate nearly perfect constrictional deformation. This paper assimilates published data, models, and interpretations to understand the forcing mechanisms that can form L tectonites. Most noncoaxial kinematic geometries that can result in constrictional deformation involve vorticity-parallel shortening. Local variations in external boundary conditions that localize components of constriction include releasing and restraining bends in shear zones, linear channels in shear zone boundaries, intersections between shear zones, and foliation triple points between ballooning diapirs. Internally, L tectonites are often localized in fold hinge zones, and rheologic variations partition constriction into discrete domains.

The most common external kinematic framework that can form L tectonites involves simultaneous transport-perpendicular shortening in two directions. Hence, large domains of L>S and L tectonites are a common feature of orogen-parallel elongation. In every case, external variations in boundary conditions and/or internal variations in structural setting and rheology localize constriction to form L tectonites. External boundary conditions are important in density-driven vertical tectonics. Elsewhere, internal variations in structural setting and rheology are more important. The most common are the formation of L tectonites in fold hinge zones and in compositionally homogeneous rocks while heterogeneous rocks accommodate constriction by folding.

1. Introduction

Deviation from plane strain is not only common in nature, it is probably the norm (Pfiffner and Ramsay, 1982, their Fig. A1). This is especially true in the middle and lower crust where complex ductile deformation zones can simultaneously accommodate many different deformation components. Unfortunately, reliable finite strain markers are exceedingly rare in nature. Therefore, geologists in the field wishing to evaluate three-dimensional deformation are often forced to make assumptions about finite strain geometry based on the shape fabrics visible in ductiley deformed rocks. Rocks with strong foliations and no visible lineations, or S tectonites, indicate flattening strain; rocks with both strong foliations and mineral lineations, or L-S tectonites, indicate near-plane strain; and rocks exhibiting strong linear alignments of minerals with no visible foliations (Fig. 1), or L tectonites, indicate constrictional strain (Flinn, 1965). Of these cases, constrictional deformation is by far the least common (Pfiffner and Ramsay, 1982, their Fig. A1). Nevertheless, constrictional or nearly constrictional deformation is an important feature at many active and ancient plate boundaries, and significant domains of L tectonites occur in a wide range of geologic settings at all scales. These include but are not limited to the hinge zones of folds (e.g., Holst and Fossen, 1987; Sylvester and Janecky, 1988; Poli and Oliver, 2001; Solar and Brown, 2001; Sullivan, 2006); contractional, extensional, and transcurrent ductile shear zones (e.g., Hossack, 1968; Chapman et al., 1979; Flinn 1992; Fossen, 1993; Fletcher and Bartley, 1994; Lin and Jiang, 2001; Sullivan, 2009); areas of density-driven vertical tectonics (e.g., Balk, 1949; Hoy et al., 1962; Bouhallier et al., 1995); zones of tectonic extrusion around rigid indenters (e.g., Dias and Ribeiro, 1994; Piazolo et al., 2004); zones of subhorizontal lower-crustal flow in large orogenic belts (Poli and Oliver, 2001; Duclaux et al., 2007; Dumond et al., 2010); and ultra-high-pressure terranes (Zulauf, 1997; Kurz et al., 2004). Extensive domains of L>S and L tectonites are also predicted by numerical simulations of transtension zones (Dewey et al., 1998; Fossen and Tikoff, 1998; Jiang and Williams, 1998) and may be a common feature of transtension in the lower crust (Dewey, 2002).

L tectonites are typically found in close spatial association with more common L-S tectonites and even S tectonites (e.g., Hossack, 1968; Holst and Fossen, 1987; Piazolo et al., 2004; Sullivan, 2006, 2009). These spatial variations between L, L-S, and S tectonites might provide significant information about the way strain is partitioned in the middle and lower crust, but this strain phenomenon has commonly been overlooked in the literature. Indeed, many

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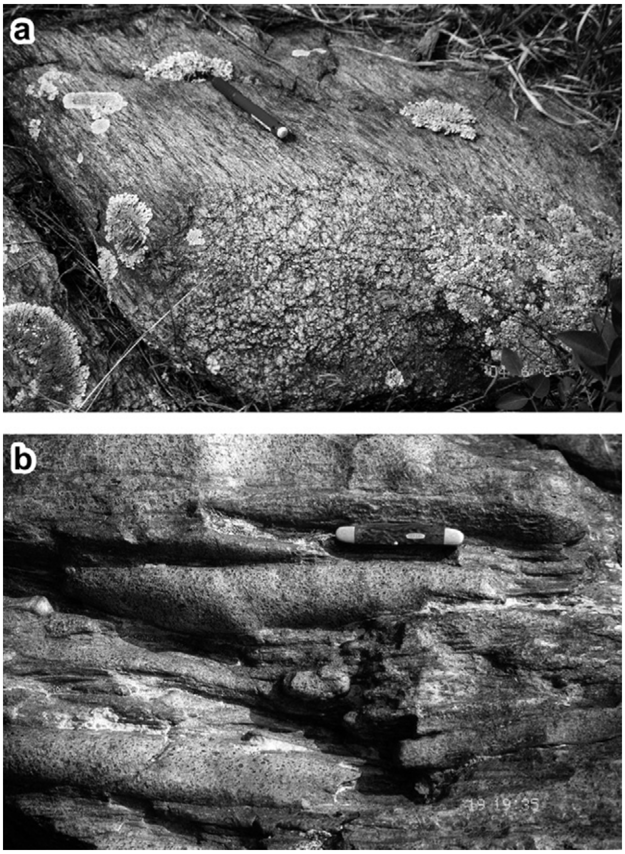

Fig. 1. Photographs of L tectonites: (a) L tectonite of the Boy Scout Camp Granodiorite from the Laramie Mountains, Wyoming, reproduced from Sullivan (2006). Pencil is parallel with the penetrative lineation. (b) Prolate clast in a deformed tuff-breccia from the Pigeon Point high-strain zone, southern Klamath Mountains, California (reproduced from Sullivan, 2009). The average dimensions of the long, intermediate, and short axes of clasts measured in this outcrop are 34.2 cm, 4.5 cm, and 3.6 cm, respectively. Pocket knife for scale is 9.8 cm long.

studies of areas with large domains of L tectonites fail to even mention them. This paucity of knowledge concerning the nature and significance of L tectonites exists, in part, because understanding the formation of L tectonites is a difficult problem requiring detailed mapping and three-dimensional structural analyses of areas that have often undergone complicated, polyphase deformational histories. Finally, the existing framework of knowledge concerning the formation of L tectonites is very limited. Therefore, this article aims to accomplish three things. First, it will outline some criteria for distinguishing L tectonites formed during a single phase of true constrictional deformation from those formed by overprinting fabric elements or other processes. Second, the bulk of the paper combines case studies of ductile deformation zones that contain L tectonites with observations of numerical, theoretical, and analogue models that predict constriction to highlight some of the mechanisms that can form L tectonites during a single progressive deformation event. Finally, a series of case studies are used to assess the relative importance of different forcing mechanisms that can lead to the formation of L tectonites. The assembled results and conclusions presented in this article provide geologists with a starting point for recognizing and interpreting large domains of constrictional strain in ductiley deformed rocks. Additionally, assessing the mechanisms that localize constriction provides a better understanding of the relative importance of the different forcing mechanisms that drive strain partitioning in all kinds of ductile deformation zones.

2. Recognizing L tectonites formed by constriction

2.1. Introduction

A variety of processes can lead to the formation of strong linear fabrics. Overprinting deformation phases can form prolate strain markers by superimposing deformations with different maximum shortening directions (Ramsay, 1967). Similarly, overprinting of nearly orthogonal planar fabrics can result in strong, penetrative intersection lineations commonly called pencil cleavage (Cloos, 1946; Crook, 1964). Therefore, it is often necessary to establish the existence of true constrictional deformation — even in rocks with suitable finite strain markers. Fortunately, true constrictional deformation normally produces unique microstructural features and distinct crystallographic fabric patterns that can be used to distinguish L tectonites formed by a single phase of constrictional deformation from other L tectonite fabrics.

2.2. Mineral shape fabrics

A suite of unique microstructural features commonly develop during constrictional or nearly constrictional deformation. The deformation fabric in constrictional L tectonites viewed on lineation-parallel faces closely resembles that seen in foliation-perpendicular faces of L-S and even S tectonites (Fletcher and Bartley, 1994; Sullivan, 2006, 2009; Sullivan and Beane, 2010). Long axes of mineral grains with anisotropic shapes are aligned, porphyroblasts and porphyroclasts commonly exhibit preferred alignments, dynamically recrystallized mineral aggregates exhibit shape-preferred orientations, and compositional banding and dissolution/precipitation features are parallel with grain-shape alignments. However, lineation-normal faces of constrictional L tectonites exhibit a unique set of microstructural features that can be used to infer true constrictional deformation. The long axes of porphyroblasts and porphyroclasts will show no shape-preferred orientation (Fletcher and Bartley, 1994; Solar and Brown, 2001; Sullivan, 2009). Individual minerals with strongly anisotropic shapes such as amphiboles or pyroxenes will be oriented such that basal sections are commonly presented on lineation-normal faces, but the intermediate axes of these minerals will show little or no preferred orientation (Sullivan, 2006, 2009). Basal cleavage traces of micas will be randomly oriented when viewed in lineation-normal sections, but the ⟨001⟩ directions will consistently be subperpendicular to the lineations (Ramsay and Huber, 1983; Fletcher and Bartley, 1994; Sullivan, 2006; Sullivan and Beane, 2010). In L tectonites that display compositional segregation, quartzo-feldspathic domains may be encircled and separated by micaceous domains (Sullivan, 2009; Sullivan and Beane, 2010). Similarly, in L tectonites where fluid-assisted diffusive mass transfer was an important deformation mechanism, porphyroclasts viewed on lineation-normal faces will commonly be completely rimmed by seams of insoluble minerals (Sullivan, 2009). If present, shear bands or micro-shears will be anastomosing and randomly oriented about the lineations (Fletcher and Bartley, 1994). Finally, dynamically recrystallized aggregates in L tectonites will generally not exhibit grain-shape-preferred orientations on lineation-normal faces despite displaying abundant evidence for lattice deformation and dynamic recrystallization including undulose extinction, subgrain development, sutured grain boundaries, and the nucleation of neoblasts (Fletcher and Bartley, 1994; Sullivan, 2006, 2009; Sullivan and Beane, 2010).

2.3. Crystallographic fabrics

Quartz is one of the most well understood minerals in terms of the crystallographic fabrics that develop during ductile