Journal of Structural Geology 101 (2017) 109–123

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Pulverized granite at the brittle-ductile transition: An example from the Kellyland fault zone, eastern Maine, U.S.A.

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ARTICLE INFO

Article history:
Received 22 February 2017
Received in revised form
12 June 2017
Accepted 4 July 2017
Available online 5 July 2017

Keywords:
Pulverization
Pulverized rock
Damage zone
Brittle-ductile transition

ABSTRACT

Granite from a 50–200-m-wide damage zone adjacent to the brittle-ductile Kellyland Fault Zone contains healed fracture networks that exhibit almost all of the characteristics of dynamically pulverized rocks. Fracture networks exhibit only weak preferred orientations, are mutually cross-cutting, separate jigsaw-like interlocking fragments, and are associated with recrystallized areas likely derived from pervasively comminuted material. Fracture networks in samples with primary igneous grain shapes further indicate pulverization. Minimum fracture densities in microcline are ~100 mm/mm^2. Larger fractures in microcline and quartz are sometimes marked by neoblasts, but most fractures are optically continuous with host grains and only visible in cathodoluminescence images. Fractures in plagioclase are crystallographically controlled and typically biotite filled. Petrologic observations and cross-cutting relationships between brittle structures and mylonitic rocks show that fracturing occurred at temperatures of 400 °C or more and pressures of 200 MPa. These constraints extend the known range of pulverization to much higher temperature and pressure conditions than previously thought possible. The mutually cross-cutting healed fractures also provide the first record of repeated damage in pulverized rocks. Furthermore, pulverization must have had a significant but transient effect on wall-rock porosity, and biotite-filled fracture networks in plagioclase form weak zones that could accommodate future strain localization.

1. Introduction

The high frequency of earthquakes along modern fault zones indicates that seismogenic fault rocks should be ubiquitous in exhumed ancient faults. However, at our present level of understanding, demonstrably seismogenic fault rocks appear rather rare. The apparent paucity of seismogenic fault rocks is in part due to overprinting and recrystallization of seismogenic rocks (e.g., Passchier, 1982; Price et al., 2012; Kirkpatrick and Rowe, 2013). However, we also have historically overlooked and/or misinterpreted many fault rocks and fault structures that are likely seismogenic (see recent review in Rowe and Griffith, 2015). For example, recent mapping has identified 100–400-m-wide zones of dynamically pulverized rocks—damage-zone rocks that exhibit intense fracturing and grain-size reduction yet record no appreciable shear offset—adjacent to several large, active strike-slip fault zones, including the San Andreas Fault, the Garlock Fault, and the Arima-Takatsuki Tectonic Line (e.g., Dor et al., 2006a, 2006b, 2008, 2009; Rockwell et al., 2009; Mitchell et al., 2011).

Theoretical considerations (Reches and Dewers, 2005), rock-deformation experiments (e.g., Doan and Gary, 2009; Yuan et al., 2011; Doan and d'Hour, 2012; Aben et al., 2016), and analyses of grain-size distributions (Wilson et al., 2005; Muto et al., 2015) are all consistent with a seismogenic origin for pulverized rock. However, the exact seismic mechanism or mechanisms leading to pulverization remain equivocal (see recent review in Xu and Ben-Zion, 2017). Pulverized rocks recognized along modern fault zones exhibit little or no healing, and they commonly grade into fault cores dominated by incohesive gouge (Wilson et al., 2005; Dor et al., 2006a, 2009; Rockwell et al., 2009; Mitchell et al., 2011; Wechsler et al., 2011; Rempe et al., 2013; Muto et al., 2015). Additionally, very high-strain-rate axial compression experiments using the split Hopkinson pressure-bar apparatus fail to produce pulverization at realistic strain rates above 20 MPa confining pressures and fail to produce pulverization at any strain rate above 60 MPa (Yuan et al., 2011). These observations have led to some speculation

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http://dx.doi.org/10.1016/j.jsg.2017.07.002
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that pulverization is only possible at very low confining pressures in the upper 2–4 km of the earthquake source region (e.g., Dor et al., 2006a; Yuan et al., 2011; Fonderiest et al., 2015). Hence, constraining the maximum depth of pulverization is a critical factor in determining what seismic mechanisms may drive the process. Currently, the two most widely invoked mechanisms are rapid tensile loading on the high-seismic-velocity sides of bi-material ruptures (e.g. Ben-Zion and Shi, 2005; Dor et al., 2006a; Xu and Ben-Zion, 2017), and passing Mach fronts from super-shear ruptures (e.g. Doan and Gary, 2009; Yuan et al., 2011). Incipient pulverization textures formed at confining pressures at or below the tensile strength of quartz indicate that rapid compressional loading is also an important mechanism under at least some conditions (Wheарty et al., 2017).

To date, pulverized rocks have been documented only along one ancient fault zone that was exhumed from less than 2 km depth (Fonderiest et al., 2015), and the potential for long-term preservation of pulverized rock is unknown. However, recognizing pulverized rocks in damage zones of ancient faults would help demonstrate seismogenic slip, and combining this paleoseismic fingerprint with careful study of adjacent fault cores could improve our understanding of the cryptic record of earthquakes in exhumed fault zones.

In this contribution we document damage-zone microstructures in granite adjacent to a bi-material interface in the Paleozoic brittle-ductile Kellyland fault zone (KFZ). Preservation of pulverization textures in the damage zone of the KFZ is significant because it: (a) extends the known range of pulverization to much higher temperatures and higher confining pressures, thereby providing some important constraints on the mechanism or mechanisms causing pulverization, and (b) shows that dynamic pulverization textures can be preserved in ancient inactive shear zones, despite complete healing in almost all grains.

2. Geologic setting

The KFZ is one of three strands of the Norumbega fault system in eastern Maine (Fig. 1). Like the San Andreas fault system, the Norumbega system formed parallel with a long-lived active margin (e.g., Hatcher, 2010), cuts many arc- and oceanic-affinity accreted terranes as well as plutonic rocks (e.g., Robinson et al., 1998; Ludman and West, 1999; Hibbard et al., 2006), and offsets the seismic Moho (Costain et al., 1990; Doll et al., 1996). Regional mapping and palenspastic reconstructions indicate that the KFZ accommodated at least 25 km of dextral strike-slip motion (Wang and Ludman, 2004). In the area of this study, the KFZ forms a bi-material interface juxtaposing chlorite-grade metasedimentary rocks of the Flume Ridge Formation with the ca. 384-Ma Deblois granite pluton (Fig. 1) (Wang and Ludman, 2004; Wang, 2007). The Deblois pluton has a 0.5–1-km-wide contact areole (Ludman et al., 2000; Riley, 2004), and U-Pb-crystallization- and biotite-^{40}Ar/^{39}Ar-cooling ages of granite collected near the study area are within error of each other (Idleman and Ludman, 1998; Ludman et al., 1999, 2000), indicating rapid cooling and shallow emplacement.

Sullivan et al. (2013) recognized three strain facies in the KFZ cutting the Deblois granite. From southeast to northwest these are: (1) a 2–3-km-wide belt of variably foliated to undeformed granite called the foliated-granite domain, (2) a 100–300-m-wide belt of foliated-granite cut by numerous small shear zones called the localized-shear-zone domain, and (3) a 200–400-m-wide belt of ultramylonite and minor mylonite derived from granite called the main-ultramylonite domain (Fig. 1B). Bulk composition does not change between undeformed granite, foliated-granite, and granite-derived ultramylonite (Sullivan et al., 2013).

Undeformed Deblois granite is texturally uniform and megacrystic to pegmatitic. It contains perthitic microcline + quartz + oligoclase + biotite + hornblende; rapakivi overgrowths of plagioclase on microcline are common (Riley, 2004; Wang, 2007). The foliated-granite domain is marked by aligned feldspar megacrysts and weakly elongated quartz and biotite grains, but many areas of this domain do not exhibit foliation. Quartz in this domain underwent fast grain-boundary-migration recrystallization and often preserves chessboard-style subgrains indicating high-temperature deformation (>600 °C; Kruhl, 1996; Stipp et al., 2002; Sullivan et al., 2013).

The localized-shear-zone domain consists of foliated-granite cut by numerous, discrete, 2-mm- to 1.5-m-wide steeply dipping mylonite and ultramylonite zones (Fig. 2A). Most shear zones are bounded by at least one discrete fracture surface. These boundaries truncate wall-rock foliations and individual mineral grains. Both synthetic and antithetic discrete brittle fractures also cut the foliated granite, and many antithetic fractures root into localized shear zones where they exhibit synthetic drag (Sullivan et al., 2013). Localized shear zones where foliation planes are cut by brittle fractures have not been documented, but foliation in localized shear zones sometimes bends around offset shear-zone boundaries. Sharp shear-zone boundaries locally transition into discrete fractures. Probable recrystallized and deformed pseudotachylyte veins are preserved in some localized shear zones (Sullivan et al., 2013). The ubiquitous association of shear zones with fractures, the presence of recrystallized and deformed brittle fault rocks, and the composition and textures of mylonites and ultramylonites described by Sullivan et al. (2013) indicate that ductile deformation in the localized shear zones was catalyzed by grain-size reduction and mechanical mixing during brittle faulting. The localized-shear-zone domain grades into the main-ultramylonite domain over 2–10 m (Fig. 1B). Granite-derived ultramylonite does not contain brittle fractures like those observed in the localized-shear-zone domain.

3. Criteria for identifying pulverized rocks

Samples of pulverized crystalline rock collected adjacent to modern fault zones exhibit a characteristic suite of microstructural features that may be used to recognize ancient pulverized rocks. These are: (a) primary grain shapes are preserved despite pervasive fracturing; (b) dilational, opening-mode fractures are common; (c) primary quartz and feldspar grains host zones of intensely comminuted material; (d) fracture sets have little or no preferred orientation and form jigsaw-like interlocking fragments; (e) fractures typically do not offset primary structures; and (f) there is little or no rotation of fragments across most fractures (c.f. Mitchell et al., 2011; Wechsler et al., 2011; Rempe et al., 2013). These textures are typically gradational with gouge and cataclasite in the fault core and intact rock outside of the damage zone (Dor et al., 2006a, 2006b; Rockwell et al., 2009; Mitchell et al., 2011; Wechsler et al., 2011; Rempe et al., 2013). Both experiments and observations of natural fault rocks indicate that healing of fractures is rapid at temperatures typical of the brittle-ductile transition with smaller fractures often healed in crystallographic continuity with their host grains (e.g., Küster et al., 2001; Trepmann et al., 2007; Anders et al., 2014; Bestmann et al., 2016). Thus, repeated seismogenic pulverization at elevated temperatures should produce multiple generations of opening-mode fractures that cut healed fractures from earlier events.

Cataclasites, dynamic dilational breccias, and implosion breccias are also associated with intense fracturing and grain-size reduction in or adjacent to large brittle-ductile fault zones. However, each of these fault rocks can be distinguished from end-member dynamically pulverized rock. Cataclasites exhibit offset and rotation of