Journal of Structural Geology 56 (2013) 118–128

Contents lists available at ScienceDirect

Journal of Structural Geology

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

Block-supported cataclastic flow within the upper crust

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A R T I C L E I N F O

Article history:
Received 27 March 2013
Received in revised form
13 August 2013
Accepted 27 August 2013
Available online 9 September 2013

Keywords:
Cataclastic flow
Ductile
Elastico-frictional
Fracturing
Canyon range

A B S T R A C T

Recent work from portions of the Sevier fold-thrust belt that have deformed primarily within the elastico-frictional regime, demonstrates that cataclastic flow can be subdivided into two types: matrix- and block supported. The two types may operate simultaneously within the same deforming material. However, their activity can vary spatially, temporally and across scales. Although block-supported cataclastic flow is a critical process in upper crustal deformation, it continues to be largely ignored and/or misunderstood, primarily because established concepts and definitions for cataclastic flow are chiefly based on matrix-supported cataclastic flow. Here, block-supported cataclastic flow is examined to better understand cataclastic flow in general and to explore its relationship with matrix-supported cataclastic flow.

1. Introduction

In any orogenic belt, a significant amount of deformation takes place within the upper ~10–15 km of the Earth's crust. This region deforms primarily through elastico-frictional processes (Sibson, 1977). Recent work has shown that the amount of work required for orogenic belt deformation (e.g. thrust sheet emplacement, folding) within the elastico-frictional regime is comparable to the amount of work required to form similar structures of similar size and average emplacement rate by crystal-plastic deformation mechanisms at greater depths, i.e. within the quasi-plastic regime (Elliott, 1976; Masek and Duncan, 1998; Ismat and Mitra, 2005a).

Cataclasis involves pervasive fragmentation of a material through penetrative fracturing (Engelder, 1974; Sibson, 1977; Paterson, 1978; Evans et al., 1990; Hirth and Tullis, 1994; Blenkinsop, 2000; Rawling and Goodwin, 2003). Cataclastic *flow* takes place once the fragmented blocks/clasts begin to frictionally slide, and possibly rotate, past one another (Engelder, 1974; Sibson, 1977; Paterson, 1978; Tullis and Yund, 1987; Babaie et al., 1991; Cladouhos, 1999a). Cataclasis is a process that commonly occurs within fault zones in the upper crust, and is typically observed at the microscale.

Deformation in the upper crust can also involve centimeter to kilometer scale folding, which can be accomplished by frictional sliding along a distributed set of faults (e.g. Marshak et al., 1982; Laubach, 1988). These folds are macroscopically ductile structures that are contemporaneous with, and formed at the same pressure-temperature conditions, as the faults. Our previous work (Ismat and Mitra, 2001a, 2005a,b; Ismat and Benford, 2007; Ismat, 2012) demonstrates that folds can form through cataclastic flow, and the faults that accommodate the flow are centimeter-scale (mesoscopic) structures, with spacings of centimeters to tens of centimeters. These fault sets define mesoscale fault-bounded blocks that slide past each other during cataclastic flow. This type of cataclastic flow is referred to here as *block-supported* cataclastic flow. The purpose of this paper is to document the evolution of block-supported cataclastic flow and explore its relationship with fault-zone (or *matrix-supported*) cataclasis, evidence of which is commonly observed at the micrometer to centimeter scale.

Block-supported cataclastic flow is often overlooked for several reasons. First, outcrop (meso)-scale fracture sets may appear to be randomly oriented. Because of this appearance, it is assumed that strain cannot be measured and so the fracture sets are ignored. But fracture sets accommodating block-supported cataclastic flow do have patterns and the cataclastic strain can be measured from net-slip markers and/or bed thickness changes (Wojtal, 1989; Ismat and Mitra, 2001a). Second, as rocks are carried to the surface, structures formed by elastico-frictional mechanisms overprint older, high temperature plastic deformation features. It is sometimes assumed that this elastico-frictional overprinting is minor compared to the strain accommodated by crystal-plastic deformation mechanisms, such as dislocation creep (e.g. Elliott, 1976). Third, evidence for cataclastic flow is seldom preserved in older orogenic belts as upper crustal rocks are generally removed by erosion. In addition, the eroded clasts making up synorogenic sediments are typically smaller than the outcrop-scale fault-bounded blocks found within the source thrust sheet, so that evidence for block-supported

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http://dx.doi.org/10.1016/j.jsg.2013.08.010

cataclastic flow is rarely preserved within those eroded sediments (Borg et al., 1960; Stearns, 1971; Borradaile, 1981; Ismat and Mitra, 2005a). In select circumstances, where thrust sheets are shielded from erosion by a layer of synorogenic sediments, evidence for cataclastic flow can be preserved in older orogenic belts (Royse, 1993; Ismat and Mitra, 2005a).

This paper uses a natural example from the Cordilleran orogen to re-examine cataclastic flow at a range of scales by addressing the following questions: (1) What geometric constraints need to be satisfied for cataclastic flow to occur? (2) What is the interplay between rocks that deform by block-supported cataclastic flow and those that deform by fault-zone cataclastic flow? (3) Should the distributed deformation by cataclastic flow be classified as ductile, brittle, both or neither?

2. Matrix- and block-supported cataclastic flow

Cataclastic flow can be sub-divided into two types, *matrix*- and *block-supported* (Fig. 1a–f) (Ismat and Mitra, 2001a, 2005b). Evidence of matrix-supported (or, 'fault-zone') cataclastic flow is generally what people think of in association with the term. (Fig. 1a,b) (e.g. Engelder, 1974; Tullis and Yund, 1987). Evidence for block-supported cataclastic flow, in contrast, is typically observed at the outcrop scale (Fig. 1d,e), and has been described in association with centimeter to kilometer scale folds formed in the elastico-frictional regime (Droxler and Schaer, 1979; Laubscher, 1979; Friedman et al., 1980; Hadizadeh and Rutter, 1983; Laubach, 1988; Ismat and Mitra, 2005b). Consequently, descriptions of block-supported cataclastic flow are typically at the mesoscale. Matrix- and block-supported cataclastic flow, however, may operate in concert to accommodate deformation (Fig. 1a–f) (Ismat and Mitra, 2001a, Ismat, 2006).

Block or clast size progressively decreases by frictional wear and continued fracturing during deformation by matrix-supported cataclastic flow. Once clasts reach a size of ~<30 μm^2 for quartzites, they cease fracturing and form a fine-grained matrix (Fig. 1a–c) (Hall, 1951; Mitra, 1984; Means, 1990; Benford, 2005). Clasts that are surrounded by this matrix are not constrained by adjacent clasts and thus, can undergo large displacements and rotate independently via granular flow and frictional sliding, and may even become aligned to form foliations (Chester et al., 1985; Rutter, 1986; Marone et al., 1990; Babaie et al., 1991; Cowan et al., 2003; Hayman et al., 2004). Although multiple foliations may be present in cataclasites, the most prominent is often the P-foliation, which is defined by shear bands and the shape preferred orientation (SPO) of clasts (Fig. 1c). Reidel shears (R_1 and R_2) likely facilitate flow in foliated cataclasites (Fig. 1c) (Chester and Logan, 1987; Marone and Scholz, 1989; Babaie et al., 1991; Logan et al., 1992; Cowan and Brandon, 1994; Cladouhos, 1999a, 1999b; Mair et al., 2002; Collettini et al., 2009).

As the name implies, in block-supported cataclastic flow, the blocks/clasts are not supported by matrix. Microscale matrix-supported cataclasite zones are, however, found along some of the fractures bounding the blocks, but compose <2% of the total rock volume (Ismat and Mitra, 2001a, 2005a). Thus, fault-bounded blocks (ranging in size from cm^2 to 10 s cm^2) are in contact and move only by frictional sliding past one another (Fig. 1e). Although blocks cannot independently rotate or move large distances in block-supported cataclastic flow, small amounts of slip on a large number of faults can accommodate significant strain (Fig. 2) (Droxler and Schaer, 1979; Friedman et al., 1980; Marshak et al., 1982; Hadizadeh and Rutter, 1983; Wojtal, 1989; Ismat and Mitra, 2001a). Because the blocks do not independently rotate, sliding does not disrupt the fault network pattern; therefore, the fault sets are well preserved (Fig. 2). Cataclastic flow generally takes places at conditions lower than greenschist facies conditions; as a result, the different generations of faults making up each stable network are preserved and can be delineated via cross-cutting relationships. Therefore, the fracture sets that accommodate cataclastic flow are

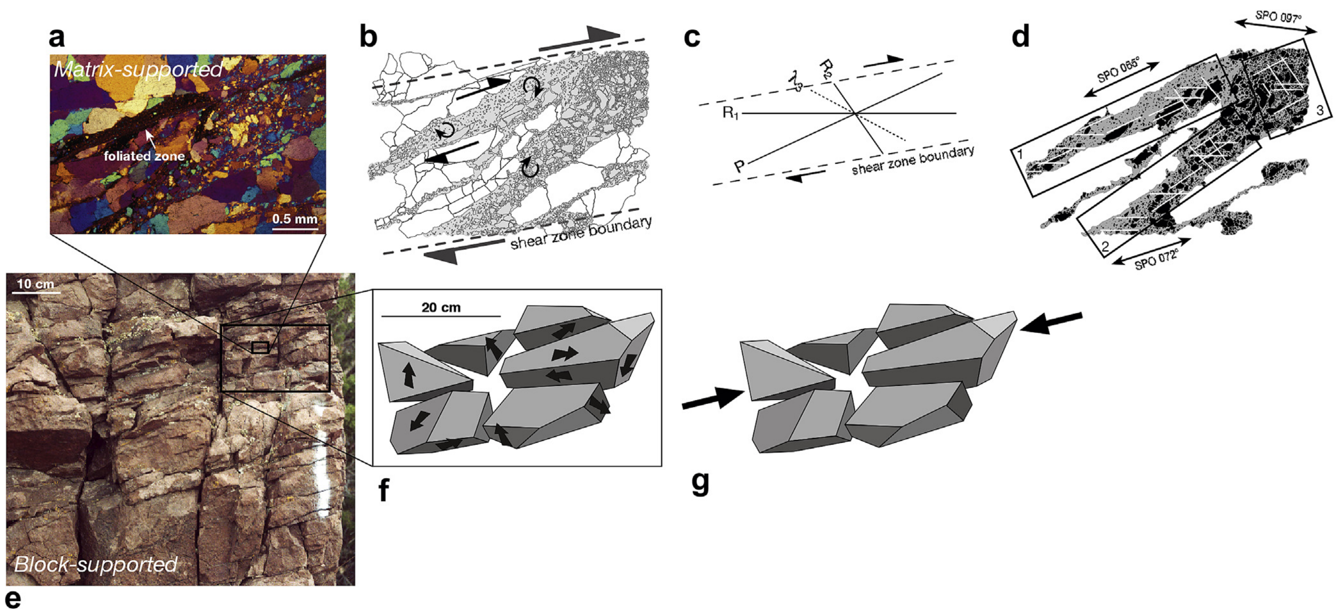

Fig. 1. (a) Photomicrograph illustrating matrix-supported cataclasite. Arrow points to localized foliated zone. (b) Sketch of photomicrograph. Shear zone boundaries and sense of shear, for the entire photomicrograph, illustrated with dashed gray lines and gray half arrows, respectively. Within the photomicrograph, the sense of shear for a smaller shear zone is identified with small, black half arrows. Circle arrows show directions of clast rotation. (c) Geometrical relationship of Riedel shears (R_1 and R_2) and P-foliation preserved in the entire photomicrograph. Inferred maximum shortening direction (λ_3), i.e. the bisector of R_1 and R_2, is shown as a dashed line. (d) Photomicrograph sketch is sub-divided into three regions, based on percent matrix. Double-headed arrows show SPO for each region. White lines within each region show locations and orientations of Riedel shears and P-foliation. (e) Outcrop photo of block-supported cataclasitic quartzites (looking north) from site 6 (see Fig. 4 for site location). (f) Representative fault-bounded blocks. Black arrows show slip directions determined from slickenlines preserved on fault surfaces. (g) Representative mesoscale fault-bounded blocks. Arrows show the average orientation of the long axis of the fault-bounded blocks.