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Micromechanisms of shear zone propagation at the brittle–viscous transition

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ABSTRACT

Our investigation of progressively strained rock samples from the margins of greenschist-facies shear zones utilizes a space-for-time approach to reveal how the mylonitic overprint of metapsammitic and -pelitic host rocks at the Cap de Creus involved brittle fracturing. We present a set of microscale observations indicating that microfractures formed immediately prior to or coevally with a fine-grained mylonite. Microfracturing dominated early stages of strain localization on the scale of the shear zones. On the microscale, centimeter-long fractures facilitated strain softening by allowing enhanced fluid access, thereby accelerating the dynamic recrystallization of quartz and a metamorphic reaction of biotite. As these two processes produce a polyphase matrix of small, dislocation-poor grains that eventually form an interconnected, rheologically weak phase, fractures become inactive. This represents a strain-dependent brittle–viscous transition. We outline this transition in a conceptual model for the rheological evolution of mid-crustal shear zones.

1. Introduction

Heterogeneous deformation at greenschist-facies metamorphic conditions involves the formation of shear zones in which a mechanically weaker foliated rock, a mylonite, is formed (e.g., Ramsay, 1980; Means, 1984, 1995; Hull, 1988). Where this happens, a strain gradient across shear zones can be used to reconstruct the evolution of a mylonite in time (Hull, 1988; Mitra, 1984; Means, 1995). This assumption, that space can be used as a proxy for time, was applied by several authors to investigate the evolution of brittle and ductile shear zones (e.g., Mitra, 1979, 1984; Means, 1984; Ingles, 1986; Watterson, 1986; Hull, 1988; Carreras, 2001; Fusseis et al., 2006). The space-for-time assumption also reflects on the way strain gradients can be interpreted in terms of the rheological history of shear zones. Means (1984) classified shear zones based on their softening/hardening evolution. He distinguished Type 1 shear zones that harden with time and therefore widen as it gets easier to deform host rock than to keep on deforming the mylonite, from Type 2 shear zones that soften and progressively reduce their actively deforming width. The space-for-time proxy is only valid for Type 2 shear zones.

The space-for-time proxy is perfectly applicable to shear zone terminations where new host rock is continuously strained during shear zone propagation. Consequently, such terminations have been studied to understand strain localization in greenschist-facies mylonitic[1] shear zones (e.g., Ramsay and Allison, 1979; Simpson, 1983; Segall and Pollard, 1983; Segall and Simpson, 1986; Buergmann and Pollard, 1992; Tourigny and Tremblay, 1997; Guermani and Pennacchioni, 1998; Pennacchioni, 2005; Mancktelow and Pennacchioni, 2005). With a few exceptions, most of these authors describe fractures at the tips of the mylonitic shear zones with orientations that usually are parallel to the shearing plane. Due to their close proximity to the shear zone tips, such fractures were generally interpreted to have influenced the formation of the shear zones.

The timing of fracture formation with respect to mylonitic shearing differs in most authors' interpretations. For example, Segall and Simpson (1986) interpret fractures in their model to be reactivated remnants of earlier deformation phases. In contrast, Mancktelow and Pennacchioni (2005) argue that localized fracturing might have been immediately precursory to ductile strain localization. The significance of the time span between fracture formation and mylonitic shearing becomes clear when the micromechanisms of strain localization are to be reconstructed. While earlier, reactivated fractures and veins represent mechanical heterogeneities that concentrate stress and thus focus mylonitic overprint, fracturing as an integral part of mylonitic shear zone formation involves some sort of a microscale brittle-to-viscous transition. Few studies investigated the microstructural evolution of this transition in great

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[1] Mylonitic deformation is accommodated by thermally activated, viscous creep mechanisms (Schmid and Handy, 1991).

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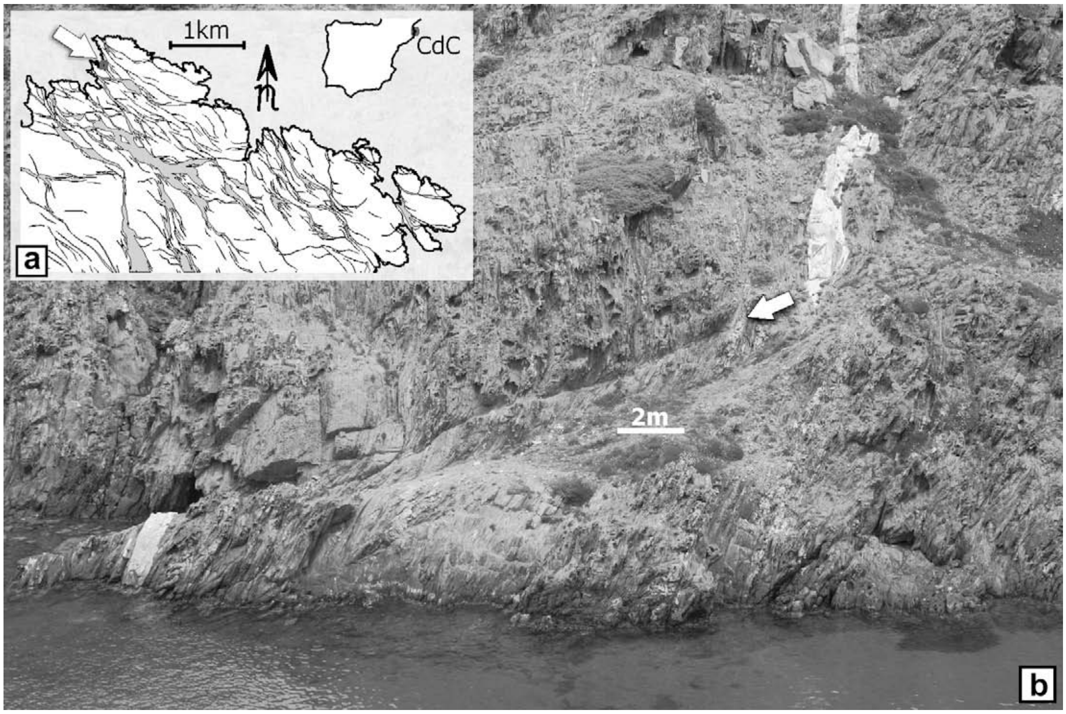

Fig. 1. (a) Location of the investigated area (arrow) within the Northern Shear Belt at the Cap de Creus peninsula (modified after Carreras, 2001); (b) Shear zone termination mapped in Fig. 2. UTM 31T 521678 east, 4687224 north, view across the Cala Prona towards the ENE.

detail, and it remains unclear exactly what grain scale processes interact as the brittle–viscous transition occurs.

In this study, which investigates greenschist-facies shear zones from the northern Cap de Creus peninsula in NE Spain, we extend our own, recently published studies of a strain-dependent brittle–viscous transition on the outcrop scale (Fusseis et al., 2006; Schrank et al., in press) to the microscale. We show how microfracturing relates to the temperature-activated deformation mechanisms during this transition. We demonstrate that during strain localization deformation is partitioned among the different mechanisms and discuss how the rheology of greenschist-facies shear zones evolves with strain and time.

2. Geological background and outcrop-scale observations

The shear zones of the Cap de Creus area (Figs. 1 and 2) formed during the retrograde evolution of a low-pressure/high-temperature metamorphism (peak metamorphic conditions 670 °C/470 MPa) associated with the Variscan orogenesis (Druguet, 2001 and references therein). The shear zones investigated in this study are exposed in the Cala Prona and Cala Serena areas along the northern shoreline of the peninsula (Fig. 1). They are hosted by a monotonous series of metamorphic pelitic and psammitic sediments composed of varying amounts of quartz (Qtz,[2] see Appendix for rock compositions), biotite (Bt), feldspar (mostly plagioclase Plag, An 20–35%), muscovite (Ms) as well as accessory chlorite (Chl), ilmenite (Ilm), tourmaline and epidote. Alternating pelitic and psammitic layers in these rocks (defining S0) are between a few centimeters to several meters thick and usually have sharp boundaries.

At least two deformation phases (D1 and D2) at prograde and peak metamorphic conditions affected these sediments prior to shear zone formation (Druguet, 2001; Carreras, 2001). During these deformational events S0 was tightly folded and sheared and a composite foliation (S0/2) formed (remnants of S1 could not be identified, Figs. 1, 2 and 12). On the microscale, S0/2 is characterized by generally well-aligned Bt^{I} (Fig. 3). In metapsammitic samples with Bt contents of up to 30%, Bt^{I} is dispersed and forms a continuous foliation (Fig. 3). With increasing mica content Bt^{I} appears clustered and organized in cleavage domains, which may be several hundred microns wide and alternate with microlithons[3] consisting of Qtz^{I} and $Plag^{I}$. In metapelites with Bt contents of up to 50%, cleavage domains may be several millimeters wide and form an interconnected network.

The shear zones investigated below formed in a statically annealed rock during retrograde cooling from about 550° to below 300 °C at lithostatic pressures of about 250 MPa (*D3 deformation event*, Carreras et al., 1977; Carreras and Garcia-Celma, 1982; Garcia-Celma, 1983; Druguet, 2001). D3 shear zones are characterized by a mylonitic foliation, S3, and a pronounced mineral lineation, L3. D3 shear zones are oriented at high angles to S0/2 (Figs. 1 and 2).

At the margins of the shear zones, S0/2 is bent (forming marginal drags) and gradually transformed into S3 (Fig. 2, Carreras and Garcia-Celma, 1982; Garcıa-Celma, 1983; Carreras, 2001). Bent S0/2 also forms monoclinal ductile beads ahead of shear zone tips (Elliott, 1976). In Fusseis et al. (2006) we concluded that the marginal drags were formed as shear zones propagated through these ductile beads. Based on the detailed shear strain evolution of the shear zone shown in Figs. 1 and 2, we classified D3 shear zones as Type 2 (softening) shear zones in the sense of Means (1984; see also fig. 5 in Fusseis et al., 2006). During increasing displacement, deformation was progressively concentrated in the narrow shear zone center and the marginal drags became inactive. Following Hull (1988) and Means (1995),

[2] Mineral abbreviations follow Bucher and Frey (1994). Supplementary roman numbering of these abbreviations refers to the generations of these minerals (e.g., Qtz^{I} – quartz, first generation).

[3] Sensu Passchier and Trouw, 2005.