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Development of shear zone-related lozenges in foliated rocks

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A B S T R A C T

Tectonic lozenges are elongate bodies bounded by relatively more deformed rocks. The focus of this study is on the 2-D structure of tectonic lozenges developed during ductile shear in rocks with a pre-existing mechanical anisotropy. On the basis of a detailed analysis of shear zones in foliated rocks from the Cap de Creus area (Variscan of the eastern Pyrenees), five mechanisms to explain the development of different types of lozenges in foliated rocks are suggested. These mechanisms are explained on the basis of the orientation of the previous foliation relative to the bulk shearing direction. It is shown that the prevailing mechanism does not majorly depend on the bulk kinematics but on the angular relationship between the pre-existing foliation and the bulk kinematic axes, and on shear zone interaction. This has implications on the use of lozenge shapes in tectonic interpretations. The fact that there is a wide range of initial orientations, propagation modes and coalescence types implies that the final lozenge geometry is not univocally related neither to the type of strain nor to the kinematic regime.

1. Introduction

Partitioning of ductile deformation in rocks produces lozenge-shaped low-strain domains wrapped around by shear zones (Reston, 1989; Simpson, 1983; Carreras, 2001). Shear zone-related lozenges have been studied since the 1980's (Bell and Rubenach, 1980; Bell, 1981; Simpson, 1983; Choukroune and Gapais, 1983; Hudleston, 1999; Carreras, 2001; Fusseis et al., 2006; Culshaw et al., 2011). Some of these previous works have attempted to infer strain and kinematic (e.g. Hanmer, 1986; Gapais et al., 1987; Lacassin, 1988; Fernández, 1993) or mechanical (e.g. Gerbi et al., 2010) attributes from their geometry. Various mechanisms have been suggested for their development, but the lack of a clear and concise nomenclature and typology for these structures has led to confronting interpretations about their origin, development and significance.

1.1. *Use of the term lozenge*

The term lozenge has been used since the late 1800s to refer to the shape of diverse geological features. In structural geology, the term lozenge refers to elongate rock masses bounded by fractures or shear zones (Graham, 1980; Simpson, 1983; Naruk, 1986; Woodcock and Fischer, 1986; Carreras, 2001; McClay and Bonora, 2001; Weinberg et al., 2004; Carreras et al., 2005; Fusseis et al., 2006; Baldwin et al., 2007; Kuiper et al., 2011). However, no precise definition has been proposed.

We propose a definition of "tectonic lozenge" as a scale-independent, 2-D generally elongate structure of rock (or mineral) bounded by relatively more deformed rocks (or minerals) and developed during heterogeneous strain accumulation in the rocks. The long axis of the structure use to form an acute angle (β, generally $<30°$) to the mean trend of the deformation zone (fault or shear zone).

As defined here, and used in most of the existing works, the term lozenge is a 2-D feature. The few studies concerning the third dimension in lozenges, ascribe them either a fusiform shape (Bell, 1981; Carreras, 2001; Chardon et al., 2009) or a prismatic shape with lensoidal or rhomboidal transverse section (e.g. Choukroune and Gapais, 1983; Hudleston, 1999).

An overview is given to the 2-D geometry of tectonic lozenges (Fig. 1a). The lozenge variety is displayed considering the aspect ratio (ratio of lozenge length to width normal to the long axis; Fig. 1b), the symmetry (acute angle between long and short axis, δ; Fig. 1b) and the straight vs. curvilinear character of the lozenge sides. Four main types are depicted: rhombic, lensoidal, rhomboidal and sigmoidal lozenges. A wider variety of lozenge shapes can be found, among which lensoidal and sigmoidal lozenges are the most characteristic. It is important to notice that this typology is only geometrical and thus not suitable to establish connections to formation mechanisms, neither from a mechanical nor from a kinematical sense.

The fact that lozenges are scale-independent structures is well documented in the literature, with reports at the regional scale

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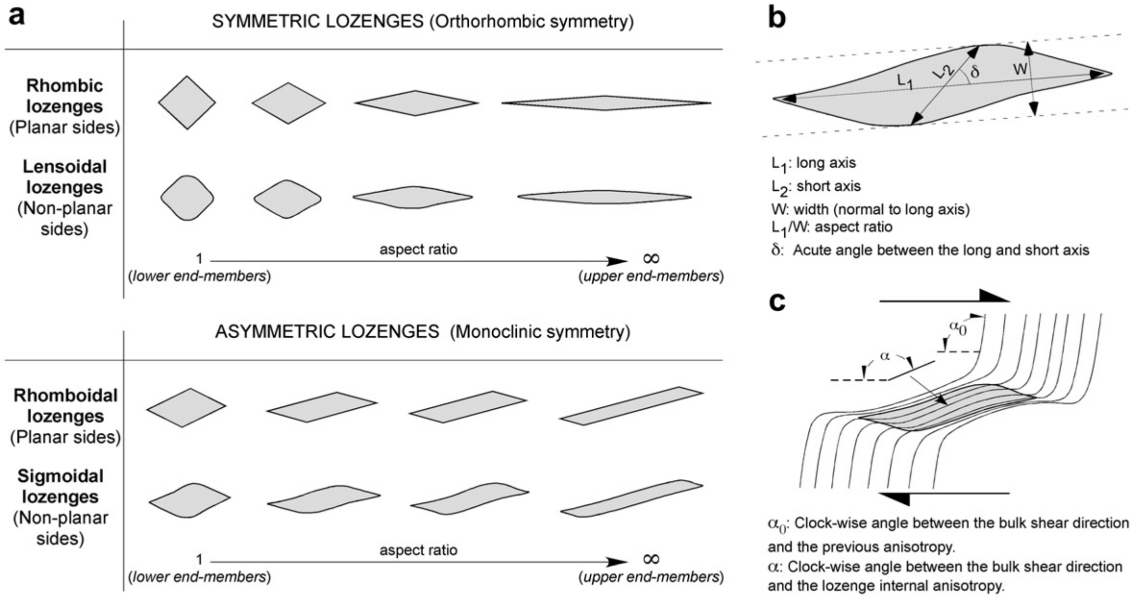

Fig. 1. Schematic representation of the diverse geometries and parameters that can be used to describe tectonic lozenges. (a) Different lozenge external shapes according to their symmetry, to their linear or curvilinear outline, and to aspect ratio. (b) Parameters used to geometrically define tectonic lozenges. (c) The angles α_0 and α_0 that are applied to lozenges in anisotropic rocks.

(Tilke, 1986; Bickford et al., 1994; Corsini et al., 1996; Czeck and Hudleston, 2003; Chardon et al., 2009; Delcaillau et al., 2011), at the meso-scale (Bell and Rubenach, 1980; Bell, 1981; Simpson, 1983; Choukroune and Gapais, 1983; Carreras et al., 2005; Fusseis et al., 2006), at the micro-scale (e.g., Ross and Wilks, 1996; Vollbrecht et al., 2006; Bédard et al., 2009) and at multi-scale (Carreras, 2001; Schrank et al., 2008).

1.2. Mechanical constraints for tectonic lozenges

Tectonic lozenges have been classically regarded from two different perspectives or approaches:

(1) Lozenges in rheologically heterogeneous rocks that are generated by rheological/lithological contrasts, where the lozenge is formed by a relatively competent material surrounded by a more deformed incompetent material (Cobbold, 1983; Bell and Rubenach, 1980; Passchier and Trouw, 1996; Treagus and Lan, 2000; Czeck et al., 2009; Jessell et al., 2009; Fagereng, 2011). The more competent material adopts a lozenge shape after deformation. This extensively documented type of lozenges (op. cit.) is therefore exclusive of lithologically heterogeneous rocks ands predominantly develops under ductile deformation conditions. This is the case, for instance, of sheared pegmatite lozenges in less competent mylonitic schists from our study area. However, these are not the object of the present work.

(2) Lozenges developed through shear zone interconnections. In this case, deformation localizes to produce sets of brittle or ductile shear zones that may isolate less deformed domains forming lozenges. They have been mostly studied and modelled by considering the simplest scenario of heterogeneous deformation in homogeneous isotropic materials. Several mechanisms have been suggested for their development. One consists on the confluence of pairs of conjugate shears *sensu lato* (Choukroune and Gapais, 1983; Gapais et al., 1987; Lamouroux et al., 1991; Hudleston, 1999; Mancktelow, 2002; Mahan and Williams, 2005; Pennacchioni and Mancktelow, 2007; Schwarz and Kilfitt, 2008; Aerden et al., 2010). Lozenges can also develop in deformation zones by intersection of different fractures of the Riedel shear zone system, as R- and R′-shears (e.g. Davis et al., 1999; Ahlgren, 2001; Carreras et al., 2010), R- and P-shears (e.g. Swanson, 2005, 2006) or R-, P-, and Y-shears (Tchalenko, 1970). Finally, they can form by the linkage of paired, sub-parallel stepped propagating shear fractures through their curving tips (Pollard and Aydin, 1984; Walsh et al., 1999; Pennacchioni, 2005; Mann, 2007; Tentler and Amcoff, 2010). In all situations lozenges of either contractional or extensional geometry may form. However, as stated by Woodcock and Fischer (1986), these different modes may operate simultaneously and/or can be indistinguishable from the observed final geometries. This is often the case in ductile shear zone networks. In this sense, Simpson et al. (1982) and Simpson (1983) relate lozenges to a general anastomosing arrangement, and Bell (1981) and Choukroune and Gapais (1983) point to strain heterogeneities that make shear zones vary strongly in direction.

All these "simplest" cases referred above show the complex interplay between several factors controlling the geometries of the lozenges, such as the initial geometry, orientation and relative proportion of different sets of bounding shears, the propagation mechanisms and the ability of rock to deform internally. But the situation becomes even more complex when layered and/or foliated rocks are considered. There is abundant literature analysing the progressive development of lozenges (or horses) and duplexes in stratified rock sequences under different tectonic regimes (e.g. Boyer and Elliott, 1982; Childs et al., 1996; Walsh et al., 1999; McClay and Bonora, 2001; Nicol et al., 2002), with particular attention being payed to the effect of layering on fault morphology (Swanson, 1990; Peacock and Sanderson, 1992). Deeper in the crust, shear zones are typically developed in crystalline rocks, such as plutonic intrusions, gneisses, but also in mid to high-grade schists and migmatites (Carreras, 2001). In this last case where the rocks are previously foliated ± layered, the arrangement of shear zones and their related lozenges is thought to be mainly controlled by the