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On stress and strain in a continuous-discontinuous shear zone undergoing simple shear and volume loss

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ABSTRACT

I summarise observations within a continuous-discontinuous shear zone to discuss the local stress and strain conditions experienced within a mixed rheology shear zone undergoing volume loss and deformation approximating simple shear. The Chrystalls Beach Complex, New Zealand, comprises phacoids formed from dismembered beds by layer-parallel extension, enclosed within a relatively incompetent matrix. Local extension is generally subparallel to the regional direction of shortening, and overall it appears that layer-parallel extension is a geometrical necessity in low angle shear zones where significant flattening occurs in response to simple shear accompanied by volume loss.

Preferential stress loading of phacoids is predicted by fibre-loading theory, and the failure of phacoids by brittle fracture is thereby governed by fibre stresses transferred from the matrix. The principal stress orientations in a phacoid are likely rotated relative to the matrix, and either parallel or perpendicular to the phacoid-matrix interface. As preferential loading of phacoids decreases the stress level in the matrix, an increased volume fraction of phacoids increases the strength of the shear zone as a whole. However, only small matrix volume fractions are required for the composite to act nearly as weak as the matrix.

1. Introduction

In intact, isotropic rocks subject to a regional triaxial stress field defined by the three principal compressive stresses $\sigma_1 \geq \sigma_2 \geq \sigma_3$, simple shear zones are inferred to initiate at 45° to σ_1 and parallel to a plane containing σ_2 (e.g. Ramsay, 1980). During progressive simple shear the finite strain ellipsoid (defined by the principal extensional strains $X \geq Y \geq Z$) rotates so that, after significant finite shear strain, X lies at a low angle to the shear zone walls and subparallel to the transport direction (e.g. Escher and Watterson, 1974; Ramsay, 1980). Therefore, it is common for low angle shear zones accommodating horizontal shortening to have a shallow plunging greatest extensional strain with a trend subparallel to the regional shortening direction (e.g. Kvale, 1953; Bridgwater et al., 1973; Barr et al., 1986).

Within exhumed examples of underthrust sediments at the base of paleo-accretionary prisms, subvertical extension veins have been observed at a high angle to subhorizontal shear planes, inferred to indicate a local subhorizontal σ_3 within low angle shear zones in a regional compressional tectonic regime (Byrne and Fisher, 1990; Fagereng, 2011b). In the active Barbados accretionary margin, AMS (Anisotropy of Magnetic Susceptibility) measurements on drill core, collected in a vertical hole through the prism and into the décollement, indicate a sharp change from subhorizontal shortening within the accretionary wedge, to subvertical shortening within underthrust sediments (Housen et al., 1996). Therefore, within some subduction-related shear zones accommodating regional horizontal shortening, local horizontal extension occurs within the shear zone. In exhumed analogues this local extension is in particular observed through boudinage of relatively competent subhorizontal layers and prevalence of subvertical extension veins (Byrne and Fisher, 1990; Raimbourg et al., 2009; Fagereng, 2011b). These observations relate to rotation of the greatest principal extensional strain towards the shear plane and accompanying subvertical shortening in the case of shallow dipping shear zones (e.g. Escher and Watterson, 1974). However, subvertical extension veins indicate a locally subhorizontal σ_3, incompatible with a compressional stress regime (e.g. Anderson, 1951). Thus, although finite strain orientations within shear zones, assuming bulk simple shear, are relatively well understood, the local stress field within a simple shear zone is not so well known. Here I present a simple analysis of the local strain and stress state within a shear zone deforming by progressive bulk simple shear, particularly as experienced by competent inclusions, inspired by observations in a continuous-discontinuous shear zone in an exhumed accretionary prism.

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2. Shear zone geometry

The term 'ductile' is here defined to describe macroscopically continuous deformation, without any implication of a particular flow mechanism. Flow mechanisms that fit this definition of ductile deformation include soft sediment deformation (independent particulate flow with no breaking of grains), diffusive mass transfer and dislocation creep. Each of these mechanisms may lead to the development of a ductile shear zone; a zone of localised macroscopically continuous rock deformation between subparallel shear zone walls, outside which comparatively little simultaneous deformation has occurred (e.g. Ramsay, 1980).

I first consider an idealised simple shear zone with the boundary conditions that (1) the shear zone walls are parallel and unstrained; (2) deformation is continuous throughout the shear zone; and (3) the displacement and finite strain profiles in any shear zone cross section are identical (Ramsay, 1980). These conditions are clearly not realistic near the termination of a shear zone, but are approximate for a tabular shear zone away from its ends. Accepting these boundary conditions is, however, only an approximation, as they do not account for strain components caused by longitudinal strain gradients (c.f. Carreras, 2001). In a mixed continuous-discontinuous shear zone the effect of shear discontinuities must also be taken into account (e.g. Horsman and Tikoff, 2005).

Assuming simple shear, the geometry of structural features observed in a ductile shear zone can be related to displacement and finite strain (e.g. Ramsay and Graham, 1970; Coward, 1976; Ramsay, 1980; Ramsay and Lisle, 2000; Cosgrove, 2007). The Y axis of the finite strain ellipsoid is parallel to the shear zone walls given the above boundary conditions. If the shear direction is parallel to the shear zone walls, and shear strain, γ, is distributed homogeneously throughout the shear zone, then γ relates to displacement, s, across the zone and shear zone width, w, so that

$$\gamma = \frac{s}{w} \tag{1}$$

In theory, a schistose ductile shear zone initiates at 45° to σ_1, and contains an initial planar fabric developing perpendicular to σ_1 (Fig. 1a). Assuming that foliation tracks finite strain, this planar fabric rotates with progressive deformation, and its orientation with respect to the shear zone boundary is a function of finite strain given by (Fig. 1b and c; Ramsay and Graham, 1970):

$$\tan 2\theta' = \frac{2}{\gamma} \tag{2}$$

where θ' is the acute angle between the foliation and the shear zone boundary (Fig. 1b). The underlying assumption that shear zones initiate at 45° to σ_1 (Ramsay, 1980) generally holds for intact rock (e.g. Mancktelow, 2002; Carreras et al., 2010), although Zheng et al. (2011) have proposed, based on a maximum-effective-moment criterion, that ductile shears initiate at an angle of about ~55° to σ_1. In foliated rocks, however, this initial angle may be affected by mechanical anisotropy and diverge from 45° (commonly >45°, Cosgrove, 1976; Gomez-Rivas and Griera, 2012). Although there may therefore be some variation in the angle at which shear zones initiate, the main point for the current study is that as finite shear strain increases, the shear zone foliation, and the greatest principal strain (X) contained within the foliation, will lie progressively closer to the shear zone margins.

Whereas foliation within the shear zone rotates with increasing γ, widening of the shear zone with time may occur and would lead to development of new foliation normal to σ_1 (at 45° to the shear zone walls) at the margins of the zone of fabric development. The shear zone fabric therefore tends to develop a curved appearance

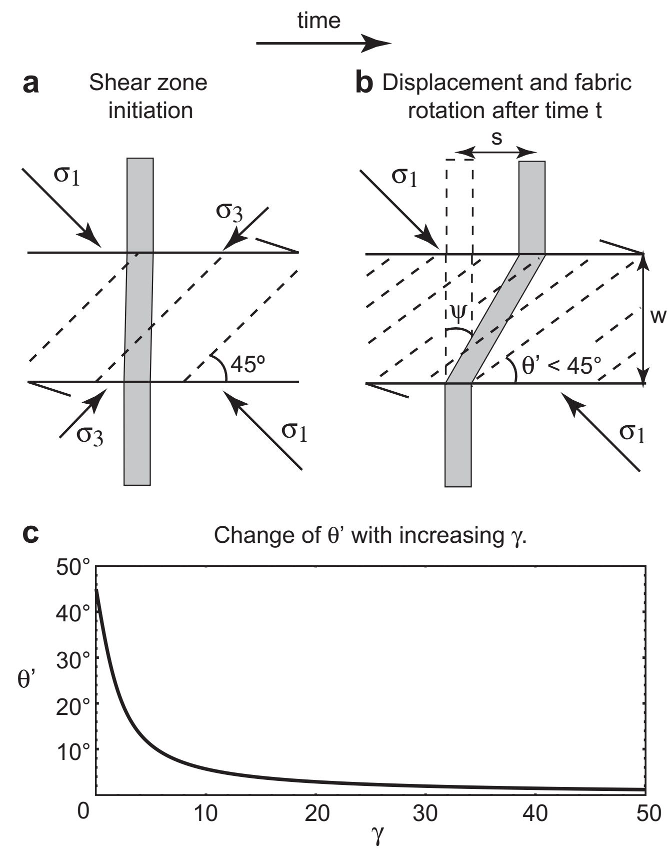

Fig. 1. Development of a homogeneous shear zone in simple shear: a) Orientation of the stress field relative to the shear zone at the first increment of simple shear, when a tectonic fabric forms perpendicular to σ_1 at 45° to the shear zone walls. b) The planar fabric within the shear zone rotates as a result of continuous deformation, decreasing the angle θ' between the shear zone walls and foliation. A marker bed perpendicular to the shear zone is offset by a distance s and has experienced angular strain ψ. c) Graph of θ' as a function of γ, note that the angle between foliation and the shear zone walls is <10° after a finite shear strain of ~5. a) and b) modified from Price and Cosgrove (1990), c) after Ramsay (1980).

over time, with foliation curving from an angle lower than 45° at the margins to a maximum of θ' in the centre of the shear zone. Similarly, narrowing of the shear zone would also lead to a curved foliation as more rotation occurs in the centre of the zone. As expressed in Eq. (2), this fabric curvature reflects the shear strain distribution within the shear zone, where the highest strain is experienced by rocks in the centre of the zone, decreasing to $\gamma \rightarrow 0$ at the margins (Ramsay and Graham, 1970; Ramsay, 1980). The total shear strain across a simple shear zone which grows with time is the integrated shear strain experienced over the width of the shear zone. Eq. (1) is therefore an approximation assuming homogeneous simple shear and no change in shear zone width over time.

A simple model of a shear zone within underthrust sediments along a subduction interface comprises ductilely deforming material contained between two rigid blocks (hanging wall and subducting slab). As a first approximation, such a zone deforms as by homogeneous simple shear, because it cannot grow into the surrounding rigid rock, at least in margins where subduction erosion is negligible. In shear zones deforming by simple shear, θ' decreases with increasing γ, and the foliation (representing the XY plane) eventually becomes subparallel to the shear zone walls if high shear strains are achieved (Fig. 1). If $\gamma = 10$ (so if $w \sim 1$ km, $s = w\gamma \sim 10$ km, assuming homogeneous simple shear), $\theta' \sim 6°$, while if γ is 100 ($s \sim 100$ km if $w \sim 1$ km) $\theta' \sim 0.6°$. Along