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Shear zones between rock units with no relative movement

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ABSTRACT

Shear zones are normally viewed as relatively narrow deformation zones that accommodate relative displacement between two “blocks” that have moved past each other in opposite directions. This study reports localized zones of shear between adjacent blocks that have not moved past each other. Such deformation zones, which we call wakes, form due to the movement of exotic blocks within a viscous medium (denser blocks sinking within a salt structure, (the paths) between separated boudins), melt in partially molten surroundings (melt movement during migmatisation), or solid blocks sinking through a partially molten magma body (stoping). From the fluid dynamics perspective these shear zones can be regarded as low Reynolds number deformation zones within the wake of a body moving through a viscous medium. While compact moving bodies (aspect ratio 1:1:1) generate axial symmetric (cone like) shear zones or wakes, elongated bodies (vertical plates or horizontal rod-like bodies) produce tabular shear zones or wakes. Unlike conventional shear zones across which shear indicators usually display consistent symmetries, shear indicators on either side of the shear zone or wake reported here show reverse kinematics. Thus profiles exhibit shear zones with opposed senses of movement across their center-lines or -planes.

We have used field observations and results from analytical and numerical models to suggest that examples of wakes are the transit paths that develop where denser blocks sink within salt structures, bodies of melt rise through migmatites, between boudins separated by progressive extension and (perhaps) where slabs of subducted oceanic lithosphere delaminate from the continental crust and sink into the asthenosphere. We also argue that such shear zones may be more common than they have been given credit for and may be responsible for some reverse kinematics reported in shear zones.

1. Introduction

A shear zone is usually defined as a relatively narrow deformation zone, planar or curvi-planar in geometry, composed of rocks more highly-strained/foliated than their surroundings. Even though these structures are relatively narrow, large-scale mylonitized shear zones a few kilometers wide have been observed (Hobbs et al., 1986). Conventionally, shear zones are accepted as forming between blocks that have moved in opposite directions relative to each other. In his classical review of the geometry of shear zones, Ramsay (1980) defined boundary conditions for the geometrically simplest shear zones; that the shear zone is parallel sided, and the displacement profiles along any cross sections of the zone are identical (i.e. the finite strain profiles and the orientations and characteristic geometric features of small scale structural features across profiles are also identical). However, he argued that even though these conditions are unrealistic since shear zones have finite length and their displacement profiles must change near their termination, “very many shear zones often approximate closely to these over quite large zone lengths”. More ‘orthodox’ shear zones where shear is dominant were called S-bands by Cobbold (1977).

Shearing results in e.g. deflection of markers and pre-existing foliation, formation of porphyroclast systems and sigmoids, rotation of porphyroblasts and the development of shear bands (genesis of mineral fish and S-C fabrics) (Mason and Manley, 1957; Reed and Tryggvason, 1974; Berthé et al., 1979; Lister and Snoke, 1984; Passchier and Simpson, 1986; Van den Driessche and Brun, 1987; Passchier, 1998; Vernon et al., 2004; Passchier and Trouw,

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1998; Mukherjee, in press). These structures have a monoclinic symmetry in cross-sections parallel to the shear direction and are frequently used as kinematic indicators to deduce the sense of shear (Passchier, 1998). Ideally such kinematic indicators show a consistent sense of shear within a shear zone (Passchier, 1998; Passchier and Trouw, 1998). However, in many orogenic shear zones, e.g. the South Tibetan Detachment System in the Himalayas as reviewed by Yin (2006) and tectonic boundaries in the Scandinavian Caledonides (Bergman and Sjöström, 1997; Gee et al., 2008), kinematic indicators are locally contradictory, i.e. show opposing senses of shear. Such contradictions can be due to at least two phases of shearing (i.e. a retro-shear on a pro-sheared zone), two conjugate shear zones that become sub-parallel during progressive deformation and/or the existence/development of tectonic lenses (Carreras, 2001). Carreras (2001) described the complex shear zones in the Cap de Creus in Spain and identified shear zones with opposite senses of shear that come to lie in close parallelism. He suggested “a progressive non-coaxial deformation regime” being responsible for the development of the complex kinematic pattern.

In this study, we present field and model evidence for the existence of wakes, a kind of merged shear zones, which form between two blocks with no motion relative to each other and where reversed kinematic patterns develop during a single phase of deformation. Many of these zones are welds where rigid or ductile bodies of rocks have passed through the reference field and are no longer visible. Froitzheim et al. (2006) described similar structures for faults and called them “extraction faults”. They explained that extraction faults form where a volume of rock is extracted between two faults with opposite sense of displacement allowing these two faults to merge together at the trailing edge of the extracted body. In the next section, we will describe different cases where kinematic reversal may occur and in the following sections give examples from both numerical and analytical models, and natural cases.

2. Reverse kinematics

There are many examples of kinematic reversals in shear zones which are inverted due to two phases of deformation. For example, in the Lewisian high-grade metamorphic complex of Gairloch, reversal of dextral shear sense to sinistral is attributed to renewed phases of deformation (Lei and Park, 1993). Cooper et al. (2010) suggested that the mylonite zone below the northern Snake Range decollement (Basin and Range) has locally experienced kinematic reversal inconsistent with movement along a single detachment fault. Two opposite senses of ductile shear have also been recorded from the South Tibetan Detachment System (STDS) in the Himalaya in terms of mineral fish, sigma structures and S-C fabrics by Argles and Edwards (2002), Mukherjee (2007, 2010a, 2010b), and Mukherjee and Koyi (2010a and b) and many others. Kinematic reversal in the Scandinavian Caledonides is the result of shift from compressional tectonics and top-to-the-east thrusting during collision of the continental plates Laurentita and Baltica, to extensional tectonics resulting in top-to-the-west backsliding of the orogenic wedge (Gee et al., 2008).

Kinematic complexity is probably most common in transpressional and transtensional shear zones, which include both a non-coaxial and a coaxial component (e.g. Fossen and Tikoff, 1998). However, there are many cases where kinematic markers show reverse polarity (i.e. mirror symmetry) along a shear-zone-like structure that develops during one phase of deformation. These structures form due to movement of an object through a host rock. A number of natural examples exist where an object that has moved through a viscous or granular medium has left a wake flanked by zones of ductile shear. Some of these are; (i) active diapirs of salt, mud or magma that have been downbuilt or risen through their host rock; (ii) tracks of organisms that have burrowed in sandy layers and dragged nearby soft bedding (Fig. 8V of Passchier, 2001); (iii) melt that cut across pre-existing foliations during migmatisation (Fig. 4); (iv) newly nucleated grains distorting the cleavage of the host grain in which they grow (Fig. 3a–b of Mukherjee and Koyi, 2009); (v) drag of pre-existing fabrics by separating boudins, and (vi) a ‘cylindrical fault’ by Hills (1953) where the litho-units are dragged in the same sense across the brittle fault.

Additional geologic examples where an object (body) moves through a viscous medium driven by gravity or a pressure gradient is where a block of country rock falls into a magma chamber (stoping; Daly, 1903) or the gravitational descent of denser blocks or sheets within a salt diapir (e.g. Koyi, 2000, 2001). During their descent, these denser blocks shear the viscous salt along their boundaries (Figs. 2 and 3). For example, a two-dimensional anhydrite block (sheet) with finite length shears the viscous salt along both its boundaries (Burchardt et al., 2011) resulting in formation of shear zones with opposed shear senses. These shear zones form as a result of viscous drag along the contacts between the anhydrite sheet and the surrounding host rock salt and keep propagating as the object moves. As the anhydrite sheet continues to sink within the viscous salt, these two shear zones merge and fuse behind it forming a wake. The wake is a shear zone (and/or secondary weld) that separated the two compartments of salt along which the anhydrite sheet moved. The wake thus consists of the merger of two initial shear zones formed on each side of the sinking sheet and is characterized by rotated foliations with the same sense of curvatures across the object reflecting the opposed senses of shear on each side of the fused surface (Fig. 1). Schmeling et al. (1988) studied the axisymmetric case of sinking or rising Stokes spheres. In their models, the cone-like wake of these bodies is characterized by strong plane strain with the axis of extension progressively tilting and lengthening into the direction of the body as one approaches the axis of movement.

Other examples of complex or even misleading kinematic patterns may form in relation to collapsing magma- or fluid-filled voids (Bons et al., 2008). Bons et al. (2008) studied how Newtonian viscous media on pure shear occupy void spaces inside them in deformation experiments, and drag the nearby markers. We do not compare these models with ours since (i) the wakes we report here do not develop under pure shear; and (ii) the deformed markers of Bons et al. (2008) are not uniformly dragged and curved at any single side of the void–viscous medium contact as the foliations/markers related to wakes do.

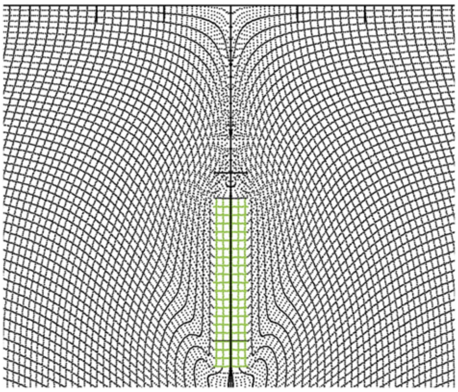

Fig. 1. Section of a two-dimensional numerical model showing a wake behind a sinking block (AR of 1:5). Note the downward drag of the horizontal markers behind the sinking block.