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Shear zone deformation determined from sigmoidal tension gashes

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ABSTRACT

The potential of using sigmoidal tension gashes as strain markers for assessing strain localisation in shear zones is discussed. The appropriate analytical methods for this purpose depend on the assumed mechanism of tension gash formation. Two such models are considered. The first is one in which the curvature of the gash is produced by passive rotation of different segments of the gash in response shear strain gradients across the shear zone. The other model is one in which the curvature of the gashes is governed by the folding of the competent rock bridges between adjacent gashes. In the latter case, the tension gashes progressively grow within spaces created by the buckling bridges and therefore lead to a bulk dilatation of the shear zone. However, for the folded bridge mechanism to continue to operate beyond shear strains greater than unity requires a significant volume loss which in turn may signal the increase of the shear strength of the zone. The geometrical characteristics of gash arrays resulting from these two mechanisms are described and criteria given for the recognition of the two types of gash arrays. A new graphical method is proposed for the analysis of deformation in shear zones containing folded-bridge tension gashes. Tension gash arrays from Marloes, West Wales are used as examples of the procedures for shear zone analysis.

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1. Introduction

Sigmoidal tension gashes are mineral veins with a characteristic geometry. They occur in arrays in which the individual veins in cross-section are s-shaped and are thicker in their central parts and a taper in thickness towards their ends (Fig. 1). Within each array, adjacent veins exhibit an en echelon or overlapping arrangement. Often, tension gash arrays at the outcrop occur in two sets exhibiting a symmetrical configuration in terms of geometry and inferred kinematics in the manner of a conjugate fault pair.

In many cases it is clear from associated deformation features, e.g., localized cleavage development, that the array of sigmoidal tension gashes occupies a shear zone; in other instances, the host rock enclosing the veins appears little deformed. The present paper restricts its consideration to arrays of sigmoidal gashes linked to shear zones.

Ideas concerning the development of the curved shape of sigmoidal tension gashes in shear zones fall into two end-member models (Fig. 2). Some explain the curvature as the result of strain-induced passive rotation of an initially straighter vein (Fig. 2a); others argue that the tension gashes owe their curvature to the mechanical strength of the slices of rock between the veins (Fig. 2b).

The mechanisms described by Ramsay and Graham (1970), Hancock (1972), Beach (1977), with or without continued widening of the gash induced by the imposed strain (Durney and Ramsay, 1973), fall under the first heading. These authors attribute the gash array and its subsequent modification to simple shear or some other non-coaxial strain history operating within a shear zone. The final curved shape of the tension gashes requires the finite strain pattern within the shear zone to be heterogeneous (Fig. 2a).

On the other hand, Nicholson and Ejiofor (1987), Nicholson and Pollard (1985) and Nicholson (2000) have suggested that sigmoidal curvature can arise from initially straight fractures but that the curved gash shape evolves during their dilatation of the gash under the influence of the mechanical competence of the intervening rock bridges (Fig. 2b). In this article, this is referred to as the folded bridge model. Smith (1999) considers a variant of the folded bridge model that considers the possibility that the initial planar fractures may predate the vein formation event and could be controlled in their orientation by mechanical anisotropy afforded by bedding planes, etc. This paper uses these concepts as the basis for practical methods of strain analysis using tension gashes.

These contrasting explanations of sigmoidality have major implications for the analysis of shear zones. In particular, the calculation of the strain distribution across a particular shear zone

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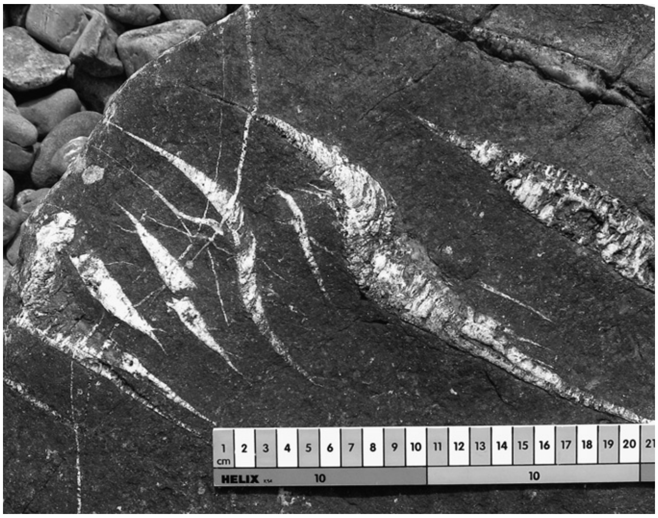

Fig. 1. Sigmoidal tension gash array at Marloes Sands, SW Wales. Ruler marked in cm.

using sigmoidal tension gashes as strain markers will depend on the exact manner in which the curvature of the veins has evolved. This paper considers the issue of determining strain and its localization from the geometrical analysis of sigmoidal tension gashes by means of both models mentioned above. The models discussed below are two-dimensional and take no account of deformation in the third dimension.

2. The passive rotation model for sigmoidal tension gashes

The passive rotation model for the formation of sigmoidal tension gashes assumes that the curvature is produced by the effects of heterogeneous strain within the shear zone, causing differential rotation of different segments of the tension gash (Fig. 3). The final orientation of each segment of the tension gash depends on its starting orientation as well as the strain that has accumulated since the propagation of the vein. The initial orientation will depend on the nature of the original fracture, e.g., whether it is a Riedel fracture (Wilson and Cosgrove, 1982) or an extensional (mode I) fracture. Beach (1975) distinguishes different types of gash arrays on the basis of the orientation of the precursor fracture. In the case of the extensional fractures formed during true (isochoric) simple shear, the expected orientation is 45° with respect to the shear zone boundary, but would be a lower or higher angle when there is respectively a positive or negative volumetric strain component. Ramsay and Graham (1970) have suggested how incremental volume changes can affect the initial orientation of the precursor fractures in shear zones. Tension gashes may develop by the dilation of pre-existing fractures (Ramsay, 1967; Smith, 1999).

In the absence of information on the original fracture orientation, α, an estimate can be obtained from the orientation of the gash tip at the edge of the shear zone (Fig. 3a). This method assumes that the shear strain gradient across the boundary varies in a continuous manner.

The final shape of the gash will also depend on the type of deformation; whether or not volume changes have accompanied simple shear (Ramsay and Huber, 1983, p. 51) and on the relative timing of the simple shear and volumetric deformations. For the case of ideal simple shear, the shear strain at points within the shear zone can be calculated by rearranging the equation given by Ramsay and Huber (1983, p. 24):

$$\gamma = \cot \alpha - \cot \alpha' \tag{1}$$

where α and α' are respectively the initial fracture orientation (i.e., gash tip) and the deformed vein orientation at points along the curved gash (Fig. 3a).

A sigmoidal shape adopted from an originally straight vein implies heterogeneous shear (Fig. 2a). The heterogeneous strain could arise from gradients of incremental shear across a shear zone of fixed width with respect to material points, by uniform shear increments across a zone of changing width with boundaries that migrate with time through material points, or some combination of these (Means, 1995).

It follows from Eq. (1) that the curvature of the vein at any point, corresponding to the rate of change of α', reflects the local gradient of shear strain, γ (Fig. 4). This geometrical property of sigmoidal gashes is illustrated in Fig. 5 which is derived from a kinematic modelling of different types of shear zones in terms of shear strain profile. These examples of shear zones were chosen to illustrate different degrees of strain localization, and correspond to different values of the intensity of strain localization, I_{loc} (Schrank et al., 2008) defined by

$$I_{loc} = 1 - \gamma_{mean}/\gamma_{max} \tag{2}$$

and possess shear profiles that are curves of superellipse shape (Gardner, 1977; Lisle, 1988). These simulations reveal that sigmoidal tension gashes with sharply curved terminations (cf Fig. 14 of Roering, 1968) indicate a shear profile with high gradients at the margin of the shear zone (low I_{loc} value; Fig. 5a and d), whereas strong curvature at the central portion of the sigmoid is diagnostic of a spiky shear profile ($I_{loc} < 1.0$; Fig. 5c and f).

The total lateral displacement across the shear zone, d_x, can be estimated in two alternative ways; either by the application the method of Ramsay (1980) which involves integration of the shear strain values obtained from Eq. (1), or graphically by the comparison of the sigmoidal gash with its

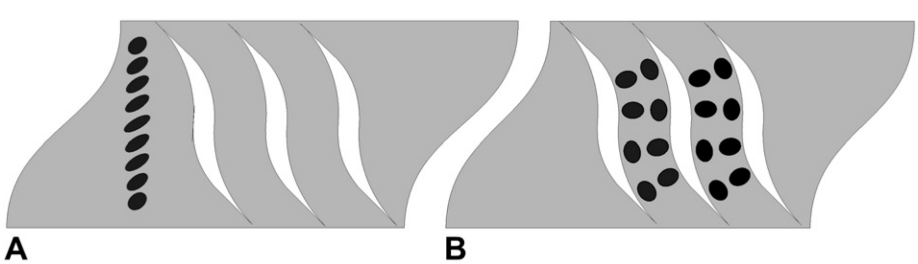

Fig. 2. End-member explanations for development of sigmoidal tension gash arrays; A, passive deformation of tension gashes with curvature produced by strain gradient in a shear zone; B, folded bridge model where bridges behave as competent beams that buckle under shortening strains associated with the shear.

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