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Modelling flanking structures using deformable high axial ratio ellipses: Insights into finite geometries

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Abstract

Flanking structures develop locally around material inhomogeneities. The evolution of these structures is investigated here by modelling peturbations around a deformable ellipse using a 2D analytical solution. Non-unique instantaneous and finite geometries are predicted, and it is shown that in terms of slip and curvature, complex histories are possible under simple shear, whereas under pure shear instantaneous geometries map directly into finite state geometries. Single flanking structures are of limited use in kinematic analysis but can help constrain the kinematics when interpreted in conjunction with other structural features. Flanking structures exhibiting a range of CE (cross-cutting element) orientations have more potential as kinematic indicators. Flanking structures serve as an excellent example of the role that material homogeneity can play in locally producing complex structures in a relatively simple bulk flow field.

Keywords: Flanking structure; Finite; Instantaneous; Mathematical model

1. Introduction

Flanking structures (Passchier, 2001) have been the focus of considerable research recently. They were recognised and described in detail by Gayer et al. (1978) and also by Hudleston (1989) who outlined the association of folds and veins in shear zones in both rocks and glaciers as ‘‘paired hook-shaped’’ asymmetric folds displaying a shear sense opposite to that of the across vein displacement sense. This behaviour is counter-intuitive and opposite to the effect of fault drag. Hudleston (1989) recognised that folds may occur as a consequence of fracture development, and that the shapes of folds depend on the mechanical properties of the fracture infill over time. More recently Druguet et al. (1997), Zubriggen et al. (1998) and Grasemann et al. (1999) have described examples of similar structures. Passchier (2001) synthesised these variously named features into a single class termed ‘‘flanking structures’’.

Mulchrone and Walsh (2006) produced an analytical solution in 2D for the behaviour of a deformable ellipse (i.e. having a different viscosity to that of the surrounding material) in a general 2D homogeneous deformation. In this paper the model of Mulchrone and Walsh (2006) is simplified and applied to high axial ratio deformable ellipses in order to model the instantaneous and finite geometries of flanking structures. Many of the equations referred to below are derived in Mulchrone and Walsh (2006).

1.1. Terminology

At least three terminologies have been applied to flanking structures in recent times. Passchier (2001) introduced a deformation-independent, purely geometric nomenclature to be applied to finite (i.e. field) flanking structures. The primary features are a CE (cross-cutting element) and HE (host element) as defined by Passchier (2001). Six different geometric categories of structure were distinguished based on the relative

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displacement sense between that across the CE and that indicated by the curving of the HE close to the CE (synthetic or s-Type, antithetic or a-Type and no across CE displacement or n-Type). Additionally the HE curvature can be described as fold-like or shear band-like (Fig. 1 and Fig. 7(a) of Passchier, 2001). Grasemann and Stüwe (2001) further divided the HE into a HE_i (the HE within the perturbation zone associated with the CE) and HE_e (the unaffected HE outside the perturbation zone) and distinguished between the rotation of the CE and that of the material within the CE, termed the CE_i. It should be noted that Grasemann and Stüwe (2001) dealt with an inclusion of axial ratio 10, therefore the behaviour of the CE_i was an important consideration. Grasemann et al. (2003) provide a terminology which applies only to a particular instant in the evolution of flanking structures. For an instantaneous flanking structure, CEs may be co-, counter or non-rotating compared with the bulk sense of shear (3 options), the displacement sense across a CE may be co- or counter-shearing again compared with the bulk shear sense (2 options). Finally, the curvature of the HE indicates convex or normal drag if the sense of local rotation of the HE is consistent with that of the displacement across the CE and reverse otherwise (2 options). This terminology is useful in the context of modelling but is of limited use in the field (see Coelho et al., 2005), since the bulk shear sense is unknown in advance. It leads to 12 possible instantaneous states. Departing from the original deformation-independent definition of Passchier (2001), Grasemann et al. (2003) define that s-Type structures are those with co-shearing CEs coupled with a contractional sense of offset; a-Type structures have counter-shearing CEs and shear bands are co-shearing with extensional sense of offset (see also Exner et al. 2004). Confusion may be caused if the different terminologies (finite and instantaneous) are applied in the wrong context. In particular, the different definitions of s-, n- and a-Type structures as applied in the finite and instantaneous states are highlighted as a potential source of confusion (Wiesmayr and Grasemann, 2005). Coelho et al. (2005) introduced a deformation independent terminology based on four parameters tilt, slip, lift and roll. A brief summary is not possible, so the reader is directed to the original paper for details.

1.2. Previous research and results

Passchier (2001) suggested five possible mechanisms for flanking fold development: (i) CE formed during or after flanking fold development, (ii) folding associated with active faulting, (iii) development associated with an alteration rim around the CE, (iv) enhanced deformation within the CE due to competency contrast, and (v) passive amplification of minor perturbations due to vein intrusion. Passchier (2001) urged caution when using flanking structures as shear sense indicators.

Grasemann and Stüwe (2001) numerically modelled the development of flanking structures using a CE of finite thickness, initially oriented at 135° to the shear direction, under dextral bulk simple shear. For CEs less viscous than the HE, they found that flanking folds, exhibited by the HE, display dextral shear sense but the displacement across the CE was sinistral, corresponding to a-Type flanking structures. By contrast, they found that for highly competent CEs (almost rigid) n-Type structures develop with dextral flanking folds. Again Grasemann and Stüwe (2001) urged caution in the use of flanking structures as kinematic indicators citing modelling of almost identical structures under pure shear by Baumann (1986; in Grasemann and Stüwe, 2001). Grasemann et al. (2003) presented the results of further numerical modelling where an infinitely thin perfectly slipping line of finite length is deformed for various initial orientations and transpressional bulk deformation types. They showed that under a wide range of kinematic conditions morphologically identical instantaneous flanking structures can arise, and that there is a relationship between bulk deformation, CE orientation and the resulting instantaneous flanking structure. Moreover, they give guidelines where flanking structures may be of use in unravelling the bulk kinematics of deformation.

Exner et al. (2004) modelled the development of flanking structures under bulk dextral shear using a ring shear apparatus. Their results were in agreement with previous numerical work but they were also able to track the progressive development of initial reverse a-Type flanking structures into n-Type and then normal s-Type flanking folds as the CE rotates under simple shear. Kocher and Mancktelow (2005) used the analytical model of Schmid and Podladchikov (2003) for a high axial ratio, weak elliptical inclusion to consider the case of reverse modelling the development of flanking structures in order to estimate both the vorticity number (W_k) and the amount of deformation. The only difficulty in applying this approach is that the orientation of the responsible bulk deformation must be assumed (i.e. for example simple shear directed along the direction of the HE with or without a component of HE-perpendicular pure shear). Wiesmayr and Grasemann (2005) extended the scope of Grasemann et al. (2003) to include transtensional bulk flow. More recently, Kocher and Mancktelow (2006) used analytical and numerical techniques to study the evolution of flanking structures in anisotropic viscous rock. They found that anisotropy can have significant effects on the relative frequency of instantaneously developing flanking structures.

2. Morphology of flanking structures

Interpreting flanking structures in the field in terms of the bulk kinematics has been demonstrated to be fraught with difficulties and instantaneous classifications are redundant in the field. Purely geometric schemes such as those proposed by Passchier (2001) and Coelho et al. (2005) claim no relation with the kinematic framework. Furthermore, the six classes identified by Passchier (2001) can be condensed into three classes (a-Type, s-Type and n-Type) because the fold-like and shear band-like are morphologically equivalent (Fig. 1a). This is because the resulting geometry is purely dependent on the initial orientational relationship between the CE and HE. It may be the case that the HE is related to the same