A 3-D perspective on segmentation of normal faults: implications for numerical modelling*

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1 Introduction

Normal faults contained within stratified rock are often segmented in 3-D. Although the three-dimensional geometry of faults can be imaged by means of high quality seismic data (e.g. Walsh et al. (1999)) segmented fault zones on a much smaller scale, e.g. a few metres, are best studied from outcrops. Field studies on vertical (i.e. cross-) sections have shown that faults refract in layered sequences, a feature that is generally attributed to either stress refraction or the linkage of overstepping segments (Peacock and Zhang (1994); Childs et al. (1996)). Furthermore, map view observational data have shown that faults often exhibit an en-echelon geometry, with segments that are laterally offset in plan view (e.g. Peacock and Sanderson (1994)). Therefore, depending on the section of observation, vertical or lateral fault segmentation provides a basis for the complexity of fault zones. In this abstract, we briefly explore consequences of the segmented nature of faults for both the parameterisation and modelling of fault zone development.

2 Field examples

Excellent examples of small-scale fault zones are exposed at Kilve foreshore on the southern margin of the Bristol Channel, UK. The faults cut a limestone-shale

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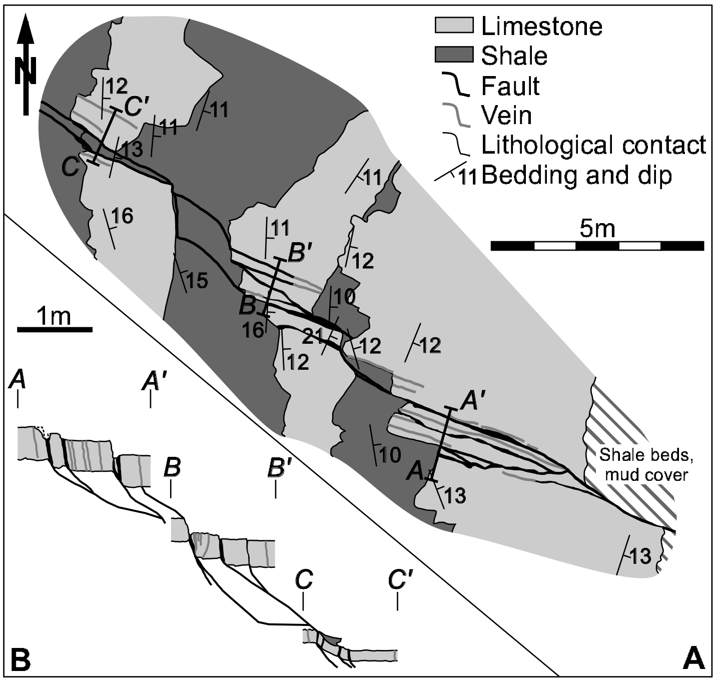

Figure 1: Map (a) and sections (b) of a highly segmented fault located west of Kilve stream at Kilve beach, Somerset, UK (N 51°11′35.6″ W 003°14′2.1″). Total displacement decreases from $40cm$ in the SE to $25cm$ in the NW.

succession of Early Jurassic age, in which the shale units are generally thicker (from a few centimeters to $> 300cm$) than the intervening limestone beds (from a few centimeters to $> 50cm$). Normal faults of Late Jurassic to Early Cretaceous age are attributed to the development of the Bristol Channel Basin (Kelly et al. (1999)). The nature of the foreshore exposure provides near 3-D definition of the geometry of individual fault zones. Fieldwork has concentrated on the analysis of small-scale faults (displacement $< 0.5m$) by detailed mapping at scales of $1 : 100$ (Fig. 1a) and the construction of multiple sections along each fault zone (Fig. 1b).

The fault zone shown in Figure 1a and 1b is located west of Kilve stream. The fault zone strikes 130° and has an overall dip of ca 50° NE within the shallowly (*ca.* 12°) ESE dipping strata. Individual faults cutting limestone beds dip *ca.* 80° and faults cutting shale dip from 60° to nearly horizontal. Total displacement of the fault decreases from $40cm$ in the SE to $25cm$ in the NW. The fault is highly segmented both laterally (in map view; Fig. 1a) and vertically (viewed in x-sections; Fig. 1b). The limestone layers contain numerous calcite filled Mode I fractures that are attributed to outer arc extension within a low amplitude precursory monocline. At increasing displacements some of these veins develop a significant Mode II and Mode III component, and are linked from one limestone

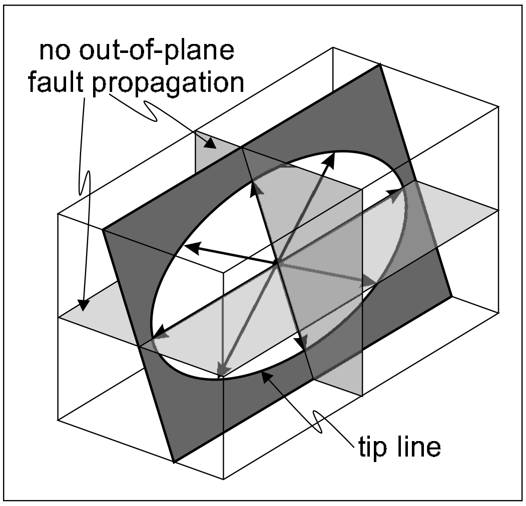

Figure 2: Schematic block diagram showing the propagation directions of an ideal fault. The tip line confines an elliptical area of failed rock (white). The fault plane propagates radially (arrows show tip line propagation direction). Only two sections (shaded) have no out-of-plane fault propagation. This fault is shown schematically as a single fault surface, but in all probability will comprise an array of sub-resolution segments.

layer to another via low angle faults in the shale. A characteristic of this segmented fault array, is that on scales greater than a few metres, the array forms a coherent system, with systematic variations in displacement across the system as a whole (i.e. it behaves like a single fault). However, given the thoroughly 3-D nature of fault segmentation, an understanding of fault zone evolution can only be achieved by acknowledging the importance of local propagation directions in relation to that of the array, or fault zone, as a whole. In the case of this fault zone, it is clear that all sections of observation must include some component of out-of-plane fault propagation (i.e. proportions of vertical and lateral fault propagation; Fig. 2), a feature which rarely underpins either conceptual or numerical models for fault zones (see below).

3 Implications of 3-D fault propagation

Numerical models often assume that a fault is a planar region within a volume of rock. This region has either different rheological properties than the host rock or is modelled as a frictional surface. The parameters used in these models are derived from extrapolated laboratory or bore hole data. Although field observations clearly show the segmented nature of fault zones none of these models implicitly incorporate geometric parameters, such as segmentation or connectivity, though they may be over-riding properties of fault localisation and growth. Our contention is that 2-D and 3-D numerical modelling on the growth of faults in rheological stratified rock could provide (i) valuable insights into the growth of fault zones and (ii) essential constraints on bulk (i.e. upscaled) geometric parameters for inclusion in numerical models of planar faults.

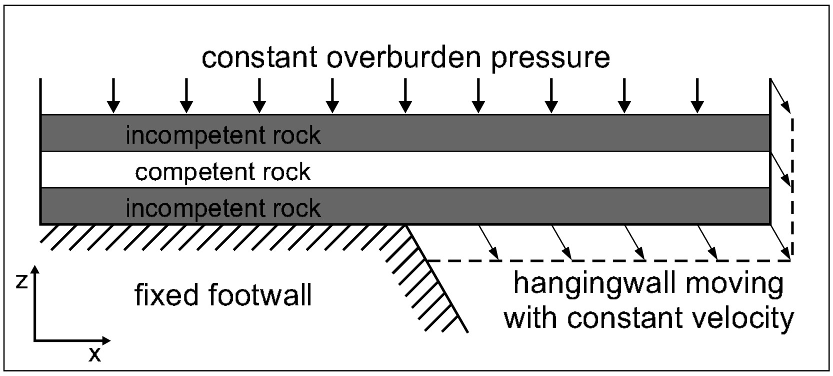

Figure 3: Schematic diagram showing the boundary conditions used in the discrete element models.

4 Numerical modelling

Numerical modelling on the growth of faults in layered sequences above a basement normal fault is being performed using PFC^{3D} (Particle Flow Code, Itasca Consulting Group), a commercial available discrete element code. The boundary conditions are similar to scaled analogue models focussing on basement-controlled normal faulting (Horsfield (1977); Tsuneishi (1978); Withjack et al. (1990)). The basement has a pre-cut fault in the centre of the model and the hangingwall moves with constant velocity (Fig. 3). With respect to the ideal fault surface shown in Fig. 2 the model is located in the plane of no lateral fault propagation. The spherical particles are centred on the $x - z$ plane and particle rotation is restricted to the y axis (plane strain). A linear contact model with frictional sliding is used. The competent rock (limestone) consists of coarse particles, that are bonded by springs which break as soon their tensile or shear strength is exceeded. The incompetent rock (shale) consists of fine, non-bonded particles. During the experiment a constant overburden pressure is applied.

This presentation describes preliminary results of the modelling. A monocline develops in the competent layer and the onset of segmentation is observed. Folding of the competent layer is accommodated by the non-cohesive nature of the "shale" (i.e. allowing flow of the "shale") and also bedding parallel slip. Our results are in agreement with (i) the analytical solutions for an elastic layer above a buried fault (Patton and Fletcher (1995)) and with (ii) our field observations.

5 Conclusions

1. Faults in stratified rock are segmented in 3-D and a knowledge of the 3-D geometry of fault zones is a pre-requisite to understanding the mechanisms of fault growth. Interpretations based exclusively on 2-D perspective of fault propagation are often erroneous.

2. Numerical models often assume that a fault is a planar region with certain rheological properties. However, fault segmentation and connectivity are parameters that have not so far been incorporated in the modelling process.
3. 2-D and 3-D modelling focusing on the growth of faults in layered sequences may improve our knowledge of the evolution and parameterisation of fault zones.

References

Childs, C., A. Nicol, J. Walsh, and J. Watterson (1996). Growth of vertically segmented normal faults. *Journal of Structural Geology 18*, 1389–1397.

Horsfield, W. (1977). An experimental approach to basement-controlled faulting. *Geologie en Mijnbouw 56*, 363–370.

Kelly, P., D. C. Peacock, D. Sanderson, and A. McGurk (1999). Selective reverse-reactivation of normal faults, and the deformation around reverse reactivated faults in the mesozoic of the somerset coast. *Journal of Structural Geology 21*, 493–509.

Patton, T. and R. Fletcher (1995). Mathematical block-motion model for deformation of a layer above a buried fault of arbitrary dip and sense of slip. *Journal of Structural Geology 17*, 1455–1472.

Peacock, D. and D. Sanderson (1994). Geometry and development of relay ramps in normal fault systems. *American Association of Petroleum Geoscientists Bulletin 78*, 147–165.

Peacock, D. P. and X. Zhang (1994). Field examples and numerical modelling of oversteps and bends along normal faults in cross-section. *Tectonophysics 234*, 147–167.

Tsuneishi, Y. (1978). Geological and experimental studies on mechanism of block faulting. *Bulletin of the Earthquake Research Institute 53*, 173–242.

Walsh, J., J. Watterson, W. Bailey, and C. Childs (1999). Fault relays, bends and branch-lines. *Journal of Structural Geology 21*, 1019–1026.

Withjack, M., J. Olson, and E. Peterson (1990). Experimental models of extensional forced folds. *American Association of Petroleum Geoscientists Bulletin 74*, 1038–1054.