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Style and sequence of deformation during extensional fault-propagation folding: examples from the Hammam Faraun and El-Qaa fault blocks, Suez Rift, Egypt

C.A.L. Jackson *, R.L. Gawthorpe, I.R. Sharp [1]

Basin and Stratigraphic Studies Group, School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Oxford Road, Manchester M13 9PL, UK

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Abstract

Kilometre-scale fault-parallel folds are identified adjacent to normal faults in the Oligo-Miocene Suez Rift, Egypt and are interpreted to have formed in response to fault-propagation folding above upward propagating blind faults. The geometry, scale and distribution of secondary structures within the folds and their cross-cutting relationships with the master faults allow the style and sequence of deformation during fault-propagation folding to be established and suggest that during the initial stages of folding, the proto-footwall underwent extension which was accommodated by layer-parallel slip in encasing mudstone horizons and linked normal faulting and block rotation in carbonate and sandstone units. The proto-hanging wall also contains dominantly extensional normal faults although locally, where the master fault had a convex-into-the-footwall map-view trace, reverse faulting and fracturing occurred. Secondary structures adjacent to the master fault were not all active simultaneously, but initiated and died at different stages during the evolution of the fault-propagation fold. The results of this study confirm many key predictions of numerical and physical analogue models but also highlight several important controls on the evolution of fault propagation folds in extensional settings which existing models cannot capture, such as the influence of the map-view trace of the propagating fault and lateral variations in cover stratigraphy lithology and strength on the style and magnitude of secondary deformation.

Keywords: Fault-propagation folding; Normal faulting; Layer-parallel slip; Extensional basins; Suez Rift

1. Introduction

Fault-propagation folding is an important process during the early stages of fault growth in extensional settings as demonstrated by several field studies (e.g. Sterns, 1978; Schlische, 1995; Janecke et al., 1998; Maurin and Niviere, 2000; Sharp et al., 2000a; Khalil and McClay, 2002; Willsey et al., 2002). The geometry and evolution of fault-propagation folds have also been investigated in the subsurface using three-dimensional seismic data (e.g. Withjack et al., 1989; Pascoe et al., 1999; Corfield and Sharp, 2000; Withjack and Callaway, 2000). Based on these field and subsurface studies, numerical and physical analogue models have been developed to investigate the controls on the overall geometric evolution of fault-propagation folds (e.g. Vendeville, 1987; Withjack et al., 1990; Mitra and Islam, 1994; Patton and Fletcher, 1995; Allmendinger, 1998; Hardy and McClay, 1999; Withjack and Callaway, 2000; Finch et al., 2004; Patton, 2004). These models provide important insights into the manner in which deformation is accommodated within the evolving fold and suggest that a combination of normal and reverse faulting, folding and bedding-parallel slip are important deformation mechanisms (Fig. 1A and B). Although recent numerical models can directly model structures accommodating faulting and folding (cf. Finch et al., 2004), the majority of such models typically only predict bulk strain distribution through time and thus the distribution and orientation of structures accommodating this strain must be inferred (e.g. Erslev, 1991; Patton and Fletcher, 1995; Allmendinger, 1998; Hardy and McClay, 1999). Physical analogue models, although able to replicate physically some of the small-scale structures, are typically constructed on the centimetre-scale; thus it is difficult to observe how secondary deformation mechanisms are related (Vendeville, 1987;

* Corresponding author. Present and correspondence address: Department of Earth Sciences and Engineering, Prince Consort Road, Imperial College, London SW7 2BP, UK. Tel.: +44 7903 033298; fax: +44 207 5947444.

E-mail address: c.jackson@imperial.ac.uk (C.A.L. Jackson).

[1] Present address: Norsk Hydro Research Centre, Sandsliveien 90, 5020, Bergen, Norway.

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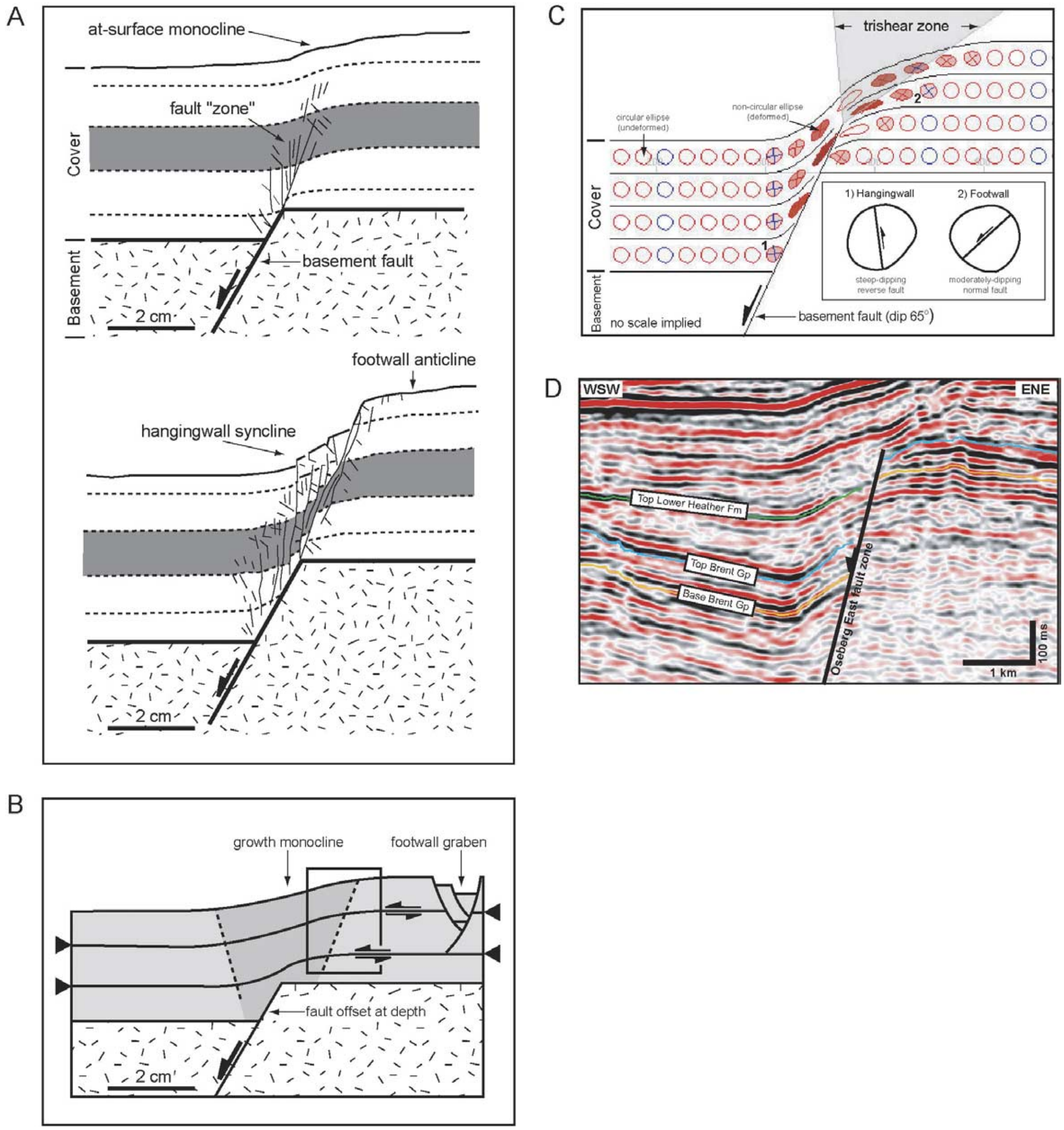

Fig. 1. (A) Cross-section from a physical analogue model of Withjack et al. (1990) illustrating the development of a fault-propagation fold above an upwardly-propagating fault-tip. Note distribution and orientation of secondary structures. (B) Summary diagram of physical analogue model by Withjack et al. (1990) illustrating the influence of layer-parallel detachments (black arrows) in the cover stratigraphy on the evolution of an extensional fault-propagation fold. (C) 'Trishear' numerical model of an extensional fault-propagation fold (Allmendinger, 1998). Shaded spheres are deformed during folding and lines within spheres are lines-of-no-finite-elongation (LNFE) used to infer the orientation of secondary faults and fractures. Inset shows attitude of secondary structures in the footwall and hanging wall inferred from LNFE. (D) Seismic section across a breached fault-propagation fold adjacent to the Oseberg East fault, North Viking Graben.

Withjack et al., 1990; Mitra and Islam, 1994; Withjack and Callaway, 2000). A similar resolution problem affects subsurface studies due to the typically low resolution of the seismic data used (Withjack et al., 1989; Pascoe et al., 1999; Corfield and Sharp, 2000).

Although outcrop analysis allows observations to be made at a scale intermediate between modelling and subsurface studies, relatively few field studies have specifically investigated the exact manner in which deformation is accommodated during fault-propagation folding (Gross et al., 1997; Keller and Lynch, 2000; Willsey et al., 2002; Grant and Kattenhorn, 2004; Fodor et al., 2005). The majority of these field studies have focused on relatively small areas adjacent to only one fault zone within the respective study areas, thus it is unclear if models derived from these studies are applicable to fault-propagation folds in other settings. In this paper we document the manner in which deformation is accommodated during fault-propagation folding through structural analysis of six normal fault zones (herein termed master faults) in the central part of the Oligo-Miocene Suez Rift, Egypt. To achieve this we describe the overall structural style of the fault-related folds, before focusing on the geometry, orientation, scale and distribution of secondary structures adjacent to the master faults. Cross-cutting relationships between the master faults and secondary structures,