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Identifying the characteristic signatures of fold-accommodation faults

Hongling Deng[a,b,*], Changhou Zhang[b,c], Hemin A. Koyi[a]

[a] *Hans Ramberg Tectonic Laboratory, Department of Earth Sciences, Uppsala University, Villavagen 16, SE-752 36 Uppsala, Sweden*
[b] *School of Earth Sciences and Resources, China University of Geosciences (Beijing), 100083 Beijing, China*
[c] *State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (Beijing), 100083 Beijing, China*

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ABSTRACT

Hand-specimen and outcrop scale examples of folds are analyzed here to identify the characteristic signatures of fold-accommodation faults. We describe and analyze the geometric and kinematic relationships between folds and their associated faults in detail including the structural position and spatial distribution of faults within a fold, the displacement distribution along the faults by applying separation–distance plots for the outcrop scale examples, and the change of cut-off angle when the fault cut across folded layers. A comparison between fold-accommodation faults and fault related folds based on their separation–distribution plots and the problem of time sequence between faulting and folding are discussed in order to distinguish fold-accommodation faults from the reverse faults geometrically and kinematically similar to them. The analysis results show that fold-accommodation faults originate and terminate within a fold and usually do not modify the geometry of the fold because of their limited displacement. The out-of-syncline thrust has a diagnostically negative slope (separation value decreasing away from the upper fault tip) in the separation–distance graph. The change of cut-off angle and the spatial distribution of faults display a close relationship with the axial surface of the fold. Our analyses show that fold-accommodation faults are kinematically consistent with the flexural slip of the fold. The interbedded strata with competence contrast facilitate formation of fold-accommodation faults. These characteristic signatures are concluded as a set of primary identification criteria for fold-accommodation faults.

1. Introduction

Before the concept of fault-related folds was introduced, the relationship between folding and faulting was generally described by two distinct models. First, folding predates fault propagation, which means that after a fold forms by buckling, its amplitude grows and the fold progressively becomes tight and asymmetric. The overturned limb of the fold is stretched, thinned and develops into a thrust. This is usually described as stretch-thrust model (Heim, 1919). Second, a fault propagates first and is involved in the subsequent folding (Buxtor, 1916), or an asymmetric anticline in the hanging wall and/or an asymmetric syncline in the footwall of a thrust occur by drag folding in response to the frictional resistance along the fault surface. Rich (1934) applied the idea of fault-bend folds to interpret that the geometry of the steep Cumberland monocline and the gentle Powell anticline are controlled by the underlying step thrust when he studied the foreland fold-thrust belts in the southern Appalachian orogen. Different models were proposed for fault-related folds (McClay, 2004, 2011). For example, the geometric and kinematic models of fault-related folds, i.e. fault-bend fold (Suppe, 1983), fault-propagation fold (Jamison, 1987; Suppe and Medwedeff, 1990; Mitra, 1990) and detachment fold (Homza and Wallace, 1995; Mitra, 2003; Suppe, 2011) were established to describe the relationship between folds associated with faults. Furthermore, the concept of trishear fault-propagation fold (Erslev, 1991; Allmendinger and Shaw, 2000; Cristallini, 2002; Johnson and Johnson, 2002; Cardozo et al., 2003) and growth strata (Suppe et al., 1992) were proposed to further describe fault kinematics.

Many geologists have realized the existence of a second class of fold-fault structures and described them. They introduce the terminology such as fold-generated imbricates, fold-generated faults, fold-accommodation faults, and fold-related faults to name the structures (Johnson, 1980; Mitra, 2002; Wu et al., 2007). These terminologies imply that the primary significance of this structure

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* Corresponding author. Hans Ramberg Tectonic Laboratory, Department of Earth Sciences, Uppsala University, Villavagen 16, SE-752 36 Uppsala, Sweden. Fax: +46 (0) 18 471 25 91.

E-mail addresses: Hongling.Deng@geo.uu.se, denghl0321@gmail.com (H. Deng).

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is that faulting is controlled by folding in contrast to fault-related folds where the fault controls the folding. The first systematic investigation of such structures was provided by Mitra (2002), in which he defined fold-accommodation faults as a secondary structure that accommodate strain variations related to structural and stratigraphic position during fold evolution. The concept of fold-accommodation faults (Mitra, 2002) has been applied to the tectonic interpretations in the Ruhr basin (Wrede, 2005) and the Tethyan sedimentary zone (Mukhopadhyay, 2008).

Studies of fold-accommodation faults have contributed to understanding the geometric and kinematic relationships between folds and faults from a new point of view, and also have the important implications for a comprehensive interpretation in cross-section restoration and structural trap mechanisms. However, the primary question is how to recognize fold-accommodation faults, distinguish them from the general reverse faults and thrusts in fault-related folds, and use the knowledge in an applicable and efficient way. Even though in previous studies a series of diagnostic characteristics in the geometry and displacement distribution have been summarized to distinguish such structures, they are either impractical (Mitra, 2002) or inadequate to general situations (Wrede, 2005; Wu et al., 2007). DENG et al. (2009) attempted to address this question by qualitatively describing hand specimen-scale and outcrop-scale fold-accommodation faults based on the definition and the classification proposed by Mitra (2002). The primary identifying characteristics were summarized, which included that fold-accommodation faults are relatively smaller than the associated folds; displacement decreases towards the core of the fold along out-of-syncline and into-anticline thrusts; cut-off angles tend to increase when the faults cut through the hinge zone of the fold; spatial distribution of fold-accommodation faults tend to arrange symmetric to the axial surface of the fold; kinematic consistency occurs between the fault vergence and the flexural-slip folding. However, some ambiguities still exist in these identifying characteristics. For example, how to compare fold-accommodation faults with the fold they reside in terms of scale? How to quantitatively illustrate the signature of displacement distribution along these faults? Spatial position of the faults relative to the folds and cut-off angle change along the faults still have some uncertainties, and thus needing further studies. In addition, DENG et al. (2009) have realized that it is difficult to classify some of natural examples into Mitra's model (2002). However, they did not give detailed analysis and discussion on these structures.

In order to introduce more rigorous signatures into the identification of fold-accommodation faults, we will describe some hand specimen-scale and outcrop-scale examples in this study. Displacement distribution along the faults from outcrop structures are analyzed by applying separation–distance graphs. The classification of fold-accommodation faults proposed by Mitra (2002) is used as a general reference in the description of our examples (Fig. 1a–e). Through comparison of Mitra's (2002) classification with the natural examples discussed in this work, we realized that out-of-syncline thrusts, into-anticline thrusts and wedge thrusts may commonly occur in buckling folds. Besides, in our examples

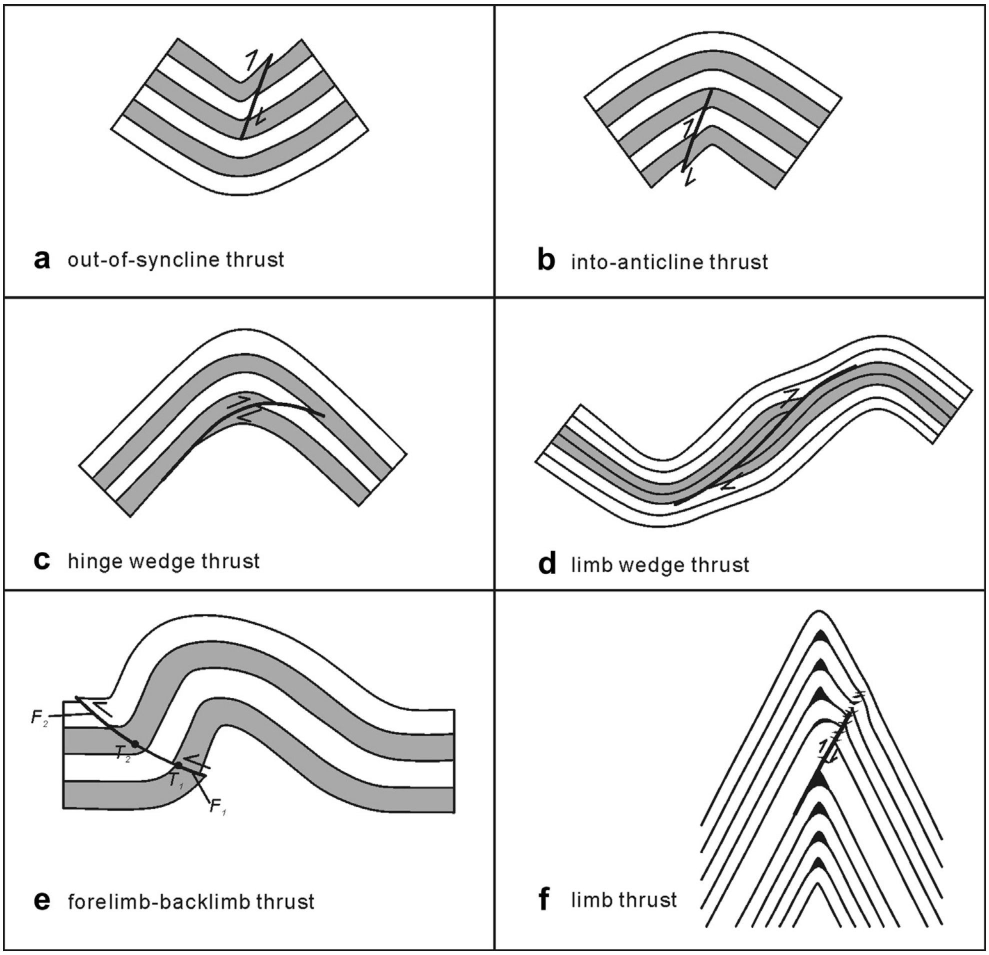

Fig. 1. a–e, part of the main types of fold-accommodation faults (after Mitra, 2002). f, limb thrust (after Ramsay, 1974).