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Shear angle and amount of extension calculations for normal faults emanating from a detachment: Implications on mechanisms to generate rollovers

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ABSTRACT

The reconstruction/restoration/modelling of normal faults (both listric and planar) emanating from a detachment at depth and their associated rollover folds, using the vertical or inclined shear method is widely utilized because its simplicity and the information it can provide. However, it has a rather serious issue derived from the uncertainty about the shear angle, the type of shear and the amount of extension that should be employed in each situation. Here we describe a new methodology that, using easily acquired input data, allows estimation of whether the shear was vertical, antithetic or synthetic and the values for both the shear dip and the amount of extension. These calculations rely on the use of graphs of throw versus heave for different horizons affected by the normal fault and the associated rollover, and are checked using an area-based method which permits the determination of whether these values are correct. These graphs may be used as a predictive tool or as a guide to show how the assumptions deviate, such as distinguishing quickly whether other mechanisms apart from vertical/inclined shear took place. The effects of syn-extension sedimentation and reverse fault reactivation on the proposed method are also examined. The analysis of experimental and natural examples shows that the initiation of some rollovers with a component of fault-propagation and/or drag folding, and/or development of a crestal collapse graben cause the estimated shear dips to be smaller than the actual values and the amounts of extension to be greater. In addition, these analyses show that the shear dip may increase with increasing extension.

1. Introduction

Normal faults emanating from detachments at depth are a type of structure widely represented in nature and, consequently, the subject of multiple studies. Many of these analyses are focused on developing techniques to reconstruct the faults and/or their associated rollover folds from the available data. Diverse methods to calculate the depth of the detachment from which the fault would emanate have been developed: a) those based on the lost area rule (adaptation of the Chamberlin (1910) method for normal faults); b) those that rely on the rotation of rigid blocks along circular faults (Moretti et al., 1988); c) lost-area diagrams (Groshong, 1994, 1996); and d) graphs of best linear fit of detachment depths (Bulnes and Poblet, 1999) adapted to normal faults. There are also techniques allowing the determination of the complete shape of the fault at depth, such as: a) those based on vertical shear, known as the chevron construction or constant heave (Verrall, 1981), or on inclined shear both synthetic and antithetic (White et al., 1986; Dula, 1991), including subsidiary faults (Song and Cawood, 2001), with layer-parallel strain (Groshong, 1990) or with fault parallel shear (Williams and Vann, 1987); b) those considering constant displacement along the fault (Williams and Vann, 1987); and c) constructions founded on flexural slip (Davison, 1986) or constant thickness beds (Morris and Ferrill, 1999) (Fig. 1). Most of these methods permit also to model the rollover resulting from the fault activity. This construction is also feasible from other techniques such as: a) the one for circular faults and rigid blocks (Moretti et al., 1988), b) models based on fault-bend folds (Groshong, 1989; Xiao and Suppe, 1992), c) finite difference assuming uncompressible flow (Waltham, 1989), and d) hangingwall collapse following the Coulomb criteria comparable to simple shear (Tearpock and Bischke, 1991). The experimental models generated in the

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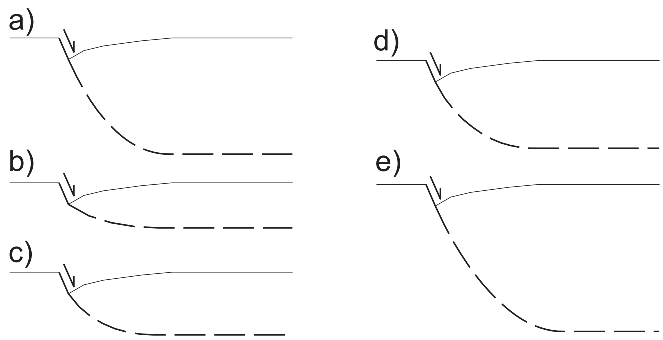

Fig. 1. Examples of listric normal faults reconstructed at depth through different methods using the same rollover geometry as input data: a) flexural slip; b) constant displacement; c) antithetic shear of 80° dip; d) vertical shear and e) synthetic shear of 80° dip.

laboratory have also substantially helped the understanding of normal faults because they allow assessment of parameters such as amount of extension, fault shape, etc. (McClay and Ellis, 1987a, 1987b; Ellis and McClay, 1988; McClay, 1989, 1990a, 1990b, 1995, 1996; Schlische et al., 2002; Henza et al., 2010 amongst others). One of the main issues derived from the plethora of available procedures is that the resulting reconstructions obtained may vary enormously depending on the technique employed (Fig. 1). Thus, the selection of one or another method is of great importance.

The methods based on vertical/inclined shear are the most utilized. Despite the simplification they imply about the particle motion, they make predictions on the fault shape and detachment depth (e.g., Verrall, 1981; White et al., 1986), the rollover morphology (e.g., Matos, 1993), the algorithms to forward model and/or restore the structures and the deformation undergone (e.g., Matos, 1993; Poblet and Bulnes, 2007) easily. Furthermore, they have been proved to be suitable methods for modelling both natural (Groshong, 1990; White and Yielding, 1991; Matos, 1993; Poblet and Bulnes, 2005a) and experimental examples (Groshong, 1990; Poblet and Bulnes, 2005a, 2005b). Consequently, the vertical/inclined shear methods are considered to be a good approximation of the behaviour of the hangingwall of normal faults during extension (McClay et al., 1995). However, the uncertainty about the type of shear and the shear angle that should be chosen in each case constitutes a crucial disadvantage for their application, as different angles result in dissimilar results (Fig. 1c–e). There are diverse approaches to estimate the shear angle and its character (synthetic, vertical or antithetic): a) shear parallel to the rollover axial traces (Xiao and Suppe, 1992), b) shear parallel to the subsidiary faults associated with the main one (White et al., 1986; Xiao and Suppe, 1992), c) the trial and error method (White and Yielding, 1991), and d) quantitative methods that require knowing the amount of layer-parallel strain and the rollover general dip (Groshong, 1990).

The horizontal extension is another parameter that controls greatly the results. Some of the methods to estimate it from the available data were proposed originally for contraction, but were adapted to extensional settings: a) comparison between unfolded bed length and structure width (Gwinn, 1970), b) maximum displacement along the fault (Chapman and Williams, 1984), c) fault heave (Ziegler, 1982; Jackson and Galloway, 1984; Barr, 1985), d) mean between the extension estimated using bed length and the maximum fault displacement (Williams and Vann, 1987), e) rollover axial traces separation (Xiao and Suppe, 1992), and f) slope of the lost-area best-fit function (Groshong, 1994, 1996). Dissimilar extension values are obtained depending on the technique employed (Poblet and Bulnes, 2005a, 2005b), which has important consequences for the predictions that can be made.

We present a new method that provides estimation of the shear properties (dip and character) and of the amount of extension to model normal faults. The main difference with previous procedures is that it is able to estimate both parameters using simply a portion of the main fault offsetting a minimum of, at least theoretically, two horizons, although to use more horizons is recommended. The method only requires simple measurements on a geological section across a fault, projecting them on a graph and finding a best-fit function for the plotted data. Theoretically, this method could be used as a predictive tool. However, its application to experimental and natural examples suggests that it supplies minimum shear dips and maximum amounts of extension that get closer to actual values for faults with high amounts of extension. Checking the results using a new area-based method, which involves comparison between the area in the present-day, deformed section, and that in an undeformed section, supports this conclusion. In addition, the method presented can help in determining how much studied structures deviate from the expected behaviour if they were solely the result of vertical/inclined shear with a uniform dip.

2. Analysis of the heave, throw and displacement in normal faults with associated rollovers

One of the aims of this work is to find a procedure that allows the determination of: 1) the shear dip, 2) the shear character (antithetic, vertical or synthetic) and 3) the amount of extension taking as input parameters the heave, throw and displacement of several horizons along a fault. This makes of capital importance a thorough analysis of how the fault slip components vary along successions offset by normal faults emanating from a detachment. In any normal fault the horizon located at the detachment level has a null throw, which implies that the heave and the displacement are the same and, assuming no strain within the hangingwall, equal to the extension. To visualize how these parameters vary for the rest of the horizons, theoretical rollover were created using the models of vertical shear (Verrall, 1981), inclined shear (White et al., 1986), flexural slip (Davison, 1986) and constant thickness beds (Morris and Ferrill, 1999). They were built using different values of extension and fault shapes (ramp-flat, segmented, cubic or arctangent functions, splines) (Fig. 2). The models created are based on a series of assumptions: a) the hangingwall is deformed as a rollover (fault-bend folding) according to the inclined or vertical shear mechanisms and combinations of mechanisms are not considered, b) the shear dip is constant over time and all along the whole hangingwall, c) the geometry of the fault and the footwall beds does not vary along the process, and d) compaction is not considered. In this paper we present only the most significant cases analyzed. For each geological section we measured the heave, throw, displacement, and stratigraphic height with respect to an

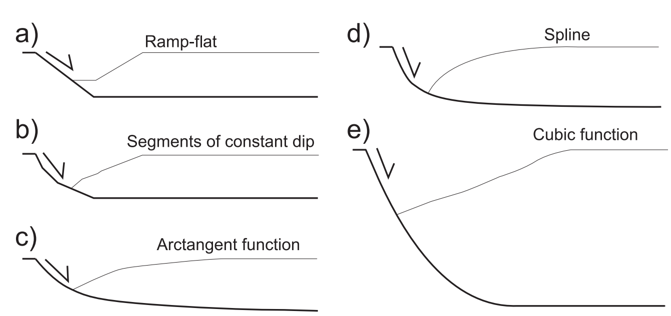

Fig. 2. Examples of rollover folds generated with antithetic shear of 80° dip in the hangingwall of different shape faults: a) ramp-flat, b) segments of constant dip, c) arctangent function, d) spline, and e) cubic function.