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2-D and 3-D modeling of detachment folds with hinterland inflation: A natural example from the Monterrey Salient, northeastern Mexico

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Abstract

Geologists now recognize the presence and abundance of detachment folds in various contractional settings. Several two-dimensional geometric and kinematic models exist to describe the development of such structures. These models typically are area-balanced, are interpreted to develop by hinge migration, limb rotation, or a combination of the two processes, and possess a constant regional level outside the fold itself. We present two new two-dimensional geometric and kinematic models for detachment folds that incorporate hinge migration and limb rotation as their deformation mechanisms. These area-balanced models differ from previous models, however, in that they allow 'hinterland inflation' to occur, thereby creating a higher local regional level in the hinterland relative to the foreland. This local regional difference across the detachment fold may reflect hinterland uplift due to thickening of the incompetent unit, foreland deflation of the incompetent unit as material migrates into the fold core during fold growth, and/or migration of material out of the fold core as the fold tightens.

We illustrate the utility of these models by constructing pseudo-three-dimensional representations of the western termination of the Nuncios Fold Complex in the Monterrey Salient, northeastern Mexico. Our results suggest that the limb rotation model more accurately portrays the overall three-dimensional fold geometry for the Nuncios Fold Complex, matches the observed hinterland inflation, and predicts more reasonable detachment depths for the structure along its length. These results agree with interpreted kinematics based on field observations and illustrate how this modeling approach may help constrain interpretations of detachment folds with hinterland inflation in areas lacking sufficient data.

Keywords: Fault-related folds; Detachment folds; Monterrey Salient, Mexico; Kinematic model

1. Introduction

Maps and cross sections of most contractional settings commonly depict fault-related folds (e.g., fault-bend folds, fault-propagation folds, detachment folds) as fundamental structural elements that comprise these complex regions (e.g., Dahlstrom, 1970; Suppe, 1983; Jamison, 1987; Mitra, 1990, 1992; Suppe and Medwedeff, 1990; Wilkerson et al., 1991; Wilkerson and Wellman, 1993; Apotria and Wilkerson, 2002). Within the last two decades, geologists have come to recognize that detachment folds are more abundant and play a more significant role in these settings than previously thought (e.g., Jamison, 1987; Mitchell and Woodward, 1988; Dahlstrom, 1990; Epard and Groshong, 1993; Groshong and Epard, 1994; Hardy and Poblet, 1994; Epard and Groshong, 1995; Homza and Wallace, 1995; Poblet and Hardy, 1995; Poblet and McClay, 1996; Homza and Wallace, 1997; Atkinson and Wallace, 2003; Wilkerson et al., 2004). Detachment folds commonly develop to accommodate shortening and displacement of rocks with contrasting mechanical properties above (or below) a sub-horizontal slip surface (i.e., a detachment; Wilkerson et al., 2004). Typically, detachment folds

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exhibit a box-fold geometry whose internal core contains an incompetent mechanical unit that may or may not deform disharmonically from the overlying competent mechanical layers (e.g., Fig. 1). In contrast to other types of fault-related folds, detachment folds lack a first-order fault ramp that steps up from the basal detachment surface.

Numerous two-dimensional geometric and kinematic models have been proposed to describe the development of detachment folds (e.g., Dahlstrom, 1990; Homza and Wallace, 1995; Poblet and McClay, 1996; Homza and Wallace, 1997; Atkinson and Wallace, 2003; Mitra, 2003). Most models create area-balanced cross sections of detachment folds (cf. Chamberlin, 1910) by prescribing geometric relationships between shortening, detachment depth, limb dips, and limb lengths due to the kinematic processes of hinge migration, limb rotation, or some combination of the two while maintaining a constant local regional stratigraphic level outside of the fold itself. Several authors (e.g., Homza and Wallace, 1997; Bulnes and Poblet, 1998; Wallace and Homza, 1998; Thomas, 2001; Mitra, 2003), however, have documented or hypothesized that the thickness of the incompetent layer may experience significant thickness changes during detachment fold development. Such changes may produce a corresponding deflation and/or inflation of the local regional stratigraphic level outside the bounds of the detachment fold anticline. In some cases, these changes are approximately equal on either side of the detachment fold anticline, whereas in others, the local regional levels exhibit differences in elevation between the hinterland and foreland (e.g., Homza and Wallace, 1997; Bulnes and Poblet, 1998; Wallace and Homza, 1998; Thomas, 2001; Mitra, 2003). Such differences in local regional levels across a fold may not exclusively reflect thickness changes in the detachment layer above a sub-horizontal detachment, but rather may also indicate fundamental differences in the underlying geological architecture (e.g., faulting, non-horizontal detachment, non-horizontal sub-detachment units, etc.).

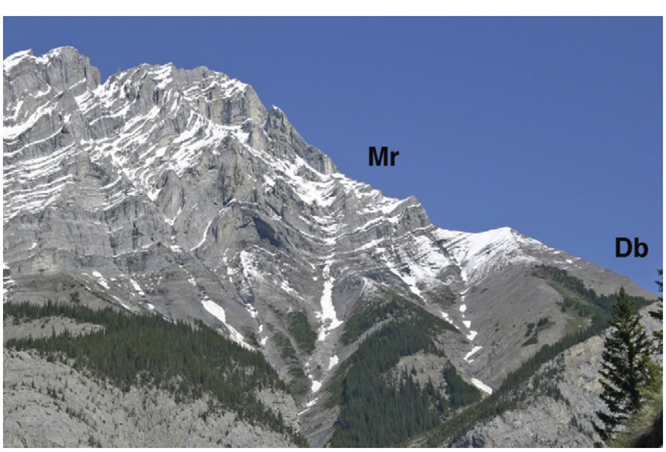

Fig. 1. Photo of detachment fold on the southeastern face of Cascade Mountain near Banff, Alberta, Canada. Mississippian Rundle Group (Mr) carbonate rocks define a small fold above a detachment within the shaly beds of the Devonian Banff Formation (Db). Structure lies within the hanging wall of the Rundle thrust sheet.

In this manuscript, we describe two new two-dimensional geometric models for detachment folds that form by the end-member processes of hinge migration and limb rotation. These area-balanced models differ from existing models, however, in that they allow 'hinterland inflation' to occur within the incompetent layer above a sub-horizontal detachment, thereby creating a higher local regional level at the trailing edge (i.e., hinterland) of the detachment fold relative to the foreland. This regional difference across the detachment folds may reflect (1) hinterland uplift due to thickening of the incompetent unit, (2) foreland deflation as material from the incompetent unit moves into the fold core as the fold increases in amplitude, and/or (3) inflation of the hinterland as material from the incompetent unit is squeezed out of the fold core as shortening progresses. While we readily acknowledge that there are multiple ways of producing differences in local regional level across natural detachment folds, this manuscript will focus on models where these differences in local regional levels are assumed to be due to thickness changes in the detachment layer above a sub-horizontal detachment. We illustrate the utility of these models by analyzing the two- and three-dimensional geometry of the western termination of the Nuncios Fold Complex in the Monterrey Salient, Mexico.

2. Model descriptions

Detachment fold models that incorporate hinterland inflation are conceptually similar to models described by Poblet and McClay (1996; their models 1 and 2; see also Wilkerson et al., 2004). Specifically, both models depict the geometry of the folded interface between the incompetent unit and the overlying competent unit as two straight fold limbs and a single flat crest that is parallel to both the underlying detachment and to undeformed layers outside the fold itself (Fig. 2). Competent unit bed length is conserved during fold development for both models because penetrative layer-parallel strain is assumed to be negligible in the competent unit and because shortening is homogeneously distributed throughout the deformed layers (i.e., there is a vertical pin line on the trailing edge). Because material is not permitted to move in or out of the plane of the cross section and because bed length of the competent unit is conserved, the cross-sectional area of the model folds is preserved (Fig. 2).

2.1. Model derivation

The following derivation is similar to that provided in Poblet and McClay (1996) with modifications that incorporate hinterland inflation (refer to Fig. 2). For both models, the uplift of the fold crest can be described by

$$u = L_b \sin(D_b) + h, \tag{1}$$

and

$$u = L_f \sin(D_f) \tag{2}$$