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Strain variation with progressive deformation in basement-involved trishear structures

Shankar Mitra*, James F. Miller[1]

School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019, USA

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Basement-involved structures associated with reverse, vertical and normal faults commonly involve non-parallel shear within a triangular deformation (trishear) zone located on the front limbs of the structures. Deformation within the trishear zone is characterized by shear gradients and an associated decrease in the dips of the beds in stratigraphically higher units. Geometric models suggest that the layer-parallel strain within the trishear zone depends on the type of fault (normal, reverse, or vertical), the dip and throw of the fault, the dip of the anticlinal or synclinal axial surfaces, and the distance of any unit above the initial tip of the trishear zone, located at the basement-sediment contact. At any given location, reverse faults typically show increasing layer parallel shortening, followed by decreasing layer parallel shortening and a transition to extension, with increasing throw. The transition from contraction to extension occurs at lower values of throw for stratigraphically lower units and also for faults with smaller dips. Vertical and normal faults exhibit increasing layer-parallel extension of all units with increasing throw, with larger extension for stratigraphically lower units. Experimental models suggest that the trishear zone can expand with increasing fault throw. The strain within the trishear zones is accommodated largely by secondary faults, which are rotated with progressive deformation. The strain variations in the experiments closely mimic those predicted by the geometric models for reverse, vertical, and normal faults.

1. Introduction

Basement-involved structures represent a common structural style in the foreland of many orogenic belts. The geometry and evolution of these structures have been explained using a number of structural models, including models associated with reverse or thrust faults (Berg, 1962; Blackstone, 1993; Stone, 1993; Brown, 1993; Spang et al., 1985; Narr and Suppe, 1994), normal faults and associated drape folds (Stearns, 1978), and vertical faults (upthrusts) which decrease in dip within the sedimentary cover (Prucha et al., 1965). Extensive analysis of subsurface seismic and well data suggests that many foreland structures are compressional structures associated with reverse faults, although the other structural types are also common.

A widely applied model to explain the geometry of the structures involves the dissipation of fault slip within a triangular deformation zone, also referred to as a trishear zone (Erslev, 1991; Erslev and Rogers, 1993), in the sedimentary units overlying the basement. The general trishear model also applies to many extensional structures in rift basins, where the basement fault slip is dissipated within broad drape folds within the sedimentary cover.

Deformation within the trishear zone has been modeled theoretically (Erslev, 1991; Freund, 1979; Hardy and Ford, 1997; Mitra and Mount, 1998; Allmendinger, 1998; Zehnder and Allmendinger, 2000), and experimentally, for both extensional (Withjack et al., 1990; Jin and Groshong, 2006), and compressional structures (Miller and Mitra, 2011). Variations of this basic model have been developed and applied to both surface and subsurface structures (Erslev, 1991; Schmidt et al., 1993; Mitra and Mount, 1998; Johnson and Johnson, 2001).

Trishear zones involve a complex evolution of strain patterns (Mitra and Mount, 1998). In this paper, we investigate the variation of layer-parallel strain with progressive deformation using theoretical and experimental models. The strain evolution is analyzed for reverse, normal, and vertical basement faults. The experimental models for all these fault geometries are conducted using similar materials and at the same scale. Therefore the similarities and differences in strain patterns in different structural settings can be easily analyzed and compared. The results of the study provide

* Corresponding author.
E-mail addresses: smitra@ou.edu (S. Mitra), mill7613@gmail.com (J.F. Miller).
[1] Current address: Conoco Phillips Co., Midland, TX 79705, USA.

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insights on the geometry and evolution of surface and subsurface basement structures, and can be used to analyze structures with limited data. They can also be used to understand the formation of secondary structures on the forelimbs of large structures.

2. Previous work on trishear folding

The basic model of trishear fault-propagation folding for basement-involved compressional structures (Erslev, 1991) postulates that slip on basement faults is dissipated by oblique shear within an initially triangular zone in the sedimentary cover. Erslev (1991) proposed both footwall and hanging wall fixed models and also discussed the differences between homogenous and heterogenous strain within the trishear zone. The deformation occurs by folding and secondary faulting within the trishear zone. With increasing deformation, the area between a pair of axial surfaces is progressively sheared, while maintaining a constant area. The area near the anticlinal axial surface decreases, whereas the area near the synclinal area increases, causing material to migrate downwards across the projection of the main basement fault (Fig. 1). In order to accommodate the material transfer, it is expected that layer parallel extension close to the anticlinal axis is balanced by layer-parallel contraction close to the synclinal axis. The trishear model has also been applied to normal and vertical faults (Jin and Groshong, 2006; Miller and Mitra, 2011). Layer-parallel strain patterns vary depending on the dip of the fault, and the structural and stratigraphic position (Mitra and Mount, 1998).

The trishear zone may be characterized by heterogenous shear between fixed axial surfaces (Erslev, 1991; Zehnder and Allmendinger, 2000). An alternate model for the development of curved beds within the trishear zone is the expansion of the trishear zone by incorporation of new material from the undeformed units on either side (Mitra and Mount, 1998). This occurs by the generation of new active axial surfaces, so that the beds are differentially rotated, resulting in a rounded to sub-angular structural geometry. This model is supported by experimental studies (Miller and Mitra, 2011), which suggest that the trishear zone initially expands, but is subsequently confined to a constant total area. At this stage, one or more faults in the network of diverging faults breaks through the entire structure. Therefore, the apex angle of the trishear zone initially increases, and is subsequently fixed in the late stages of deformation. The outermost axial surfaces, which are also the last to form, are the bounding axial surfaces of the trishear zone.

Additional variations of trishear deformation, such detachments between the basement and cover, and internal deformation of the basement (Schmidt et al., 1993), result in a number of end-member and hybrid models (Mitra and Mount, 1998).

This paper addresses the strain patterns in trishear zones for basement-involved structures with different fault dips. Geometric models are compared with results from experimental models to study the variation in strain associated with a number of key factors such as the fault dip, orientation of the anticlinal and synclinal axial surfaces, the basement fault throw, and the stratigraphic position of a unit relative to the top of basement, which also represents the initial tip of the triangular zone.

3. Geometric models

In this section, we develop quantitative relationships for layer-parallel strains for area-balanced basement structures formed by trishear deformation. The approach was originally discussed briefly by Mitra and Mount (1998), and is expanded here to study the detailed variations in strain in the trishear zone for units with different stratigraphic positions and associated with different fault dips for reverse, vertical, and normal faults. The total layer-parallel strain is analyzed for each unit within the trishear zone, as compared to the strain at discrete points as analyzed by Allmendinger (1998). These detailed studies are compared with the results of experimental models of basement structures.

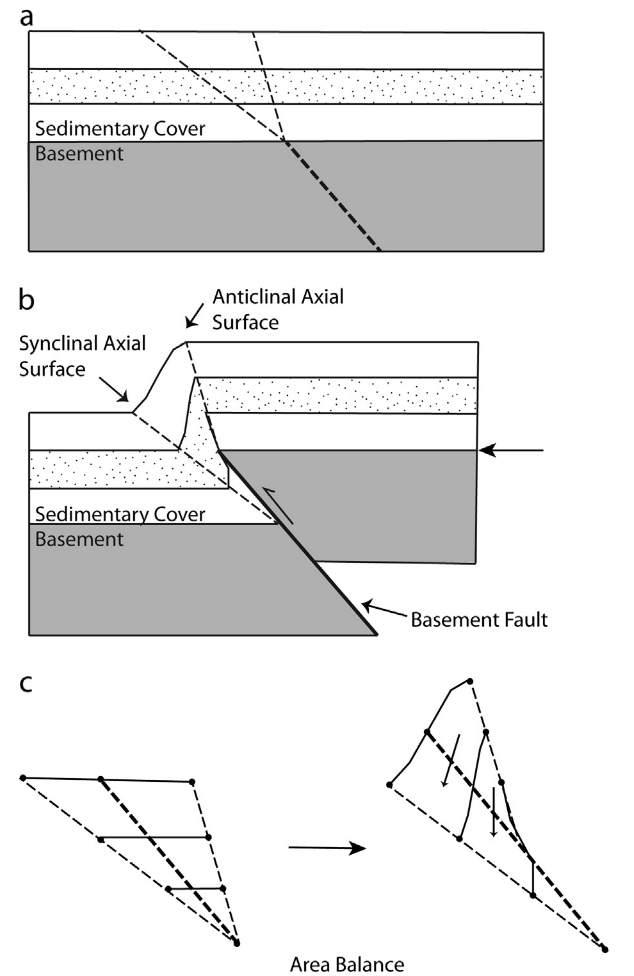

Fig. 1. Trishear deformation of associated with a basement-involved compressive structure. a–b. Basement faulting results in the shearing of a triangular zone in the sedimentary cover units. The trishear zone is bounded by anticlinal and synclinal axial surfaces, and involves steepening of beds of stratigraphically lower units in the trishear zone. c. Area balancing of the trishear zone shows transfer of material from the anticlinal to the synclinal axis across a projection of the fault.

The models are developed for the hanging wall fixed trishear model with homogenous deformation between fixed axial surfaces (Erslev, 1991), also described as model 1a in Mitra and Mount (1998). The general theory is independent of whether the fault is a reverse, vertical, or normal fault. A fault in the basement dipping θ_b terminates upward in a trishear deformation zone within the sedimentary cover units (Fig. 2). The trishear zone is bounded by an anticlinal axial plane dipping θ_a and a synclinal axial plane dipping θ_s. T represents the throw on the fault, and t_s represents the thickness of stratigraphic units between the top of the basement and the sedimentary unit being analyzed. Area balancing of the structure requires that the area loss in the hanging wall of the fault projection must be equal to the area gain in the footwall for each of the sedimentary units.

The area gain is given by the triangle BMB′, and the area loss is given by the triangle AMA′, so that triangles AMA′ and BMB′ are congruent.