Journal of Structural Geology 95 (2017) 60–76

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Strain modelling of extensional fault-propagation folds based on an improved non-linear trishear model: A numerical simulation analysis

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A R T I C L E I N F O

Article history:
Received 2 July 2016
Received in revised form
4 November 2016
Accepted 10 December 2016
Available online 13 December 2016

Keywords:
Strain analysis
Extensional fault-propagation fold
Trishear model
Numerical simulation
Shape factor

A B S T R A C T

This paper focuses on the strain modelling of extensional fault-propagation folds to reveal the effects of key factors on the strain accumulation and the relationship between the geometry and strain distribution of fault-related folds. A velocity-geometry-strain method is proposed for the analysis of the total strain and its accumulation process within the trishear zone of an extensional fault-propagation fold. This paper improves the non-linear trishear model proposed by Jin and Groshong (2006). Based on the improved model, the distribution of the strain rate within the trishear zone and the total strain are obtained. The numerical simulations of different parameters performed in this study indicate that the shape factor R, the total apical angle, and the P/S ratio control the final geometry and strain distribution of extensional fault-propagation folds. A small P/S ratio, a small apical angle, and an R value far greater or far smaller than 1 produce an asymmetric, narrow, and strongly deformed trishear zone. The velocity-geometry-strain analysis method is applied to two natural examples from Big Brushy Canyon in Texas and the northwestern Red Sea in Egypt. The strain distribution within the trishear zone is closely related to the geometry of the folds.

1. Introduction

Extensional fault-propagation folds are widespread in areas such as the North Sea (Withjack et al., 1989), the Gulf of Suez (Gawthorpe et al., 1997; Sharp et al., 2000; Jackson et al., 2006), the Rocky Mountains (Janecke et al., 1998), and the Gilbertown Graben System (Jin et al., 2009). They are usually caused by slip on a blind normal fault. When the tip of the blind fault moves upwards at a slower speed than the slip on the fault, synclines and anticlines come into being (Ferrill et al., 2004).

Extensional fault-propagation folds attract the attention of geologists due to the common presence of hydrocarbons trapped in these structures, and many studies focuse on their geometry, kinematics, and dynamics (Gawthorpe et al., 1997; Jin et al., 1998; Withjack et al., 1990; Schlische, 1995; Hardy and McClay, 1999; Cardozo et al., 2003; Jin and Groshong, 2006). These studies indicate that the formation of an extensional fault-propagation fold is closely related to an inverted triangular (upward widening) deformation zone referred to as "the trishear kinematic zone".

The trishear model was first proposed by Erslev (1991) to explain and predict the geometry of fault-propagation folds and was then used to study the folds that formed in an extensional environment. Hardy and Ford (1997), Allmendinger (1998), Hardy and McClay (1999), and Gawthorpe and Hardy (2002) presented various symmetric trishear models to describe and analyse the effects of key parameters on the final geometries of the fold and the growth strata. Several non-linear numerical trishear models were also proposed (Zehnder and Allmendinger, 2000; Jin and Groshong, 2006) to explain the existence of asymmetric trishear zones, which were shown to be more consistent with reality based on field observations and experiments (Withjack et al., 1990).

Geologists tend to pay more attention to the velocity field within the trishear zone and less attention to the corresponding strain rate and final strain distribution. The strain rate and total strain are two key variables in the deformation process and are important for analysing the generation and relaxation of stress. Therefore, the relationship between the final geometry and the strain distribution of a fold requires further exploration.

In this paper, we focus on the strain modelling of an extensional fault-propagation fold to reveal the relationship between the final geometry and the strain distribution of the fold and the effects of key factors on the strain accumulation. We propose a velocity-

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http://dx.doi.org/10.1016/j.jsg.2016.12.009

geometry-strain method to analyse the total strain and its accumulation process within the trishear zone. We improve the nonlinear trishear model proposed by Jin and Groshong (2006) and use it to show the velocity field and strain rate distribution within the trishear zone using 3D images and contour maps. By integrating the velocity and strain rate with time, we obtain the final geometry and strain distribution of the fold, which allows us to discuss their relationship and the effects of three key parameters on them. Finally, we apply the strain model to two examples from Big Brushy Canyon in Texas and the northwestern Red Sea in Egypt and determine the velocity field, final geometry, and strain distribution. We recreate the deformation and strain accumulation process using velocity-geometry-strain analysis and obtain a good estimate of the geometry and strain distribution.

2. The improved model and its velocity field

The velocity of each point can be decomposed into two components in the X and Y directions by establishing the coordinate system shown in Fig. 1:

$$\boldsymbol{V}(X,Y) = \boldsymbol{V_x}(X,Y) + \boldsymbol{V_y}(X,Y) \tag{1}$$

The boundary conditions of the two velocity components can be obtained and be described as follows:

$$V_x = V_0 \quad V_y = 0 \;\; where\ Y = X\ tan(\varphi_1) \tag{2.1}$$

$$V_x = 0 \quad V_y = 0 \;\; where\ Y = X\ tan(\varphi_2) \tag{2.2}$$

The question is how to describe the velocity variation within the trishear zone. Jin and Groshong (2006) introduced a new shape factor R and proposed a simple formula to describe the change in X-direction velocity, from V_0 at the left upper trishear boundary to 0 at the right lower trishear boundary, as follows:

$$\mathrm{Vx} = \mathrm{V}_0\left(1 - \frac{l_{LP}}{l_{LR}}\right)^{1/R} \tag{3}$$

This formula shows that the X-direction velocity decreases nonlinearly along the line LR and is closely related to the distance between the points P and L. This formula can be used to simulate various asymmetric trishear zones by choosing different values for the factor R. We retained these basic concepts and made the following improvements to this formula. (1) We use R rather than (1/R) to simplify the formula; thus, the subsequent derivation is simpler because R is more concise and more convenient. (2) The factor R is put in parentheses, which has a noticeable effect on the velocity in the Y direction. This improvement makes the model better able to simulate layer-parallel shearing. These modifications produce the following expression:

$$\mathrm{Vx} = \mathrm{V}_0\left(1 - \left(\frac{l_{LP}}{l_{LR}}\right)^R\right) = \mathrm{V}_0\left(1 - \left(\frac{m_1x - y}{(m_1 - m_2)x}\right)^R\right) \tag{4}$$

where $m_1 = \tan(\varphi_1)$ and $m_2 = - \tan(\varphi_2)$.

We maintain the assumption that the cross-sectional area is constant during the deformation process, which can be described mathematically as follows:

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0 \tag{5}$$

Using Eqs. (4) and (5), we can obtain the equation for the Y-direction velocity:

$$\mathrm{Vy} = \mathrm{V}_0\left(-\frac{Ry + m_1x}{(R+1)x} \times \left(\frac{m_1x - y}{(m_1 - m_2)x}\right)^R\right) + C \tag{6}$$

Substituting the boundary conditions of Eq. (2) into Eq. (6), we get

$$C = 0 \tag{7.1}$$

$$C = \frac{\mathrm{m}_1 + m_2R}{R+1} \times \mathrm{V}_0 \tag{7.2}$$

Thus, we have

$$\mathrm{m}_2R + m_1 = 0 \tag{8}$$

Surprisingly, Eq. (8) is the same as that in the Jin and Groshong model, indicating that when two of the three parameters (the hanging wall apical angle φ_1, footwall apical angle φ_2, and factor R) are given, the third one can be determined. As shown in Fig. 2, the relationship between φ_1 and φ_2 varies with different values of

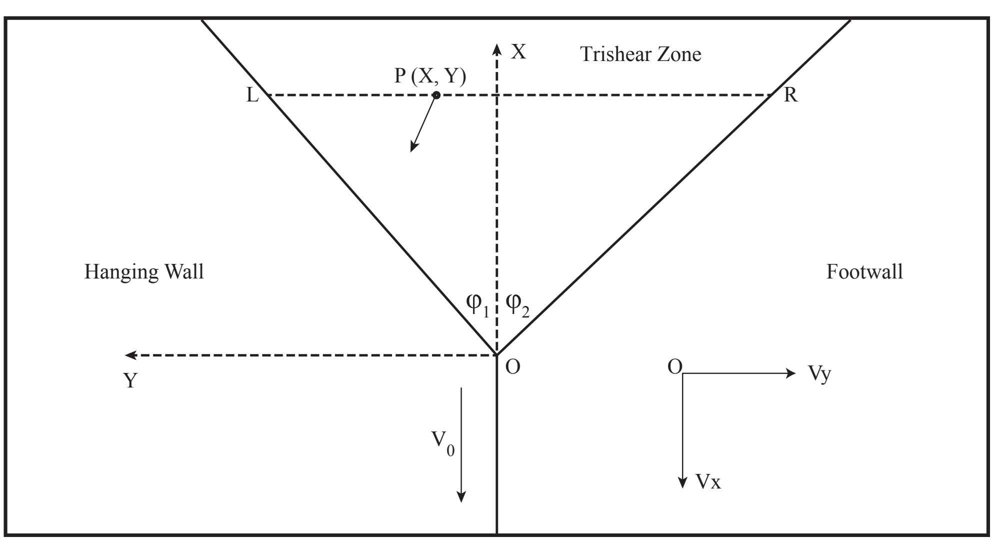

Fig. 1. Basic geometry factors describing the trishear zone. For convenience, we use a vertical X-axis and a horizontal Y-axis, and the origin is the fault tip. P (X,Y) represents any point in the trishear zone. When describing the velocity field, we use a new coordinate system in the right bottom corner; thus, V_0 is positive.