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Kinematic modeling of folding above listric propagating thrusts

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ABSTRACT

We describe a kinematic approach to simulate folds above listric propagating thrusts. The model is based on a pre-defined circular thrust geometry with a maximum central angle beyond which the thrust is planar, inclined shear above the circular thrust, and trishear in front of the thrust. Provided the trajectory of thrust propagation is established, the model can be run forward and backwards. We use this last feature to implement a global simulated annealing, inverse modeling strategy. This inverse modeling strategy is applied to synthetic folds as well as two real examples in offshore Venezuela and the Niger Delta toe-thrust system. These three examples illustrate the benefits of the algorithm, particularly in predicting the possible range of models that can fit the structures. Thrust geometry, depth to detachment level, and backlimb geometry have high impact in model parameters such as backlimb shear angle and fault slip; while forelimb geometry is critical to constrain parameters such as fault propagation to fault slip ratio and trishear angle. Steep to overturned beds in forelimb areas are often not imaged by seismic, so in the absence of additional well data, considering all possible thrust-fold geometries is critical for the modeling and whatever prediction (e.g. hydrocarbon trap integrity) is made from it.

1. Introduction

Listric thrusts that shallow with depth to sole out into a sub-horizontal detachment are common in fold and thrust belts, particularly in deepwater toe-thrust belts such as in the Gulf of Mexico, northwest Borneo and Nigeria (Morley et al., 2011). Folds associated with these structures often display a transition in deformation from detachment folding to fault propagation folding with increasing shortening (faulted detachment folds of Mitra, 2002). Variations of fold geometry in cross section and along strike are highly dependent on the thickness and mechanical stratigraphy of the units involved in the deformation (e.g. thickness and ductility of the units in the core of the structure as opposed to thickness, competence and layered anisotropy of the units above; Mitra, 2002). Steeply dipping to overturned bedding and fault adjacent areas are problematic in these structures, because these areas are often incompletely imaged in seismic surveys. Uncertainty in these "no-seismic-image" zones has strong impact on reservoir appraisal and evaluation of trap integrity (Kostenko et al., 2008).

In an experiment involving the interpretation of a seismic image from a deepwater fold and thrust belt by a group of structural geology experts, Torvela and Bond (2011) concluded that the majority of the participants produced interpretations that were compliant with key features of kinematic models such as trishear (Erslev, 1991; Allmendinger, 1998). As important as this study is to point human bias in geologic interpretation, it has some shortcomings. First, a categorical division of kinematic models was used as the framework to assess the experts' interpretation (Torvela and Bond, 2011, their Table 1). However, detachment, fault-propagation, and fault-bend folds can be considered as points along a continuum of fault propagation to fault slip ratio (P/S) variation (Allmendinger et al., 2004, their Figure 5). Second, a simple step in decollement was used as the base scenario to evaluate backlimb geometries in the kinematic models (Torvela and Bond, 2011, their Figure 3). Nevertheless, kink-type and trishear models can be run on listric faults, resulting in complex, non-planar backlimb geometries (e.g. Hardy, 1995, his Figure 4). Third, planar layer-cake geometry was assumed as the initial state of the models (Torvela and Bond, 2011, their Figure 3). Yet, non-planar and non-parallel layer geometries acknowledging pre-kinematic thinning and folding (e.g. low amplitude detachment folding) can also serve as an initial template of the models. And fourth, and most important, there was no assessment of the fitness of the kinematic models. In other words, for an image/observation driven interpretation with gaps or high uncertainties in no-seismic-image zones, how good is the performance of a kinematic model in replicating the data and their uncertainties? What

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is the actual uncertainty of the model's solution? And ultimately, what is the range of models or possible scenarios that can fit the data and fill the gaps?

In this paper, we use a 2D trishear-based implementation of fault propagation folding on listric thrusts, and globally optimized inversions to approach deepwater compressional folds. Trishear in front of a listric thrust, together with inclined shear in the backlimb is implemented in forward and reverse mode. Restoration of the fold to a simple pre-kinematic configuration consisting of a Gaussian-like fold or a straight line is the criterion to assess the fitness of a given model parameters combination. Estimation of the models that best restore the structure is based on a global optimization (Cardozo et al., 2011). We apply this inverse modeling strategy to a synthetic model (to fully evaluate the performance of the inversion), and two natural examples including a compressional fold in offshore Venezuela (Dee et al., 2007), and the Alpha structure in the outer toe-thrust belt of the Niger Delta (Kostenko et al., 2008). In these three cases, we discuss the performance of the implementation, its benefits and limitations, and the uncertainty of the solution (i.e. the spread of models that can fit the structure).

2. Forward modeling

The implementation we use in this paper models the fault as a circular arc with a given center and radius of curvature (CC and RC), and maximum central angle ($\theta_{\max}$, Fig. 1a). The fault thus increases in dip as it propagates upwards from a detachment level, up to a maximum dip (controlled by $\theta_{\max}$) beyond which it is planar (Fig. 1a). Linear, symmetric trishear (equation 6 of Zehnder and Allmendinger, 2000, with concentration factor $s = 1$) operates in front of the propagating fault (Fig. 1b). This requires a continuous update of the trishear Cartesian coordinate system (with x and y axes parallel and perpendicular to the fault) as the fault propagates along its curved trajectory. In the backlimb, inclined shear takes place (Fig. 1b), such that the velocity vectors are parallel to the fault, and change in orientation across parallel kinks (gray lines in Fig. 1c) that make an angle α (shear angle) with the vertical. This results in a change of fault slip magnitude across each kink according to the equation (Hardy, 1995):

$$R = \frac{1.0}{(\sin\delta/(\partial f/\partial x) + \cos\delta)} \tag{1}$$

where R is the relative change in fault slip magnitude across the kink, δ is the dip of the fault segment after the kink, and $(\partial f/\partial x)$ is the slope of the kink ($\tan(90^\circ - \alpha)$). Notice that since fault slip magnitude changes across the parallel kinks (Fig. 1b), the fault does not propagate at a constant rate along its curved trajectory, but at a rate given by the fault propagation to fault slip ratio (P/S) times the incremental slip entering the trishear zone. Fault parallel slip could also be implemented in the backlimb. This would result in constant fault slip behind the trishear zone and backlimb geometry concentric to the listric thrust. However, deepwater compressional folds often display a backlimb not concentric to the listric thrust.

Fig. 1 shows an example of the implementation in forward mode. In the initial state (Fig. 1a) the beds display a symmetric Gaussian fold whose x coordinate from the center, and y coordinate from the regional of each bed are defined by:

$$y = A\,e^{-\frac{x^2}{2\sigma^2}} \tag{2}$$

where A is the fold amplitude and σ is the standard deviation. From the base of the model, the fold amplitude decreases linearly upwards according to the equation:

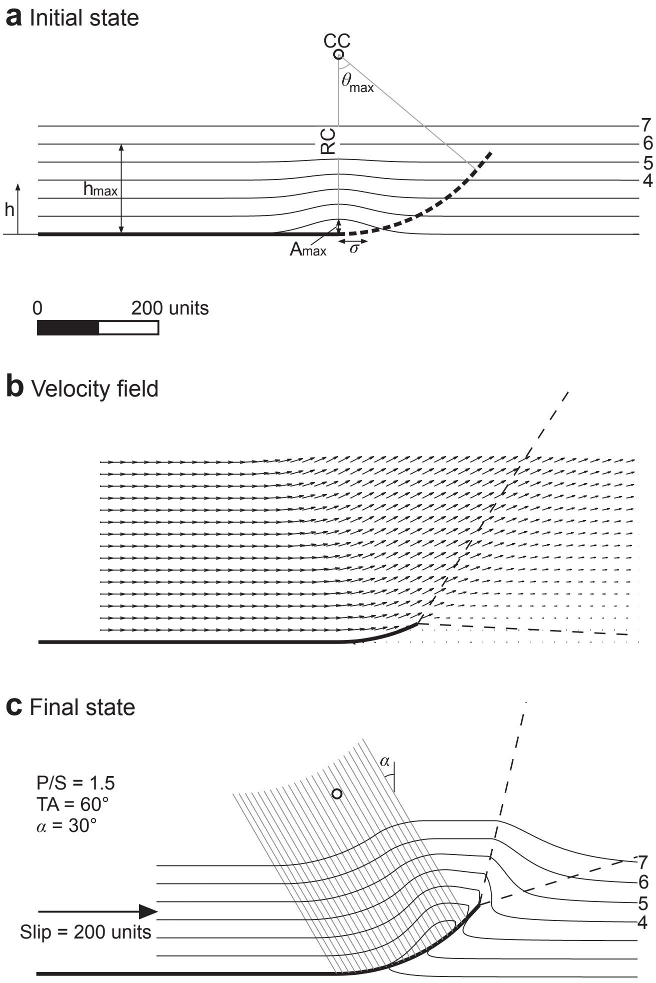

Fig. 1. Example of kinematic model. a. Initial state. Dashed line is trajectory of fault propagation. b. Velocity vectors halfway through the deformation. Entering slip vectors are equal to the incremental slip (1 unit). c. Fold geometry after deformation. Gray lines are kink axes. Beds 4–7 are used in the inversions (Figs. 2 and 3). In b and c, dashed lines ahead the thrust are trishear zone boundaries. Other symbols are explained in the text.

$$\begin{aligned} A &= \tfrac{h_{\max}-h}{h_{\max}} * A_{\max} \quad \text{for } h \le h_{\max} \\ A &= 0 \quad \text{for } h > h_{\max} \end{aligned} \tag{3}$$

where $A_{\max}$ is the fold amplitude at the lowest bed, and $h_{\max}$ is the vertical extent of folding (Fig. 1a). This initial geometry could represent a low amplitude detachment fold or a salt roller. The beds are then deformed using a fault propagation to fault slip ratio (P/S) of 1.5, an apical angle of the triangular zone of shear (trishear angle) of 60°, an entering fault slip of 200 units, an angle of shear (α) of 30°, and 200 increments of slip (slip increment = 1.0 unit). In addition, the maximum central angle of the fault ($\theta_{\max}$) is 50°. Fig. 1c shows the deformed model.

3. Inverse modeling

As long as the trajectory of propagation of the thrust is defined, the model can be run backward to restore beds. Inverse modeling thus consists of searching for the model parameters combination that best restores beds to their original orientation. The agreement between the initial and restored geometry of the beds for a particular choice of model parameters is measured by an objective