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Defining a 3-dimensional Trishear Parameter Space to Understand the Temporal Evolution of Fault Propagation Folds

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ABSTRACT

The application of trishear, in which deformation occurs in a triangular zone in front of a propagating fault tip, is often used to understand fault related folding. A key element of trishear, in comparison to kink-band methods, is that non-uniform deformation within the triangle zone allows the layer thickness and length to change during deformation. By varying three controlling parameters independently (trishear propagation/slip ratio, trishear apical angle and fault dip), we construct a three-dimensional parameter space to demonstrate the variability of resultant geometry feasible with trishear. We plot published natural examples in this parameter space and identify two clusters and show that the most applicable typical trishear propagation/slip ratio is 2-3, while the trishear apical angle varies from 30° to 100°. We propose that these findings can help estimate the best-fit parameters for natural structures. We then consider the temporal evolution of specific geometric examples and factors that increase the complexity of trishear including: (1) fault-dip changes and (2) pre-existing faults.

To illustrate the applicability of the parameter space and complex trishear models to natural examples, we apply our results to a sub-surface example from the Qaidam basin in northern Tibetan Plateau.

KEYWORDS: trishear, parameter space, clusters of natural examples, trishear complexity

1. Introduction

It has been extensively documented from outcrop and sub-surface studies that there is an intimate relationship between folding of sedimentary sequences and underlying faults, although a variety of different models are invoked, including fault-bend fold (Jamison, 1987; Medwedeff and Suppe, 1997; Suppe, 1983; Tavani et al., 2005), fault-propagation fold (Jamison, 1987; Mitra, 1990; Suppe and Medwedeff, 1990) and detachment folding (Dahlstrom, 1990; Jamison, 1987; Mitra, 2003; Poblet and McClay, 1996) to explain specific examples. Many of these models utilise a kink band method (Fig.1a, b) that maintains a constant layer thickness and line length, which results in uniform dips and homogeneous deformation of the fold limbs (Suppe, 1983; Suppe and Medwedeff, 1990). An alternative approach is the trishear model that has a precondition of maintaining section area during deformation (Erslev, 1991) (Fig.2) and is often applied to examples in which non-uniform dip and inhomogeneous strain occurs within the faults; examples of such folds are evident in experimental analogue studies (Bose et al., 2009; Ellis et al., 2004; McQuarrie, 2004; Miller and Mitra, 2011), numerical models (e.g., Allmendinger, 1998; Cristallini and Allmendinger, 2001; Erslev, 1991; Hardy and Ford, 1997) and natural geological structures (e.g., Allmendinger, 1998; Cristallini and Allmendinger, 2001; Erslev, 1991; Erslev and Mayborn, 1997; Erslev and Rogers, 1993).

The simplest trishear model and its potential application has been discussed in many studies (Allmendinger et al., 2004; Cardozo, 2005, 2008; Cardozo and Aanonsen, 2009; Cardozo et al., 2005; Cardozo et al., 2011; Gold et al., 2006; Jin and

Groshong, 2006; Jin et al., 2009; Lin et al., 2007). Allmendinger (1998) demonstrated the geometric complexities resulting from varying parameters associated with a single fault, while Allmendinger et al. (2004) considered the resulting geometry when multiple faults with opposing dips are modelled. The conceptual trishear model of Erslev (1991) has subsequently been quantified to account for definition of the parameters controlling the trishear geometry by the later studies (e.g., Cristallini and Allmendinger, 2001; Cristallini et al., 2004; Hardy and Ford, 1997; Zehnder and Allmendinger, 2000).

By varying the controlling parameters, further modifications also allow a spectrum of trishear models, including basic (homogeneous) trishear models (Hardy and Ford, 1997), heterogeneous trishear models (Erslev, 1991), asymmetric trishear models (Zehnder and Allmendinger, 2000), extensional trishear models (Jin and Groshong, 2006), reverse trishear models (Cruden and McCaffrey, 2001), evolving apical angle trishear models (Allmendinger, 1998) and Quadshear models (Welch et al., 2009), where propagation of two pre-existing faults towards each other is used to model fault development in mechanically heterogeneous sequences.

Despite these studies, there has been little attention to the spectrum of potential trishear geometry, which limits the application of the trishear mechanism in understanding natural structures.

In this paper, we focus on the trishear deformation associated with reverse faults. Given the significant degrees of freedom available within the trishear algorithm, it can be difficult to define appropriate parameters, hence derive a unique solution, for natural structures. Therefore, here we evaluate the effect of varying each parameter independently and consider the effect on the resultant geometry; we illustrate the results by defining a three-dimensional parameter space, where the three controlling parameters can vary independently of each other. With natural examples plotted in the parameter space, we propose a range of parameter values that best represent natural structures. As an important element of the trishear model is the temporal evolution of the structure, we build a new three-dimensional parameter space to consider how the structures most represented in natural systems evolve with time. Finally, a natural example from the Lenghu5 structure (Qaidam Basin, Northern Tibetan Plateau) is interpreted using the trishear parameter space and the strain quantification, which provides a new workflow of applying trishear algorithm to complex natural structures.

2. Three-dimensional parameter space and clusters of natural examples

Within the trishear model (Fig.2), the deformation is concentrated within a triangle zone in front of the propagating fault tip. Compared with the simple shear algorithm (Withjack and Peterson, 1993), the particles in the triangle zone no longer migrate parallel to the fault trace, but with a displacement component from the hanging wall side to the footwall side. The migration velocity within the triangle zone decreases from the maximum on the hanging wall trishear boundary to zero on the footwall trishear boundary. This non-uniform migration within the triangle zone allows the layer thickness and length to change during the trishear deformation; however, the section area is kept constant. In this paper, we choose to model three of the parameters in the trishear algorithm, which are the trishear p/s ratio (the fault propagation/slip ratio); the trishear apical angle; and the fault dip. For example, when the fault slips from point A to point B, the fault tip propagates from point A to point C (Fig.2). The ratio between the length of AC and AB is the trishear p/s ratio.

In order to evaluate the effects of the parameters on the resulting geometry, a three-dimensional parameter space is created, with three axes representing each of the parameters (Fig.3). By varying the three parameters, the parameter space is constructed, allowing the construction of a variety of trishear models with different geometries. In this parameter space, the trishear models are constructed using 2D MOVE (Midland Valley), in which we assume heterogeneous deformation (trishear zones = 10) in the trishear zone and 'Fault Parallel Flow' algorithm outside the trishear zone.

As described in previous studies, the development of a monocline in front of the fault tip and coincident thinning of hanging wall strata and thickening of footwall strata are consequences of the general algorithm and are therefore common to all trishear models (Fig.3). These features are consistent with the observations in natural trishear examples, e.g., rotation structures (Fig.1c). Although these geometries are common to all examples the specific resultant geometries vary significantly depending upon the specific parameters that are used (Fig.3). For example, with some trishear apical angles and reverse fault dips, low trishear p/s ratio leads to high magnitude of hanging wall thinning and footwall thickening. By comparing the trishear models distributed in the parameter space, the effects of the parameter selection on the geometry of trishear models are summarized below:

i. With a constant fault slip, the amplitude of the hanging wall uplift has a positive correlation with fault dip that is unaffected by p/s ratio or apical angle whereas the fault tip propagation is positively correlated with high p/s ratio and unaffected by apical angle or fault dip.

ii. Parameters of low fault dip, low p/s ratio and high apical angle result in a high magnitude of hanging wall thinning and footwall thickening.

iii. Parameters of low fault dip, low p/s ratio and high apical angle form a wide monocline.

iv. The monocline in front of the fault tip can be overturned with parameters of high fault dip, high p/s ratio and low apical angles.

Many natural structures have been explained by the application of trishear algorithm (e.g., Allmendinger, 1998; Allmendinger et al., 2004; Cardozo, 2005; Cardozo and Aanonsen, 2009; Cardozo et al., 2005; Champion et al., 2001; Gold et al., 2006; Hardy and Ford, 1997; Lin et al., 2007). We use 13 published examples of trishear and characterise them according to their trishear parameters. The 13 natural trishear examples are plotted in the parameter space according to their best-fit parameters (Fig.4). Two clusters of the natural trishear examples are observed, although there are several examples located outside of the clusters. The two clusters are best described by p/s ratios of 2-3, trishear apical angles from 30°-100°, and fault dips of 25°-45°. We propose that these findings can be used to estimate the best-fit trishear parameters when applying trishear algorithm to natural structures. It is also important to highlight the relatively small sample set, hence more natural trishear examples need to be added in this parameter space in the future to define more reliable clusters. As noted in previous studies (Hardy and Finch, 2007; Loveless et al., 2011; Roche et al., 2012), competent packages are likely to develop steep faults while incompetent packages can develop shallow or even bedding-parallel faults. In the parameter space, the trishear models associated with high angle reverse faults, which are not well-described by the clusters, may correspond to the steep faults developed in competent packages.

3. Temporal evolution of trishear models

In the previous section we considered the clustering of natural examples in a static parameter space; it is also clearly important to consider how the temporal evolution impacts on the resulting geometry. To illustrate this temporal evolution we need to consider how deformed the structure is, therefore, we define a **deformation stage** $\boldsymbol{R_i}$ for a reference horizon by the following equation:

$$\mathrm{R}_i = \mathrm{h}/\boldsymbol{h_i} \qquad \textbf{(Equation 1)}$$

In the above equation, $\boldsymbol{h}$ is the hanging wall uplift and $\boldsymbol{h_i}$ is the depth from hanging wall to the fault tip (Fig.2, Fig.5).

It is important to note that the deformation stage parameter $\boldsymbol{R_i}$ is not unique within a trishear model, but is variable for different horizons at different levels within the structure. The $\boldsymbol{R_i}$ value, therefore, depends on the selection of the reference horizon used for calculation. In Fig.5, a trishear model (left) with the parameters p/s ratio of 2.5, fault dip of 30° and apical angle of 50° is used to illustrate the impact of the selection of the reference horizon. The $\boldsymbol{R_i}$ values are calculated for the horizons that have not been propagated through by the underlying fault. The diagram (right) suggests a decreasing $\boldsymbol{R_i}$ value from h_8 to h_1 upward through the model.

We take one of the clustered points on the parameter space (p/s ratio of 2.5) and consider how varying trishear apical angle (30°, 50°, 70° and 100°) and reverse fault dip (30° and 45°) alter the resultant geometry. For this example, a new three-dimensional space is generated here, with two horizontal axes representing the trishear apical angle and the reverse fault dip, and the vertical axes representing the **deformation stage** $\boldsymbol{R_i}$ (Fig.6). Given the variability of the $\boldsymbol{R_i}$ value for different horizons, here we select the top horizon as the reference for the calculation. In this parameter space, three $\boldsymbol{R_i}$ values are set, which are 0.2, 0.5 and 0.8.

The parameter space of trishear models introduced above provides a platform for the application of trishear algorithms to natural structures. Although it is still difficult to identify unique solutions for the natural structures because of the significant degrees of freedom available with the trishear parameters, we can narrow the range of the parameters and estimate the temporal evolution of the structure by using the parameter space. For example, with a natural structure, by comparing the first-order structural geometry with the trishear models in the parameter space, the range of best-fit parameters for this structure can be determined. With the best-fit parameters suggested by the parameter space, the deformation stage can be identified by comparing the hanging wall geometry of the natural structures with the trishear forward models in the parameter space.

4. Quantification of the strain associated with the trishear algorithm

As the deformation associated with the trishear algorithm is always constrained within the triangle zone in front of the fault tip, it is possible to calculate the strain of the folded beds, which is the ratio of the hanging wall uplift ($\boldsymbol{h}$) versus the width of the folded beds ($\boldsymbol{w}$). Fig.7a delineates the trigonometric relationship of the key variables, and we hereby define the **strain** $\boldsymbol{e}$ as Eq.2:

$$\boldsymbol{e} = \boldsymbol{h}/\boldsymbol{w} \qquad \textbf{(Equation 2)}$$

$$As \qquad \boldsymbol{w} = L_{AC} = L_{JK} - L_{FH} - L_{DC}$$

$$= L_{BK}/\tan(\angle BJK) - L_{FJ} \times \cot(\angle FHJ) - L_{DH} \times \tan(\angle DHC)$$

$$= H/\tan(\boldsymbol{\alpha} - \boldsymbol{\theta}/2) - h \times \cot \boldsymbol{\alpha} - H \times \tan(\pi/2 - \boldsymbol{\alpha} - \boldsymbol{\theta}/2)$$

$$= H \times \cot(\boldsymbol{\alpha} - \boldsymbol{\theta}/2) - h \times \cot \boldsymbol{\alpha} - H \times \cot(\boldsymbol{\alpha} + \boldsymbol{\theta}/2)$$

$$and \qquad \boldsymbol{R_i} = \frac{h}{h_i} = \frac{h}{h + H - h \times (p/s)}$$

$$thus, \qquad \mathbf{1}/\boldsymbol{e} = [\mathbf{1}/\boldsymbol{R_i} + (\boldsymbol{p}/\boldsymbol{s}) - \mathbf{1}] \times [\mathbf{cot}(\boldsymbol{\alpha} - \boldsymbol{\theta}/\mathbf{2}) - \mathbf{cot}(\boldsymbol{\alpha} + \boldsymbol{\theta}/\mathbf{2})] - \mathbf{cot}\,\boldsymbol{\alpha}$$

(Equation 3)

In Eq.3, the four involved variables are the **strain** $\boldsymbol{e}$, the **deformation stage** $\boldsymbol{R_i}$, the **fault dip** $\boldsymbol{\alpha}$ and the **apical angle** $\boldsymbol{\theta}$. In order to avoid the variability of the $\boldsymbol{R_i}$ value for different reference horizons (see Fig.5), we select a trishear model with only one single layer. The equation demonstrates that the strain increases when the deformation progresses (i.e., increasing deformation stage). With a given natural structure, the strain $\boldsymbol{e}$ can be calculated by measuring the hanging wall uplift and width of the folded beds in the monocline. If the subsurface data provided possible range of deformation stage $\boldsymbol{R_i}$ and fault dip $\boldsymbol{\alpha}$, then the plot of apical angle $\boldsymbol{\theta}$ and p/s ratio can be generated based on Eq.3 (e.g., Fig.7b, strain $\boldsymbol{e}$ = 0.5, deformation stage $\boldsymbol{R_i}$ = 1 and fault dip $\boldsymbol{\alpha}$ = 45°). Although it is still difficult to apply the equations to identify the unique solutions for natural structures, these equations and plots can narrow the range of the variables, particularly when the surface and subsurface data provide better constraints to the variables.

5. Complex trishear geometry

The above parameter space and the evolution of a specific structure only show trishear models that are applicable in simple natural structures with one constant-dipping fault and where displacement is not substantial enough to cause overturning. In many natural examples, structures are commonly related to either a more complex fault or a set of related faults (e.g., Allmendinger, 1998; Allmendinger et al., 2004).

The complexity of the fault systems obviously inhibits the application of trishear algorithm in natural structures and results in a large population of possible scenarios. Therefore, here we summarise the key additional factors that may influence the resultant geometry and promote increased complexity of trishear models. The three factors that we will analyse are: the change in fault dip during propagation, multiple faults and pre-existing faults. Trishear models are created by integrating these contributing factors (Fig.8 and Fig.9). We anticipate that the generated models are useful for predicting subsurface structures based on high-resolution fieldwork data (surface data, e.g., fault/stratum dips, layer thickness variation, second-order structures), particularly when the subsurface data is insufficient in the study area. The key controls of each of these factors are reviewed individually below.

5.1 Fault-dip change

In many multi-layer sequences, fault dip of any one layer may be controlled by the thickness or competence of the layer (e.g., Hardy and Finch, 2007; Loveless et al., 2011; Roche et al., 2012) and may change upward through the stratigraphy. In the scenario where there are basement-involved structures, the fault may initially be steep in the competent basement but will become shallower as it propagates through the overlying sedimentary cover that is relatively incompetent (Hardy and Finch, 2007). In contrast, in the scenario where there are only thin-skinned structures, the fault can initiate parallel to the mechanical stratigraphy and then propagate upward to cut through the upper layers (Hardy and Finch, 2007). To represent these two scenarios, two series of trishear forward models are created (Fig.8), with the trishear algorithm applied on an upward-steepening reverse fault in Fig.8a and an upward-shallowing reverse fault in Fig.8b, respectively. The upward-steepening reverse fault modelled in Fig.8a$_{1\text{-}3}$ initiates with a shallow dip angle of 20° and the stepwise increment of fault-dip is 10° until it reaches 70°, while the upward-shallowing reverse fault modelled in Fig.8b$_{1-3}$ initiates with a steep dip angle of 70° and the upward stepwise decrease in fault-dip is 10° until it reaches 20°. For both scenarios, the p/s ratio is set as 2.5 (suggested by the clusters of natural examples in the parameter space), while the trishear apical angle is set as 50° (a medium value of the apical angle range suggested by the clusters of natural examples in the parameter space).

The upward-steepening and upward-shallowing reverse faults form very different hanging wall and footwall geometries with the former experiencing more deformation than the latter. The hanging walls are uplifted during the deformation while the foot-walls stay in the original position. However, the hanging wall and footwall geometries are different in the two series of models. The upward-steepening reverse fault forms an anticline in the hanging wall, with a gentle backlimb and overturned forelimb; whereas the upward-shallowing reverse fault forms a monocline in the hanging wall and the hanging wall shows downward steepening dips towards the triangle defor-mation zone. For the footwall geometry, the footwall adjacent to the fault trace shows more thickening in the model of an upward-steepening fault than that in the model of an upward-shallowing fault.

In previous studies, two categories of structures are observed in compressional sys-tems, which are thin-skin fold-and-thrust belts and thick-skin/basement-involved belts. In thin-skin fold-and-thrust belts, the deformation concentrates primarily in the sedi-mentary cover rather than the basement, e.g., Canadian Rocky Mountain-style fore-land fold-and-thrust belts (Bally et al., 1966; Barclay and Smith, 1992; Price, 1981). In contrast, in thick-skin/basement-involved belts, the basement rocks are shortened along steep dipping reverse faults and are associated with relatively low transport distances and compression (Coward, 1983), e.g., the Laramide uplifts (Schmidt et al., 1993). The upward shallowing model in Fig.8a is more akin to a thick skinned scenario in contrast to Fig.8b which is more likely to represent thin skinned deformation. This is in agreement with the study of Erslev and Rogers (1993) and Erslev et al. (2013). Therefore, it is assumed that an upward-steepening reverse fault tends to develop in thin-skin deformation whereas an upward-shallowing reverse fault is likely to develop at the basement-cover contact. In a number of examples, thin-skin style and basement-involved style can coexist in a single structure on some scales, as the steep faults that penetrate the basement rocks can change to be sub-horizontal when they reach sedimentary cover and then help the horizontal initiation of the thin-skin detachments (Hayward and Graham, 1989). In this scenario, the degree of decoupling between basement and sedimentary cover becomes more important. This is also supported by the results of physical experiments (Bose et al., 2009; McClay and Whitehouse, 2004).

5.2 Pre-existing fault(s)

The reactivation of pre-existing faults may also form complex structural geometries together with the younger faults. Examples permitting high geometric complexity by allowing the inclusion of multiple faults in a section are demonstrated by Allmendinger et al. (2004). However, it is also vital to understand the surface geometrical control on the complex fault deformation in subsurface.

Fig.9 shows examples of the trishear models in which deeper pre-existing faults are present beneath the upper reverse faults. As discussed above, the reverse faults in these models can be upward-steepening for thin-skinned structures or upward-shallowing for thick-skinned/basement-involved structures. The sets (a) and (b) apply upward-steepening reverse faults in the trishear modelling (Fig.9a,b), while the sets

(c) and (d) apply upward-shallowing reverse faults (Fig.9c,d). Both the same and opposing thrusting directions are modelled (same direction in Fig.9a,c and opposite direction in Fig.9b,d). The trishear models in Fig.9a,b show similar geometries to the anticlines formed in Sub-Andean belt of southern Bolivia (Belotti et al., 1995) where the middle weak layer can decouple the shallow depth strain from the deep subsurface (e.g., Burliga et al., 2012; Willingshofer and Sokoutis, 2009). Fig.9c,d delineates of basement-involved structures with upward-shallowing faults when propagating into the sedimentary cover, which is commonly observed in many studies in thick-skinned structures (e.g., Bose et al., 2009; Butler et al., 2004). In particular, Fig.9c shows an analogue model that may represent the bifurcation of an early single reverse fault or the splay faults coming off from a single reverse fault, to form a triangular strain confined by the multiple faults. In nature, a single reverse fault may initiate within a fault-propagation fold and subsequently bifurcate or form splays when propagating through the upper sedimentary cover, e.g., the Absaroka thrust sheet case (Lamerson, 1982; Mitra, 1990). In this scenario, the earlier formed fold geometry may be modified during the subsequent fault bifurcation or generation of splay faults.

The models (a) and (b) all form anticlines in the surface, although different subsidiary structures (i.e., minor anticlines and synclines in the footwall) are developed in (a) and (b). For example, the subsurface minor folds in model (a) has wider wavelength than that in model (b). For the upward-shallowing reverse faults, the models (c) and (d) all form monoclines in the surface, but the hanging wall has a higher uplift in model (c) than in model (d). Moreover, in model (d), minor synclines are developed at both ends of the central common footwall, resulting in a syncline-like geometry. Different combinations of upper reverse faults and lower pre-existing faults can form very different structural styles. However, as the surface geometry is a reflection of subsurface structures, there are still some features that can be used to illustrate the overall structure and predict the subsurface structures. For example, the symmetry, wavelength and amplitude of the folds depend on the subsurface structures and therefore these features can be used to predict the subsurface structures. According to the simulated models in Fig.9, the following inferences are drawn:

i. Reverse faults are implied to be upward-steepening if the fold observed in the surface is an anticline and upward-shallowing if the surface fold is a monocline.

ii. For upward-steepening reverse faults, asymmetric anticlines suggest reverse faults with same transport direction, while relative symmetric anticlines suggest opposite-directing reverse faults.

iii. For upward-shallowing reverse faults, opposite-directing reverse faults result in smaller hanging wall uplift.

6. Application to the Lenghu5 structure, Qaidam Basin

A natural example from the Lenghu5 structure in Qaidam basin of the Northern Tibetan Plateau (e.g., Yin et al., 2008a; Yin et al., 2008b) is selected to demonstrate the applicability of our trishear modelling and our suggested workflow (Fig.10 a-c). The surface data (Fig.10a) suggest that the underlying reverse fault accounts for the development of the anticline in the SW hanging wall. The structures adjacent to the reverse fault cannot be well-described by the kink band model, therefore, we apply a trishear algorithm to interpret the Lenghu5 structure. In order to apply the trishear algorithm to the structure, the appropriate simplification is conducted to obtain the primary structural geometry (Fig.10b). The primary structure is also rotated clockwise to make the footwall horizontal. By comparing the geometry of the blue layer with the trishear models in the parameter space (Fig.3), it is suggested that the trishear model in the space with the parameters of p/s ratio of 2.0, reverse fault dip of 45°, and apical angle of 50° shows the most similar geometry with the simplified Lenghu5 structure (Fig.10c). We can also measure the strain $\boldsymbol{e}$ of the best-fit trishear model (Fig.10c) to compare with that of the Lenghu5 structure. The best-fit trishear model in Fig.10c presents strain $\boldsymbol{e}$=0.99, which shows a high similarity to the strain $\boldsymbol{e}$=0.92 presented in the Lenghu5 structure (fig.10b).

However, in the plots shown in Fig.10d created by applying the Eq.3 with fault dip $\boldsymbol{\alpha}$=45°, $\boldsymbol{R_i}$=2.54 and strain $\boldsymbol{e}$=0.92, the corresponding apical angle $\boldsymbol{\theta}$ = ~40° does not quite match the apical angle $\boldsymbol{\theta}$ = 50° in the best-fit trishear model (Fig.10c). We propose that the mismatch of the apical angle is caused by the fault complexity that has not been considered above. As shown in the seismic section (Fig.11a), the Lenghu5 anticline is mainly controlled by the underlying reverse faults F_1, F_2 and F_3. Two anticlines are observed in this structure: the surface anticline above F_1 and deeper subsurface anticline beneath F_1. The upward decreasing displacement of F_1 suggests a trishear algorithm is applicable in this structure. Moreover, reverse faults F_1 and F_2 all present upward-steepening shapes, which is highly comparable with the complex trishear models shown in Fig.9b. Therefore, we applied the trishear algorithm forward modelling to simulate the structural evolution of the Lenghu5 structure by allowing multiple curved faults in a single section. Fig.11b-e depicts the progressive development models of the Lenghu5 structure simulated using 2D Move (Midland Valley).

The parameters suggested by the best-fit trishear model in the parameter space are used in the trishear forward modelling (apical angle of 50° and p/s ratio of 2.0, suggested in Fig.10c). The comparison between the fault displacement and the fault tip propagation of F_2 also suggests a trishear p/s ratio of 2.0. In order to simulate the upward steepening reverse faults F_1 and F_2, we used the interpreted F_1 and F_2 as templates to define the stepwise values of upward steepening angles. In Fig.11b, normal fault F_2 was developed to form a half-graben in the J_r sediments followed by deposition of post-extension sequence from E_{1+2} to N_{2-1}; in Fig.11c-d, the geological environment changed to be compressional which results in the inversion of F_2 and the development of the reverse fault F_1; after uplift and erosion to present, Fig.11e presents a good match to the geometry of the Lenghu5 structure. The models in Fig.11b-e constrain the structural evolution of the Lenghu5 structure.

7. Discussion

7.1 Geometric constraints of trishear algorithm

A suite of trishear geometries can be formed by varying the combination of the input parameters, which inhibits the application of trishear algorithm directly to natural structures. In this study, we have constructed a simple parameter space to evaluate the effect of varying each parameter independently and to help determine the temporal evolution of the natural structures. The spectrum of structural geometries is much broader and the resulting structures can be more complex when integrating fault-dip change and pre-existing fault(s) in a single section. Therefore, some appropriate simplification of natural structures is needed before applying the parameter space: i.e., the first-order geometry can be used as initial constraints to compare with the trishear models in the parameter space. The previously simplified structural complexity is then reproduced in the final trishear models to compare with the original natural structures, which can help test the validity of the application of the trishear algorithm to the natural structures.

In the parameter space (Fig.4), the clusters of plotted natural examples are concentrated in the space with shallow reverse fault dip. This is because most of these examples are from thin-skin structures where the thrusting involves only the sedimentary cover whereas the basement is unaffected in the deformation (Poblet and Lisle, 2011), e.g., foreland fold-and-thrust belts in Canadian Rocky Mountain (Bally et al., 1966; Barclay and Smith, 1992; Price, 1981) and Turner Valley anticline in Alberta Foothills (Gallup, 1954; Gallup, 1951; Mitra, 1990). However, in the trishear parameter space, there are also a series of trishear models with high angle reverse faults that are very likely to be basement-involved and can be related to thick-skin structural inversion. The contractional inversion of older extensional faults has now been widely recognized in fold-and-thrust belts, for instance, in the Neuquen Basin in Argentina (Rojas et al., 1999), the Spanish Pyrenees (Muñoz, 1992), Alps (Pfiffner et al., 2000; Schmid et al., 1996), Apennine Mountains (Coward et al., 1999), Papua New Guinea (Buchanan and Warburton, 1996; Hill, 1991; Hill et al., 2004). In contrast to thin-skin structures, the basement involvement in thick-skin structures have not been transported over long horizontal distances as the steep faults penetrate the basement and lead to basement uplifts (Poblet and Lisle, 2011). However, the thin-skin fold-and-thrust belts (basement-unaffected) and thick-skin belts (basement-involved) can coexist in a single structure. The coexistence of these different structural styles might be common in many orogenic belts. For example, the Rocky Mountains-USA Cordillera exhibits thin-skin deformation in the interior and thick-skin deformation in the outer part (Hamilton, 1988); the steep faults that penetrate the basement become sub-horizontal when reaching the sedimentary cover and promote the horizontal initiation of the thin-skin detachments such as in the Alps (Hayward and Graham, 1989).

7.2 Influence of stratigraphy on trishear algorithm

In this paper, the parameter space concept focus on the geometrical constraints of the trishear algorithm. We also considered curved reverse faults, multiple faults and pre-existing faults when applying trishear algorithms to natural structures. However, it needs to be recognised that lithology and mechanical strength also play a role on the trishear models, with the parameters being very different depending upon mechanical stratigraphy (Alonso and Teixell, 1992; Hardy and Finch, 2007; Hardy and Ford, 1997). It has been suggested that rocks with high competency present higher trishear p/s ratios than low competent rocks, e.g., sandy units show higher trishear p/s ratio than clay-rich units (Hardy and Ford, 1997). Hardy and Finch (2007) also employed a discrete-element technique (Finch et al., 2003; Finch et al., 2004) to investigate sedimentary cover deformation in response to contractional faulting. The fault zone deformation was simulated with different settings: in the homogeneous weak cover model, a wide and open triangular zone was developed in front of the fault tip and significant thinning and thickening were observed within the triangular zone, which broadly agreed with the predictions of the trishear kinematic models (Allmendinger, 1998; Erslev, 1991; Hardy and Ford, 1997); while in the strongly heterogeneous layered models, a much narrower kink-like triangular zone was observed in front of the fault tip and layer thickness was roughly preserved within the triangular zone. In the physical modelling of Dixon (2004), the relatively homogeneous weak stratigraphy resulted in a trishear-like ductile deformation (low trishear p/s ratio) whereas the model with strong bedding-controlled heterogeneity is prone to form through-going reverse faults (high trishear p/s ratio). All these mechanical and physical models suggest the important role of stratigraphy and strength in the cover deformation (see also Welch et al., 2009), however, are likely to be second order controls superimposed upon the first order geometry outlined here.

8. Conclusion

In this paper, we have presented a three-dimensional parameter space to evaluate the effects of different trishear parameters on the geometries of trishear models. The parameter space associated with the identified clusters of natural structures can be used to constrain the best-fit trishear parameters needed to apply trishear algorithms to natural structures. We also consider the temporal evolution of a specific example to demonstrate the variation in deformation stage of the structures. The strain of trishear models is also quantified, with the plots providing possible solutions for interpreting natural structures. On the basis of the parameter space, fault-dip change, multiple faults and pre-existing faults, are integrated in the trishear models, to understand the possible complex structures that can form. A natural example of application was employed to verify the applicability of trishear algorithm. We anticipate that the application of the parameter space, and the resulting geometry associated with temporal evolution, will assist in reducing the uncertainty associated with fault related folds.

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Figure 2. Conceptual model of trishear algorithm, based on Hardy and Ford (1997).

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Figure 4. Clusters of natural trishear examples in the three-dimensional parameter space. In the parameter space, 13 natural examples are plotted in and two clusters are observed. The clusters suggest that the most applicable trishear p/s ratio is 2-3 and the trishear apical angle varies from 30° to 100°. The majority of these natural trishear examples show shallow fault dips of 25°-45°.

Figure 5. Diagram delineating the impact of the selection of the reference level, i.e., the horizon used to calculate the deformation stage $\boldsymbol{R_i}$. Here a trishear model (left) with the parameters p/s ratio of 2.5, fault dip of 30° and apical angle of 50° is selected, in which we only calculate the $\boldsymbol{R_i}$ of the horizons that have not been propagated through by the underlying fault. The deformation stage $\boldsymbol{R_i}$ is not unique for a trishear model, but is variable for different horizons. The right diagram suggests a decreasing $\boldsymbol{R_i}$ value from h8 to h1 upward through the model.

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Figure 10. The workflow of applying trishear algorithm to the Lenghu5 structure, Qaidam Basin, Northern Tibetan Plateau.

Figure 11. The forward trishear models depicts the structural evolution of the Lenghu5 structure by allowing multiple curved reverse faults in trishear forward modelling.

Table 1. A cluster of natural trishear examples in published studies and their corresponding best-fit parameters.