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1 **Defining a 3-dimensional Trishear Parameter Space to Understand the** 2 **Temporal Evolution of Fault Propagation Folds**

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7 **ABSTRACT**

8 The application of trishear, in which deformation occurs in a triangular zone in front
9 of a propagating fault tip, is often used to understand fault related folding. A key ele-
10 ment of trishear, in comparison to kink-band methods, is that non-uniform defor-
11 mation within the triangle zone allows the layer thickness and length to change dur-
12 ing deformation. By varying three controlling parameters independently (trishear
13 propagation/slip ratio, trishear apical angle and fault dip), we construct a three-
14 dimensional parameter space to demonstrate the variability of resultant geometry
15 feasible with trishear. We plot published natural examples in this parameter space
16 and identify two clusters and show that the most applicable typical trishear propaga-
17 tion/slip ratio is 2-3, while the trishear apical angle varies from 30° to 100°. We pro-
18 pose that these findings can help estimate the best-fit parameters for natural struc-
19 tures. We then consider the temporal evolution of specific geometric examples and
20 factors that increase the complexity of trishear including: (1) fault-dip changes and (2)
21 pre-existing faults.

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

25 **KEYWORDS:** trishear, parameter space, clusters of natural examples, trishear com-
26 plexity

27 **1. Introduction**

28 It has been extensively documented from outcrop and sub-surface studies that there
29 is an intimate relationship between folding of sedimentary sequences and underlying
30 faults, although a variety of different models are invoked, including fault-bend fold
31 ([Jamison, 1987](#); [Medwedeff and Suppe, 1997](#); [Suppe, 1983](#); [Tavani et al., 2005](#)),
32 fault-propagation fold ([Jamison, 1987](#); [Mitra, 1990](#); [Suppe and Medwedeff, 1990](#))
33 and detachment folding ([Dahlstrom, 1990](#); [Jamison, 1987](#); [Mitra, 2003](#); [Poblet and](#)
34 [McClay, 1996](#)) to explain specific examples. Many of these models utilise a kink
35 band method (Fig.1a, b) that maintains a constant layer thickness and line length,
36 which results in uniform dips and homogeneous deformation of the fold limbs ([Suppe,](#)
37 [1983](#); [Suppe and Medwedeff, 1990](#)). An alternative approach is the trishear model
38 that has a precondition of maintaining section area during deformation ([Erslev, 1991](#))
39 (Fig.2) and is often applied to examples in which non-uniform dip and inhomogene-
40 ous strain occurs within the faults; examples of such folds are evident in experi-
41 mental analogue studies ([Bose et al., 2009](#); [Ellis et al., 2004](#); [McQuarrie, 2004](#); [Miller](#)
42 [and Mitra, 2011](#)), numerical models (e.g., [Allmendinger, 1998](#); [Cristallini and](#)
43 [Allmendinger, 2001](#); [Erslev, 1991](#); [Hardy and Ford, 1997](#)) and natural geological
44 structures (e.g., [Allmendinger, 1998](#); [Cristallini and Allmendinger, 2001](#); [Erslev, 1991](#);
45 [Erslev and Mayborn, 1997](#); [Erslev and Rogers, 1993](#)).

46 The simplest trishear model and its potential application has been discussed in many
47 studies ([Allmendinger et al., 2004](#); [Cardozo, 2005, 2008](#); [Cardozo and Aanonsen,](#)
48 [2009](#); [Cardozo et al., 2005](#); [Cardozo et al., 2011](#); [Gold et al., 2006](#); [Jin and](#)

49 [Groshong, 2006](#); [Jin et al., 2009](#); [Lin et al., 2007](#)). [Allmendinger \(1998\)](#) demonstrat-
50 ed the geometric complexities resulting from varying parameters associated with a
51 single fault, while [Allmendinger et al. \(2004\)](#) considered the resulting geometry when
52 multiple faults with opposing dips are modelled. The conceptual trishear model of
53 [Erslev \(1991\)](#) has subsequently been quantified to account for definition of the pa-
54 rameters controlling the trishear geometry by the later studies (e.g., [Cristallini and](#)
55 [Allmendinger, 2001](#); [Cristallini et al., 2004](#); [Hardy and Ford, 1997](#); [Zehnder and](#)
56 [Allmendinger, 2000](#)).

57 By varying the controlling parameters, further modifications also allow a spectrum of
58 trishear models, including basic (homogeneous) trishear models ([Hardy and Ford,](#)
59 [1997](#)), heterogeneous trishear models ([Erslev, 1991](#)), asymmetric trishear models
60 ([Zehnder and Allmendinger, 2000](#)), extensional trishear models ([Jin and Groshong,](#)
61 [2006](#)), reverse trishear models ([Cruden and McCaffrey, 2001](#)), evolving apical angle
62 trishear models ([Allmendinger, 1998](#)) and Quadshear models ([Welch et al., 2009](#)),
63 where propagation of two pre-existing faults towards each other is used to model
64 fault development in mechanically heterogeneous sequences.

65 Despite these studies, there has been little attention to the spectrum of potential
66 trishear geometry, which limits the application of the trishear mechanism in under-
67 standing natural structures.

68 In this paper, we focus on the trishear deformation associated with reverse faults.
69 Given the significant degrees of freedom available within the trishear algorithm, it
70 can be difficult to define appropriate parameters, hence derive a unique solution, for
71 natural structures. Therefore, here we evaluate the effect of varying each parameter
72 independently and consider the effect on the resultant geometry; we illustrate the re-

73 sults by defining a three-dimensional parameter space, where the three controlling
74 parameters can vary independently of each other. With natural examples plotted in
75 the parameter space, we propose a range of parameter values that best represent
76 natural structures. As an important element of the trishear model is the temporal evo-
77 lution of the structure, we build a new three-dimensional parameter space to consid-
78 er how the structures most represented in natural systems evolve with time. Finally,
79 a natural example from the Lenghu5 structure (Qaidam Basin, Northern Tibetan
80 Plateau) is interpreted using the trishear parameter space and the strain quantifica-
81 tion, which provides a new workflow of applying trishear algorithm to complex natural
82 structures.

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

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

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

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

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

- 120 ii. Parameters of low fault dip, low p/s ratio and high apical angle result in a
121 high magnitude of hanging wall thinning and footwall thickening.
- 122 iii. Parameters of low fault dip, low p/s ratio and high apical angle form a wide
123 monocline.
- 124 iv. The monocline in front of the fault tip can be overturned with parameters of
125 high fault dip, high p/s ratio and low apical angles.

126 Many natural structures have been explained by the application of trishear algorithm
127 (e.g., Allmendinger, 1998; Allmendinger et al., 2004; Cardozo, 2005; Cardozo and
128 Aanonsen, 2009; Cardozo et al., 2005; Champion et al., 2001; Gold et al., 2006;
129 Hardy and Ford, 1997; Lin et al., 2007). We use 13 published examples of trishear
130 and characterise them according to their trishear parameters. The 13 natural trishear
131 examples are plotted in the parameter space according to their best-fit parameters
132 (Fig.4). Two clusters of the natural trishear examples are observed, although there
133 are several examples located outside of the clusters. The two clusters are best de-
134 scribed by p/s ratios of 2-3, trishear apical angles from 30°-100°, and fault dips of
135 25°-45°. We propose that these findings can be used to estimate the best-fit trishear
136 parameters when applying trishear algorithm to natural structures. It is also im-
137 portant to highlight the relatively small sample set, hence more natural trishear ex-
138 amples need to be added in this parameter space in the future to define more relia-
139 ble clusters. As noted in previous studies (Hardy and Finch, 2007; Loveless et al.,
140 2011; Roche et al., 2012), competent packages are likely to develop steep faults
141 while incompetent packages can develop shallow or even bedding-parallel faults. In
142 the parameter space, the trishear models associated with high angle reverse faults,

143 which are not well-described by the clusters, may correspond to the steep faults de-
144 veloped in competent packages.

145 **3. Temporal evolution of trishear models**

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

$$151 \quad R_i = h/h_i \quad \text{(Equation 1)}$$

152 In the above equation, h is the hanging wall uplift and h_i is the depth from hanging
153 wall to the fault tip (Fig.2, Fig.5).

154 It is important to note that the deformation stage parameter R_i is not unique within a
155 trishear model, but is variable for different horizons at different levels within the struc-
156 ture. The R_i value, therefore, depends on the selection of the reference horizon used
157 for calculation. In Fig.5, a trishear model (left) with the parameters p/s ratio of 2.5,
158 fault dip of 30° and apical angle of 50° is used to illustrate the impact of the selection
159 of the reference horizon. The R_i values are calculated for the horizons that have not
160 been propagated through by the underlying fault. The diagram (right) suggests a de-
161 creasing R_i value from h_8 to h_1 upward through the model.

162 We take one of the clustered points on the parameter space (p/s ratio of 2.5) and
163 consider how varying trishear apical angle (30°, 50°, 70° and 100°) and reverse fault
164 dip (30° and 45°) alter the resultant geometry. For this example, a new three-
165 dimensional space is generated here, with two horizontal axes representing the

166 trishear apical angle and the reverse fault dip, and the vertical axes representing the
 167 **deformation stage R_i** (Fig.6). Given the variability of the R_i value for different hori-
 168 zons, here we select the top horizon as the reference for the calculation. In this pa-
 169 rameter space, three R_i values are set, which are 0.2, 0.5 and 0.8.

170 The parameter space of trishear models introduced above provides a platform for the
 171 application of trishear algorithms to natural structures. Although it is still difficult to
 172 identify unique solutions for the natural structures because of the significant degrees
 173 of freedom available with the trishear parameters, we can narrow the range of the
 174 parameters and estimate the temporal evolution of the structure by using the param-
 175 eter space. For example, with a natural structure, by comparing the first-order struc-
 176 tural geometry with the trishear models in the parameter space, the range of best-fit
 177 parameters for this structure can be determined. With the best-fit parameters sug-
 178 gested by the parameter space, the deformation stage can be identified by compar-
 179 ing the hanging wall geometry of the natural structures with the trishear forward
 180 models in the parameter space.

181 **4. Quantification of the strain associated with the trishear algorithm**

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

$$187 \quad e = h/w \quad \text{(Equation 2)}$$

$$\begin{aligned} \text{As} \quad w &= L_{AC} = L_{JK} - L_{FH} - L_{DC} \\ &= L_{BK}/\tan(\angle BJK) - L_{FJ} \times \cot(\angle FHJ) - L_{DH} \times \tan(\angle DHC) \end{aligned}$$

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

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

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

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

188

(Equation 3)

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

202 5. Complex trishear geometry

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

208 The complexity of the fault systems obviously inhibits the application of trishear algo-
209 rithm in natural structures and results in a large population of possible scenarios.
210 Therefore, here we summarise the key additional factors that may influence the re-
211 sultant geometry and promote increased complexity of trishear models. The three
212 factors that we will analyse are: the change in fault dip during propagation, multiple
213 faults and pre-existing faults. Trishear models are created by integrating these con-
214 tributing factors (Fig.8 and Fig.9). We anticipate that the generated models are use-
215 ful for predicting subsurface structures based on high-resolution fieldwork data (sur-
216 face data, e.g., fault/stratum dips, layer thickness variation, second-order structures),
217 particularly when the subsurface data is insufficient in the study area. The key con-
218 trols of each of these factors are reviewed individually below.

219 *5.1 Fault-dip change*

220 In many multi-layer sequences, fault dip of any one layer may be controlled by the
221 thickness or competence of the layer (e.g., [Hardy and Finch, 2007](#); [Loveless et al.,](#)
222 [2011](#); [Roche et al., 2012](#)) and may change upward through the stratigraphy. In the
223 scenario where there are basement-involved structures, the fault may initially be
224 steep in the competent basement but will become shallower as it propagates through
225 the overlying sedimentary cover that is relatively incompetent ([Hardy and Finch,](#)
226 [2007](#)). In contrast, in the scenario where there are only thin-skinned structures, the
227 fault can initiate parallel to the mechanical stratigraphy and then propagate upward
228 to cut through the upper layers ([Hardy and Finch, 2007](#)). To represent these two
229 scenarios, two series of trishear forward models are created (Fig.8), with the trishear
230 algorithm applied on an upward-steepening reverse fault in Fig.8a and an upward-
231 shallowing reverse fault in Fig.8b, respectively. The upward-steepening reverse fault
232 modelled in Fig.8a₁₋₃ initiates with a shallow dip angle of 20° and the stepwise incre-

233 ment of fault-dip is 10° until it reaches 70° , while the upward-shallowing reverse fault
234 modelled in Fig.8b₁₋₃ initiates with a steep dip angle of 70° and the upward stepwise
235 decrease in fault-dip is 10° until it reaches 20° . For both scenarios, the p/s ratio is set
236 as 2.5 (suggested by the clusters of natural examples in the parameter space), while
237 the trishear apical angle is set as 50° (a medium value of the apical angle range
238 suggested by the clusters of natural examples in the parameter space).

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

250 In previous studies, two categories of structures are observed in compressional sys-
251 tems, which are thin-skin fold-and-thrust belts and thick-skin/basement-involved belts.
252 In thin-skin fold-and-thrust belts, the deformation concentrates primarily in the sedi-
253 mentary cover rather than the basement, e.g., Canadian Rocky Mountain-style fore-
254 land fold-and-thrust belts (Bally et al., 1966; Barclay and Smith, 1992; Price, 1981).
255 In contrast, in thick-skin/basement-involved belts, the basement rocks are shortened
256 along steep dipping reverse faults and are associated with relatively low transport
257 distances and compression (Coward, 1983), e.g., the Laramide uplifts (Schmidt et al.,

258 [1993](#)). The upward shallowing model in Fig.8a is more akin to a thick skinned sce-
259 nario in contrast to Fig.8b which is more likely to represent thin skinned deformation.
260 This is in agreement with the study of [Erslev and Rogers \(1993\)](#) and [Erslev et al.](#)
261 [\(2013\)](#). Therefore, it is assumed that an upward-steepening reverse fault tends to
262 develop in thin-skin deformation whereas an upward-shallowing reverse fault is likely
263 to develop at the basement-cover contact. In a number of examples, thin-skin style
264 and basement-involved style can coexist in a single structure on some scales, as the
265 steep faults that penetrate the basement rocks can change to be sub-horizontal
266 when they reach sedimentary cover and then help the horizontal initiation of the thin-
267 skin detachments ([Hayward and Graham, 1989](#)). In this scenario, the degree of de-
268 coupling between basement and sedimentary cover becomes more important. This
269 is also supported by the results of physical experiments ([Bose et al., 2009](#); [McClay](#)
270 [and Whitehouse, 2004](#)).

271 *5.2 Pre-existing fault(s)*

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

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

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

298 The models (a) and (b) all form anticlines in the surface, although different subsidiary
299 structures (i.e., minor anticlines and synclines in the footwall) are developed in (a)
300 and (b). For example, the subsurface minor folds in model (a) has wider wavelength
301 than that in model (b). For the upward-shallowing reverse faults, the models (c) and
302 (d) all form monoclines in the surface, but the hanging wall has a higher uplift in
303 model (c) than in model (d). Moreover, in model (d), minor synclines are developed
304 at both ends of the central common footwall, resulting in a syncline-like geometry.

305 Different combinations of upper reverse faults and lower pre-existing faults can form
306 very different structural styles. However, as the surface geometry is a reflection of

307 subsurface structures, there are still some features that can be used to illustrate the
308 overall structure and predict the subsurface structures. For example, the symmetry,
309 wavelength and amplitude of the folds depend on the subsurface structures and
310 therefore these features can be used to predict the subsurface structures. According
311 to the simulated models in Fig.9, the following inferences are drawn:

312 i. Reverse faults are implied to be upward-steepening if the fold observed in
313 the surface is an anticline and upward-shallowing if the surface fold is a mon-
314 ocline.

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

318 iii. For upward-shallowing reverse faults, opposite-directing reverse faults re-
319 sult in smaller hanging wall uplift.

320 **6. Application to the Lenghu5 structure, Qaidam Basin**

321 A natural example from the Lenghu5 structure in Qaidam basin of the Northern Ti-
322 betan Plateau (e.g., [Yin et al., 2008a](#); [Yin et al., 2008b](#)) is selected to demonstrate
323 the applicability of our trishear modelling and our suggested workflow (Fig.10 a-c).
324 The surface data (Fig.10a) suggest that the underlying reverse fault accounts for the
325 development of the anticline in the SW hanging wall. The structures adjacent to the
326 reverse fault cannot be well-described by the kink band model, therefore, we apply a
327 trishear algorithm to interpret the Lenghu5 structure. In order to apply the trishear
328 algorithm to the structure, the appropriate simplification is conducted to obtain the
329 primary structural geometry (Fig.10b). The primary structure is also rotated clockwise
330 to make the footwall horizontal. By comparing the geometry of the blue layer with the

331 trishear models in the parameter space (Fig.3), it is suggested that the trishear mod-
332 el in the space with the parameters of p/s ratio of 2.0, reverse fault dip of 45°, and
333 apical angle of 50° shows the most similar geometry with the simplified Lenghu5
334 structure (Fig.10c). We can also measure the strain e of the best-fit trishear model
335 (Fig.10c) to compare with that of the Lenghu5 structure. The best-fit trishear model in
336 Fig.10c presents strain $e=0.99$, which shows a high similarity to the strain $e=0.92$
337 presented in the Lenghu5 structure (fig.10b).

338 However, in the plots shown in Fig.10d created by applying the Eq.3 with fault dip
339 $\alpha=45^\circ$, $R_i=2.54$ and strain $e=0.92$, the corresponding apical angle $\theta = \sim 40^\circ$ does not
340 quite match the apical angle $\theta = 50^\circ$ in the best-fit trishear model (Fig.10c). We pro-
341 pose that the mismatch of the apical angle is caused by the fault complexity that has
342 not been considered above. As shown in the seismic section (Fig.11a), the Lenghu5
343 anticline is mainly controlled by the underlying reverse faults F_1 , F_2 and F_3 . Two anti-
344 cline are observed in this structure: the surface anticline above F_1 and deeper sub-
345 surface anticline beneath F_1 . The upward decreasing displacement of F_1 suggests a
346 trishear algorithm is applicable in this structure. Moreover, reverse faults F_1 and F_2
347 all present upward-steepening shapes, which is highly comparable with the complex
348 trishear models shown in Fig.9b. Therefore, we applied the trishear algorithm for-
349 ward modelling to simulate the structural evolution of the Lenghu5 structure by allow-
350 ing multiple curved faults in a single section. Fig.11b-e depicts the progressive de-
351 velopment models of the Lenghu5 structure simulated using 2D Move (Midland Val-
352 ley).

353 The parameters suggested by the best-fit trishear model in the parameter space are
354 used in the trishear forward modelling (apical angle of 50° and p/s ratio of 2.0, sug-

355 gested in Fig.10c). The comparison between the fault displacement and the fault tip
356 propagation of F_2 also suggests a trishear p/s ratio of 2.0. In order to simulate the
357 upward steepening reverse faults F_1 and F_2 , we used the interpreted F_1 and F_2 as
358 templates to define the stepwise values of upward steepening angles. In Fig.11b,
359 normal fault F_2 was developed to form a half-graben in the J_r sediments followed by
360 deposition of post-extension sequence from E_{1+2} to N_{2-1} ; in Fig.11c-d, the geological
361 environment changed to be compressional which results in the inversion of F_2 and
362 the development of the reverse fault F_1 ; after uplift and erosion to present, Fig.11e
363 presents a good match to the geometry of the Lenghu5 structure. The models in
364 Fig.11b-e constrain the structural evolution of the Lenghu5 structure.

365 **7. Discussion**

366 *7.1 Geometric constraints of trishear algorithm*

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

380 In the parameter space (Fig.4), the clusters of plotted natural examples are concen-
381 trated in the space with shallow reverse fault dip. This is because most of these ex-
382 amples are from thin-skin structures where the thrusting involves only the sedimen-
383 tary cover whereas the basement is unaffected in the deformation (Poblet and Lisle,
384 2011), e.g., foreland fold-and-thrust belts in Canadian Rocky Mountain (Bally et al.,
385 1966; Barclay and Smith, 1992; Price, 1981) and Turner Valley anticline in Alberta
386 Foothills (Gallup, 1954; Gallup, 1951; Mitra, 1990). However, in the trishear parame-
387 ter space, there are also a series of trishear models with high angle reverse faults
388 that are very likely to be basement-involved and can be related to thick-skin structur-
389 al inversion. The contractional inversion of older extensional faults has now been
390 widely recognized in fold-and-thrust belts, for instance, in the Neuquen Basin in Ar-
391 gentina (Rojas et al., 1999), the Spanish Pyrenees (Muñoz, 1992), Alps (Pfiffner et
392 al., 2000; Schmid et al., 1996), Apennine Mountains (Coward et al., 1999), Papua
393 New Guinea (Buchanan and Warburton, 1996; Hill, 1991; Hill et al., 2004). In con-
394 trast to thin-skin structures, the basement involvement in thick-skin structures have
395 not been transported over long horizontal distances as the steep faults penetrate the
396 basement and lead to basement uplifts (Poblet and Lisle, 2011). However, the thin-
397 skin fold-and-thrust belts (basement-unaffected) and thick-skin belts (basement-
398 involved) can coexist in a single structure. The coexistence of these different struc-
399 tural styles might be common in many orogenic belts. For example, the Rocky Moun-
400 tains-USA Cordillera exhibits thin-skin deformation in the interior and thick-skin de-
401 formation in the outer part (Hamilton, 1988); the steep faults that penetrate the
402 basement become sub-horizontal when reaching the sedimentary cover and promote
403 the horizontal initiation of the thin-skin detachments such as in the Alps (Hayward
404 and Graham, 1989).

405 7.2 Influence of stratigraphy on trishear algorithm

406 In this paper, the parameter space concept focus on the geometrical constraints of
407 the trishear algorithm. We also considered curved reverse faults, multiple faults and
408 pre-existing faults when applying trishear algorithms to natural structures. However,
409 it needs to be recognised that lithology and mechanical strength also play a role on
410 the trishear models, with the parameters being very different depending upon me-
411 chanical stratigraphy (Alonso and Teixell, 1992; Hardy and Finch, 2007; Hardy and
412 Ford, 1997). It has been suggested that rocks with high competency present higher
413 trishear p/s ratios than low competent rocks, e.g., sandy units show higher trishear
414 p/s ratio than clay-rich units (Hardy and Ford, 1997). Hardy and Finch (2007) also
415 employed a discrete-element technique (Finch et al., 2003; Finch et al., 2004) to in-
416 vestigate sedimentary cover deformation in response to contractional faulting. The
417 fault zone deformation was simulated with different settings: in the homogeneous
418 weak cover model, a wide and open triangular zone was developed in front of the
419 fault tip and significant thinning and thickening were observed within the triangular
420 zone, which broadly agreed with the predictions of the trishear kinematic models
421 (Allmendinger, 1998; Erslev, 1991; Hardy and Ford, 1997); while in the strongly het-
422 erogeneous layered models, a much narrower kink-like triangular zone was ob-
423 served in front of the fault tip and layer thickness was roughly preserved within the
424 triangular zone. In the physical modelling of Dixon (2004), the relatively homogene-
425 ous weak stratigraphy resulted in a trishear-like ductile deformation (low trishear p/s
426 ratio) whereas the model with strong bedding-controlled heterogeneity is prone to
427 form through-going reverse faults (high trishear p/s ratio). All these mechanical and
428 physical models suggest the important role of stratigraphy and strength in the cover

429 deformation (see also Welch et al., 2009), however, are likely to be second order
430 controls superimposed upon the first order geometry outlined here.

431 **8. Conclusion**

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

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602

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612 space. In the parameter space, 13 natural examples are plotted in and two clusters
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631 Trishear forward models of an upward-shallowing reverse fault. The fault dip chang-
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633 Figure 9. Trishear forward models of reverse faults affected by pre-existing faults. (a
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637 all simulated.

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642 Table 1. A cluster of natural trishear examples in published studies and their corre-
643 sponding best-fit parameters.