



Deposited via The University of Leeds.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/148574/>

Version: Accepted Version

---

**Article:**

Pei, Y, Paton, DA, Knipe, RJ et al. (Cover date: Jan Feb 2020) Field-based investigation on fault architecture: a case study from the Lenghu fold-and-thrust belt, Qaidam basin, NE Tibetan Plateau. *Geological Society of America Bulletin*, 132 (1/2). pp. 389-408. ISSN: 0016-7606

<https://doi.org/10.1130/B35140.1>

---

(c) 2019, Geological Society of America. This is an author produced version of a paper published in the *Geological Society of American Bulletin*. Uploaded in accordance with the publisher's self-archiving policy.

**Reuse**

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

**Takedown**

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing [eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.

1 **Field-based investigation on fault architecture: a case study from the Lenghu fold-**  
2 **and-thrust belt, Qaidam basin, NE Tibetan Plateau**

3 Yangwen PEI<sup>a, b, \*</sup>, Douglas A. PATON<sup>c</sup>, Rob J KNIPE<sup>c</sup>,

4 W Henry LICKORISH<sup>d</sup>, Anren LI<sup>e</sup>, Kongyou WU<sup>a</sup>

5 <sup>a</sup> School of Geosciences, China University of Petroleum, Qingdao, 266580, China

6 <sup>b</sup> Laboratory for Marine Mineral Resources, Qingdao National Laboratory for Marine Science and  
7 Technology, Qingdao 266071, China

8 <sup>c</sup> School of Earth & Environment, University of Leeds, Leeds, LS2 9JT, England

9 <sup>d</sup> 22 140 Point Drive NW, Calgary T3D 4W3, Canada

10 <sup>e</sup> Central Area Exploration Division, Saudi Aramco, Dhahran, 31311, Kingdom of Saudi Arabia

11 \* Corresponding author: Y. PEI (email: [peiyangwen@upc.edu.cn](mailto:peiyangwen@upc.edu.cn)).

12 **Abstract**

13 The fault zone architecture of a thrust fault zone is critical for understanding the strain  
14 accommodation and structural evolution in contractional systems. The fault architecture  
15 is also important for understanding fluid flow behaviour both along and/or across thrust  
16 fault zones and for evaluating potential fault related compartmentalisation. Because  
17 meso-scale (1-100 m) structural features are normally beyond the seismic resolution,  
18 high-resolution outcrop in-situ mapping (5-10 cm resolution) was employed to study the  
19 deformation features of a thrust fault zone located in the Qaidam Basin, northeastern  
20 Tibetan Plateau. The excellent exposure of outcrops enables the detailed investigation of  
21 the Lenghu thrust fault zone and its architecture. The Lenghu thrust fault, a seismically  
22 resolvable fault with up to ~800m of throw, exhibits a large variation of fault architecture  
23 and strain distribution along the fault zone. Multiple structural domains with different levels  
24 of strain were observed and are associated with the fault throw distribution across the  
25 fault. Based on previously proposed models and high-resolution outcrop mapping, an up-  
26 dated fault zone model was constructed to characterize the structural features and evo-  
27 lution of the Lenghu thrust. The possible parameters that impact fault architecture and

28 strain distribution, including fault throw, bed thickness, lithology and mechanical hetero-  
29 geneity were evaluated. Fault throw distributions and linkages control the strain distribu-  
30 tion across a thrust fault zone, with local folding processes contributing important ele-  
31 ments in Lenghu especially where more incompetent beds dominate the stratigraphy.  
32 Mechanical heterogeneity, induced by different layer stacking patterns, controls the de-  
33 tails of the fault architecture in the thrust zone. The variations in bed thicknesses and  
34 mechanical property contrasts are likely to control the initial fault dips and fault/fracture  
35 density. Large fault throws are associated with wide strain accommodation and damage  
36 zones, although the relationship between the development and width of the fault zone  
37 with the throw accumulation remains to be assessed. By presenting the high resolution  
38 mapping of fault architecture this study provides an insight into the sub-seismic fault zone  
39 geometry and strain distributions possible in thrust faults and reviews their application to  
40 assessing fault zone behaviour.

#### 41 **Keywords**

42 Detailed outcrop mapping, fault architecture, strain distribution, deformation mechanisms,  
43 mechanical stratigraphy

#### 44 **1. Introduction**

45 The detailed meso-scale fault zone architecture controls the strain accommodation of  
46 faults and impacts on the fluid flow properties of the fault zones (e.g., [Loveless et al., 2011](#);  
47 [Seebeck et al., 2014](#); [Childs et al., 2017a](#); [Childs et al., 2017b](#); [Dimmen et al., 2017](#);  
48 [Ferrill et al., 2017a](#); [Ferrill et al., 2017b](#); [Homberg et al., 2017](#); [Peacock et al., 2017a](#);  
49 [Peacock et al., 2017b](#); [Cawood and Bond, 2018](#); [Cooke et al., 2018](#); [Pei et al., 2018](#)). In  
50 order to understand the detailed fault architecture, previous studies have investigated the  
51 deformation features of a mechanically layered sequence of beds that are subject to de-  
52 formation (e.g., [Ferrill and Morris, 2003](#); [Welch et al., 2009b](#); [Ferrill et al., 2017a](#); [Ferrill](#)

53 [et al., 2017b](#)). The work shows that faults tend to form first in the brittle beds (e.g. sand-  
54 stones or carbonates), while the weak/ductile beds (e.g. clay beds) can deform by distrib-  
55 uted shearing to accommodate the overall strain (e.g., [Eisenstadt and De Paor, 1987](#);  
56 [Peacock and Sanderson, 1991](#); [McGrath and Davison, 1995](#); [Childs et al., 1996a](#);  
57 [Schöpfer et al., 2006](#); [Childs et al., 2009](#); [Davies et al., 2012](#); [Childs et al., 2017a](#); [Childs](#)  
58 [et al., 2017b](#); [Ferrill et al., 2017a](#); [Ferrill et al., 2017b](#); [Vasquez et al., 2018](#)). Several  
59 quantitative dynamic models have also been presented (e.g., [Egholm et al., 2008](#); [Welch](#)  
60 [et al., 2009b](#); [Homberg et al., 2017](#); [Nicol et al., 2017](#); [Peacock et al., 2017b](#)) to analyse  
61 the mechanics of faulting and clay/shale smearing along faults in layered sand and  
62 shale/clay sequences (e.g., see also review in [Grant, 2017](#)). These models, from primarily  
63 extensional fault arrays, predict that the isolated initial faults formed within the brittle beds  
64 will grow until they eventually link up with increasing strain by propagating across the  
65 ductile intervals to create a complex fault zone architecture ([Peacock and Sanderson,](#)  
66 [1991, 1992](#); [Childs et al., 1996a](#); [Walsh et al., 1999](#); [Walsh et al., 2003](#); [Soliva and](#)  
67 [Benedicto, 2004](#); [van der Zee and Urai, 2005](#); [Davies et al., 2012](#); [Ferrill et al., 2012](#);  
68 [Ferrill et al., 2014](#); [Ferrill et al., 2017a](#); [Ferrill et al., 2017b](#)). Outcrop studies supporting  
69 these models of fault zone architecture include the Moab fault, in Utah ([Davatzes and](#)  
70 [Aydin, 2005](#)); the minor normal-fault arrays exposed within Gulf of Corinth rift sediments,  
71 Central Greece ([Loveless et al., 2011](#)); and faults in the multilayer systems in the South-  
72 Eastern basin, France ([Roche et al., 2012a](#); [Roche et al., 2012b](#)). Fault zone models  
73 defining the fault zone architecture have also been proposed in crystalline rocks (e.g.,  
74 [Caine et al., 1996](#)); in poorly lithified sediments (e.g., [Heynekamp et al., 1999](#); [Rawling](#)  
75 [and Goodwin, 2003, 2006](#); [Sosio De Rosa et al., 2018](#)); within poorly consolidated sedi-  
76 ments by ([Loveless et al., 2011](#)) and in transpressional faults ([Choi et al., 2016](#)).

77 However, most of these published studies have focused on the deformation features of  
78 extensional normal faults. There is still uncertainty on the detailed fault architecture de-  
79 velopment of thrust faults, although some studies have illustrated the impact of mechan-  
80 ical stacking on faulting deformation in thrust belts (Woodward and Rutherford Jr, 1989;  
81 Lloyd and Knipe, 1992; Woodward, 1992; Pfiffner, 1993; Cawood and Bond, 2018). In  
82 order to enhance the understanding of the evolution of fault architecture in thrust zones,  
83 we have studied the detailed (1m-10km scale) fault zone architectures of a thrust fault in  
84 the Lenghu fold-and-thrust belt of the Qaidam basin, northeastern Tibetan Plateau (e.g.,  
85 Yin et al., 2008a; Yin et al., 2008b; Pei et al., 2014; Pei et al., 2017b). The fault architec-  
86 ture and strain distribution across the Lenghu thrust fault were investigated using high-  
87 resolution stratigraphic logging, satellite image interpretation and detailed outcrop map-  
88 ping. The Lenghu thrust fault zone outcrops were separated into three general strain lev-  
89 els (high, medium and low), related to the fault throw magnitudes and the amount of layer  
90 disruption. A more detailed thrust fault model was constructed to demonstrate the fault  
91 architecture and deformation processes. The effects of parameters that may influence  
92 the fault architecture and strain distribution (e.g., fault throw, bed thickness, stratigraphy,  
93 and mechanical heterogeneity) were then evaluated.

## 94 **2. Geological Setting**

95 The Qaidam basin, an oil/gas-bearing Mesozoic-Cenozoic, fault-bound, sedimentary  
96 basin, is located in the northern edge of the Tibetan Plateau (Fig. 1). Topographically, the  
97 Qaidam basin covers an area of  $\sim 120,000 \text{ km}^2$  and has an average elevation of  $\sim 3 \text{ km}$   
98 (based on the SRTM DEM data). In map view, the Qaidam basin is a rhombic shaped  
99 basin, and its N-S width changes from  $\sim 150 \text{ km}$  in the east to  $\sim 300 \text{ km}$  in the west (Yin  
100 et al., 2007; Yin et al., 2008a; Yin et al., 2008b). Tectonically, the Qaidam basin is  
101 bounded by the Qilian Shan-Nan Shan thrust belt to the northeast (e.g. Molnar and  
102 Tapponnier, 1975; Burchfiel et al., 1989; Tapponnier et al., 1990; Meng et al., 2001; Yin

103 [et al., 2008a](#)), the left-lateral strike-slip Altyn Tagh fault to the northwest (e.g. [Meyer et](#)  
104 [al., 1998](#); [Cowgill et al., 2000](#); [Cowgill et al., 2003](#); [Cowgill et al., 2004a](#); [Cowgill et al.,](#)  
105 [2004b](#); [Yue et al., 2004](#); [Cowgill, 2007](#); [Yin et al., 2007](#)), and the Qimen Tagh-Eastern  
106 Kunlun thrust belt to the south and southwest (e.g. [Chen et al., 1999](#); [Meng et al., 2001](#);  
107 [Jolivet et al., 2003](#); [Yin et al., 2007](#); [Craddock et al., 2012](#); [Mao et al., 2016](#)). The stratig-  
108 raphy of the Qaidam basin is divided into three main packages, which are metamorphic  
109 basement, late Palaeozoic-Mesozoic sediments and Cenozoic sediments (e.g., [Cui et al.,](#)  
110 [1995](#); [Deng et al., 1995](#); [Gao et al., 1995](#); [Xia et al., 2001](#)). Based on outcrop observations,  
111 seismic sections, boreholes, terrestrial fossils, basin-scale stratigraphic correlation, fis-  
112 sion-track and  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of detrital micas ([Huo, 1990](#); [Yang et al., 1992](#); [Song and](#)  
113 [Wang, 1993](#); [Huang et al., 1996](#); [Xia et al., 2001](#); [Qiu, 2002](#); [Sun et al., 2005](#); [Rieser et](#)  
114 [al., 2006a](#); [Rieser et al., 2006b](#)), a division and time assignments of Mesozoic to Cenozoic  
115 sediments have been proposed. The Qaidam basin contains thick Cenozoic sediments  
116 ( $E_{1+2}$ - $Q_1$ , >54.8 Ma - present) up to 16 km thick and locally-developed thin Mesozoic sed-  
117 iments ( $J_r$ , 206 - 65 Ma) (e.g., [Huang et al., 1996](#); [Yin et al., 2008b](#)). The Qaidam basin  
118 contains different structural hierarchies: the first-order structure is a large-scale, regional  
119 structure composed of a series of tight anticlines and open synclines with associated  
120 faults extending for ~380kms along strike and to a maximum depth of up to ~16km. The  
121 second-order structures are regional scale folds/faults, including inverted normal faults in  
122 Mesozoic sediments and thrust faults in Jurassic-Eocene sediments that indicate a com-  
123 plex geological history of the Qaidam basin ([Wang et al., 2006a](#); [Yin et al., 2008b](#)). The  
124 central thickening of Cenozoic sediments suggests the Qaidam basin was controlled by  
125 NE-SW contraction associated with the uplift of the Tibetan Plateau (e.g., [Molnar and](#)  
126 [Tapponnier, 1975](#); [Xia et al., 2001](#); [Pang et al., 2004](#); [Wang and Burchfiel, 2004](#); [Wang](#)  
127 [et al., 2006b](#); [Zhou et al., 2006](#); [Zhu et al., 2006](#)). The detailed Qaidam basin strain history  
128 is complex and involves some along strike extension that may have been associated with

129 oblique slip on deep faults and/or the interference of propagating folds (Mao et al., 2016).  
130 The total shortening of the central Qaidam basin since 65 Ma is estimated as  $20 \pm 2$  km,  
131 which leads to an estimated shortening rate of  $0.30 \pm 0.04$  mm/yr (Zhou et al., 2006; Yin  
132 et al., 2008b; Liu et al., 2009).

133 The Lenghu fold-thrust belt, located in the northern portion of the Qaidam basin, is a ~ 15  
134 km wide asymmetric anticline controlled by the underlying Lenghu thrust fault (Fig. 1),  
135 developed during the regional NE-SW oriented contraction (e.g., Chen et al., 2005; Wang  
136 et al., 2006a; Mao et al., 2016; Pei et al., 2017a; Pei et al., 2017b). The Lenghu thrust  
137 fault, with a fault throw ranging from ~300 m to ~800 m (Pei et al., 2017a), dips steeply  
138 SW at angles of 60 - 70° in the shallow subsurface, extending along strike NW to SE for  
139 ~ 80 km. An anticline belt has developed in the hanging wall of the Lenghu thrust fault.

140 The stratigraphy of the Lenghu fold-thrust belt is dominated by Neogene sediments, com-  
141 prising primarily siltstone and sandstone (Fig. 1). The detailed stratigraphy of the Lenghu  
142 fold-thrust belt was logged on the ground along traverses that were positioned sub-per-  
143 pendicular to the strike of the Lenghu fold-and-thrust belt (modified after Pei et al., 2017a;  
144 Pei et al., 2017b). The stratigraphy can be divided into four main packages (Fig. 2), (i)  $S_a$ ,  
145 the oldest package, comprises fine sandstones and red/grey/mottled siltstones, with a  
146 thickness of ~ 170 m ( with individual bed thickness ranging from 1 m to ~10 m); (ii)  $S_b$ ,  
147 the lower middle sequence, includes fine-medium sandstones interbedded with very a  
148 few thin red/grey siltstones and its thickness is ~ 440 m (with individual bed thickness  
149 ranging from 0.5 m to ~5 m); (iii)  $S_c$ , the upper middle package, is ~ 340 m thick (with  
150 individual bed thickness ranging from 0.5 m to ~20 m), shows a similar lithology to  $S_b$ , but  
151 with thin interbedded medium-coarse sandstones; (iv)  $S_d$ , the upper sequence, contains  
152 coarse-very coarse sandstones with a thickness exceeding 250 m (with individual bed  
153 thickness ranging from 0.5 m to ~25 m). Here the rocks finer than silty sandstone were

154 classified as incompetent layers, whereas rocks no finer than silty sandstone were clas-  
155 sified as competent layers. This allows us to estimate the competent : incompetent ratios  
156 and level of mechanical heterogeneity of each individual package. These four packages  
157 represent different levels of mechanical heterogeneity (see Fig. 2): the  $S_a$  package has a  
158 high mechanical heterogeneity (competent : incompetent = 81% : 19%), the  $S_b$  package  
159 has a low mechanical heterogeneity (competent : incompetent = 100% : 0%), the  $S_c$  pack-  
160 age has a medium to high mechanical heterogeneity (competent : incompetent = 99% :  
161 1%), and the  $S_d$  package has a medium mechanical heterogeneity (competent : incom-  
162 petent = 97% : 3%). The excellent outcrops of the Lenghu thrust fault zone provide a  
163 good platform to assess the meso- and micro-scale structural features within the fault  
164 zones developed in these sequences.

### 165 3. Data and Methods

166 In this study, we integrated remote sensing data (e.g., Landsat images) and field obser-  
167 vations (e.g., stratigraphy, fault system maps, and detailed maps of fault outcrops), to  
168 understand the detailed fault architecture and its controlling parameters. As meso-scale  
169 structural features are below seismic resolution, high-resolution landsat images were in-  
170 terpreted with validation by stratigraphic logging (Fig. 2) and outcrop structural mapping  
171 (Fig. 3). The Lenghu thrust fault zone, e.g., F1 - F3 (Fig. 4) and F4 (Figs. 5-9), were  
172 mapped in detail to investigate the meso-scale structural features. Mapping included  
173 measurement of; fault azimuth/dip, fault throw, fault populations and linkages, and an  
174 assessment of the mechanical stratigraphy. The strain distribution across the fault zones  
175 was determined based on the level of estimated fault throws and the deformation of li-  
176 thologies present. Representative thrust fault outcrops with different levels of deformation,  
177 fault throw, bed thickness, stratigraphy, mechanical heterogeneity were mapped in detail  
178 to understand the meso-scale fault architecture occurring along the thrust fault zone (Fig.  
179 10). The overall throw on the Lenghu thrust at the selected outcrops ranges from ~300 m

180 to ~800 m. Deformation responses of interbedded competent and incompetent layers  
181 were investigated based on the outcrop observations and measurements (Figs. 11). A  
182 more detailed static model of a thrust fault zone was then built, based on previous models  
183 and the high-resolution outcrop study reported here (Figs. 12). Schematic structural evo-  
184 lutionary models of the different vertical stacking sequences were built to assess the con-  
185 trol of stratigraphy and mechanical heterogeneity on fault development in the thrust fault  
186 zone (Figs. 13).

#### 187 **4. Strain Distribution and Fault Architecture**

188 Landsat image interpretation and fault outcrop mapping were employed to evaluate the  
189 strain distribution (e.g., folding and faulting) along strike of the Lenghu fold-thrust belt  
190 (Fig. 2). The Lenghu thrust faults (red curves and plots in the stereonet in Fig. 3) devel-  
191 oped from NE-SW shortening. An asymmetric anticline, with a steep or overturned NE  
192 fore-limb and relatively shallow dipping backlimb, is developed in the hanging wall of the  
193 Lenghu thrust. The topographic culmination (green triangle in Fig. 3) corresponds to the  
194 flat crest of the hanging wall anticline. The fault zone of the Lenghu fold-thrust belt is not  
195 a single fault plane in outcrop, but comprises a main thrust fault and several small splay  
196 faults. The main thrust fault, with a throw of up to 650 m, accounts for 85 – 90% of the  
197 overall fault throw of the fault zone (Pei et al., 2017a; Pei et al., 2018), although several  
198 splay faults are also observed in either the hanging wall or footwall. The splay faults, with  
199 throws of < 300 m, are not evenly distributed but concentrated along the hanging wall  
200 anticline crest and generate a number of fault bound lenses in the fault zone. Normal  
201 faults, with fault throws of up to tens of meters, form in the hanging wall (see the purple  
202 curves and plots in the stereonet in Fig. 3). The majority (~ 90%) of the minor structures  
203 develop in the fault zone and the hanging wall, suggesting that the strain is mostly con-  
204 centrated in the hanging wall to the fault zone. In addition, the normal faults in the hanging  
205 wall are mostly concentrated in the silt-rich units (i.e., *Sa* - *Sb*, Fig. 3) present in the fold

206 crest area and near the main Lenghu thrust. The frequency of these structures decreases  
207 away from the main fault to the SW. The normal faults often terminate at the Lenghu  
208 Thrust (Fig. 3) and appear to represent a late fault extensional strain and extensional  
209 reactivation of the Lenghu Thrust where part of the normal fault activity is taken up on the  
210 main thrust (see Fig. 7 and Section 4.2). This along strike extension may be associated  
211 with local accommodation of oblique slip (e.g., Mao et al., 2016) or a regional E-W exten-  
212 sion.

#### 213 4.1. Strain distribution and cross fault zones

214 A set of well-exposed outcrops (approximate section size 50 m × 30 m) in the Lenghu  
215 field enables us to link the structures present on satellite images, at the > 100 m scale,  
216 with structures at a scale of < 100 m. Three well-exposed outcrops of the main thrust fault  
217 were mapped in detail (Fig. 4) to allow the generation of sections F1, F2 and F3 (see  
218 positions in Fig. 3). These three SW-NE traverses cut through the hanging wall of the  
219 main thrust fault ~ 50 m apart and are orientated sub-parallel with each other. The three  
220 outcrops all include the main fault and the adjacent damage zones of the Lenghu thrust  
221 fault where different sedimentary stacking sequences are present.

222 The stereonet of measured fault strike/dip of the outcrops F1, F2 and F3 demonstrate a  
223 high-angle central fault zone and a splay thrust fault in the hanging wall, responding to  
224 the NE-SW shortening (Fig. 4). An anticline with a flat crest against the Lenghu thrust  
225 fault was developed in the hanging wall. Although the hanging wall folding clearly absorbs  
226 shortening, the overall strain is dominated by fault deformation (i.e., the Lenghu thrust  
227 fault and its splay faults). By restoring a regional seismic section, Pei et al. (2018) evalu-  
228 ated the contribution of faulting and folding deformation to the overall strain in the Lenghu  
229 Fold-Thrust belt, which are 80% and 20%, respectively. The steeply dipping main fault  
230 zone contains disrupted and sheared stratigraphic units composed of foliated fault rocks

231 (primarily originally siltstones and subordinate sandstones), which accounts for the ma-  
232 jority of the fault zone deformation in the central portion of the outcrop. The siltstones  
233 form vertical domains where they have been smeared into the fault zone from the hanging  
234 wall stratigraphy, while the sandstones are faulted and deformed by brittle deformation.  
235 The bedding within the central fault domains cannot be identified because of the intense  
236 deformation. The shearing into high strain fault zones generates silt smears and sand  
237 inclusions. The outcrops F1, F2 and F3 illustrate the lateral variation in the fault zone  
238 architecture along strike of the Lenghu fold-thrust belt. The strain distribution across the  
239 fault zone presents a similar pattern between the three outcrops (see the estimated strain  
240 curves in Fig. 4). The central portion of the fault zone mapped shows high strain defor-  
241 mation, while the moderate and low strain deformation are unevenly distributed around  
242 this domain.

#### 243 **4.2. Meso-scale fault architecture**

244 An additional outcrop, F4 (Fig. 5a), in the southern end of the Lenghu fold-thrust belt,  
245 (see position in Fig. 3) also demonstrates the detailed meso-scale fault architecture.  
246 Based on the regional section analysis by Pei et al. (2018), the fault throw on the main  
247 thrust fault here is 640 – 847 m, large enough to be imaged in a seismic reflection section.  
248 The Lenghu thrust at F4 is not a single-plane fault, but composed of several splay faults  
249 and domains with varying amounts of strain (Fig. 5). Fig. 5b demonstrates the well-ex-  
250 posed outcrop of F4 and the structural interpretation. By integrating the stratigraphic se-  
251 quences, Fig. 5c presents a composite of the detailed maps of five individual outcrops of  
252 splay faults; F4-1, F4-2, F4-3, F4-4 and F4-5. The outcrop F4-5 was not mapped in detail,  
253 because of the heavy weathering present. The outcrops F4-1 to F4-4 present different  
254 levels of fault throws and strain indicated by the amount of layer disruption. The uneven  
255 fault throw distribution (Fig. 5c) across the Lenghu thrust fault zone allows us to subdivide  
256 this fault zone into three structural domains with different levels of strain. These are (i). a

257 high strain domain: splay fault zone F4-4 (Fig. 6) and F4-5; (ii). a medium strain domain:  
258 splay fault zone F4-3 (Fig. 7); and (iii). a low strain domain: splay fault zones F4-1 (Fig.  
259 8) and F4-2 (Fig. 9). Each of these domains are reviewed separately below.

#### 260 **(1) High strain domain: splay fault zone F4-4**

261 The high strain domain F4-4 (Fig. 6a), defined by intense deformation, well developed  
262 fault rocks and bed disruption, is directly in contact with the slightly deformed hanging  
263 wall (see position in Fig. 5). The stratigraphy of outcrop F4-4 fault is dominated by mottled  
264 fine-medium siltstones (see the stratigraphic column recorded in field, Fig. 6b, c). The F4-  
265 4 presents a steeply dipping fault zone (70 - 80°), ~ 5 m wide, with sheared lithologies of  
266 foliated fault rocks composed primarily of siltstones and some sandstones. This fault zone  
267 architecture is controlled by a series of NW-SE striking high-angle thrust faults with rela-  
268 tive large throws (up to 650 m, based on stratigraphic correlation in Pei et al. (2018)),  
269 together with several SW-directed back thrust faults with smaller offsets (<1 m), demon-  
270 strating NE-SW shortening (Fig. 6d). The siltstones form sheared domains apparently  
271 derived from both the hanging wall and the footwall. The sandstones are faulted and ex-  
272 tended by discrete fault offsets to generate boudins in the attenuated layers. Although the  
273 fault rocks are variable in the fault zone of F4-4, the original bedding cannot be identified  
274 because of the intense shearing and faulting. In the northeast end of F4-4, the sub-hori-  
275 zontal footwall bedding shows only slight deformation. A distinct slip surface separates  
276 the steeply dipping and sheared fault zone from the footwall stratigraphy, suggesting this  
277 slip surface forms the northeast boundary of the main fault zone F4-4.

#### 278 **(2) Medium strain domain: splay fault zone F4-3**

279 The medium strain domain F4-3 (Fig. 7a) is based on the more continuous layer continuity  
280 compared to F4-4. F4-3 is located on the northeast side of the high strain domain F4-4  
281 (see position in Fig. 5). The stratigraphy of F4-3 is mainly composed of brown siltstones  
282 and grey sandstones (Fig. 7a, b). Thrust faults with measurable fault throws (5 cm - 5 m)

283 are well developed in this outcrop. The cumulative throw on these thrust faults is ~ 8 m.  
284 The bedding adjacent to the fault core dips steeply ( $> 50^\circ$ ) and is folded. However, in  
285 contrast with the high strain domain F4-4, the outcrop F4-3 contains low angle thrust  
286 faults (dips of  $30 - 50^\circ$ ) that offset beds in a tightly folded zone. Through-going faults are  
287 developed in the thick homogeneous units (either the thick sandstone or the siltstone  
288 beds) in the top or bottom of the section) while fault segments and lenses are developed  
289 where the stratigraphic heterogeneity increases (e.g., interbedded thin sandstones and  
290 siltstones in the central section, Fig. 7c). The stereonet of the fault planes indicate NE-  
291 SW shortening (Fig. 7d).

### 292 **(3) Low strain domain: splay fault zones F4-2 and F4-1**

293 A stack of small thrust faults representing a low strain domain, indicated by the small  
294 cumulative throw ( $< 2\text{m}$ ) and relatively low levels of layer folding, were also mapped in the  
295 profile of fault F4, i.e., F4-2 (Fig. 8a, b) and F4-1 (Fig. 9a, b).

296 The maximum throw at F4-2 reaches up to 2 m within the imbricated thrust faults (Fig.  
297 8b). The outcrop F4-2 contains lithologies dominated by the upper siltstones and lower  
298 sandstones (Fig. 8c). More folding is observed in the silty layers (middle section) than in  
299 the sandy layers (lower section). This is likely to reflect the different mechanical properties  
300 of the stratigraphic sections with different silt/sand ratios. The strain (faulting and folding)  
301 decreases away from the largest throw thrust fault towards the edges of the outcrop and  
302 fault zone shown. The stereonet of the fault planes indicate NE-SW shortening (Fig. 8d).

303 The thrust fault imbricates form at lower angles ( $20 - 40^\circ$ ) than in the high strain domain  
304 (e.g., F4-4 and F4-5) and the medium strain domain (e.g., F4-3). Fault splays are devel-  
305 oped along the thrust faults, particularly where the fault propagates from sandstone layers  
306 to siltstone layers.

307 A second low strain thrust fault F4-1, shown in Fig. 9b, is a small pop-up structure along  
308 a minor fold axis in the Lenghu thrust footwall. The outcrop is in the domain where beds

309 have low dips away from main thrust fault (Fig. 9b). The lower layers involved in F4-1 are  
310 primarily sandstones while the top layers are siltstone-dominated (Fig. 9c). F4-1 is a struc-  
311 ture composed of a series of sub-parallel NW-SE trending thrust faults and SW back-  
312 thrusting faults. The stereonet of the fault planes also indicate the NE-SW contraction  
313 (Fig. 9d). The silt-rich layers (upper section) of the fore-thrust show more folding than in  
314 the sandy layers (lower section), which is similar to that observed in the outcrop F4-2.  
315 Fault lenses were also developed along the thrust faults and back-thrusts, particularly  
316 where the fault propagates from sandy layers to silt-rich layers.

317 Based on the outcrop mapping of the Fault F4, the deformation is primarily in the high  
318 strain fault domains F4-4/F4-5; the medium strain fault F4-3 is located in the intermediate  
319 hanging wall or footwall of the high strain splay faults; and the low strain splay fault zone  
320 domains, F4-1 and F4-2, are developed as isolated structures in the more external foot-  
321 wall of the high strain fault (Fig. 10). In terms of the fault zone geometry, the high strain  
322 faults form steeper fault zones than the medium and low strain faults. In addition, the fault  
323 zone width and complexity appears higher where throws are larger, although the evolu-  
324 tion of the fault zone width with changes in throw cannot be assessed from the limited  
325 number of outcrops described here. For example, the high strain fault F4-4 has a fault  
326 zone width of ~ 7 m (Fig. 6), whereas the low strain fault F4-2 and F4-1 form fault zones  
327 widths below 0.5 m (Figs. 8 and 9).

## 328 **5. Deformation Responses and Thrust Fault Model**

329 The strain distribution across fault zones and meso-scale fault architectures of the well-  
330 exposed outcrops, together with the deformation responses associated with thrust fault-  
331 ing are considered in this section. A thrust fault model is then presented for the detailed  
332 fault zone architecture evolution followed by an evaluation of the role of fault throw and  
333 stratigraphy on strain accommodation.

## 334 5.1. Deformation Responses

335 Deformation responses to the thrust faulting are considered at the meso-scale and in-  
336 clude an evaluation of the general strain level developed in the competent beds, the in-  
337 competent beds, and the impact of the different mechanically layered sequences present  
338 in the study area.

339 The competent beds, e.g., sandstones, are prone to brittle deformation, e.g., fractures or  
340 faults in the study area. The faults with minor offsets are considered to initiate early when  
341 the stress is applied. The through-going faults then develop later in the strain history.  
342 Although this is considered a continuous process, both the fractures/very low offset faults  
343 and the through-going faults with higher throws can be observed in a single outcrop. It is  
344 not possible to assign low strain features to an early time stage in the fault zone develop-  
345 ment – they may have initiated at any stage in the fault zone evolution. The deformation  
346 of competent beds is linked to a very high fault propagation/slip ratio (see Erslev, 1991).  
347 The fault lenses can also form in the developing fault zone at different stages, either from  
348 fault linkage (Peacock and Sanderson, 1991; Childs et al., 1996a; Walsh et al., 2003;  
349 Lindanger et al., 2007; Childs et al., 2009; Ferrill et al., 2012) and/or from short-cut faulting  
350 (Knipe, 1985) or asperity reduction on the fault surface (Childs et al., 1996b; Walsh et al.,  
351 1999; Ferrill et al., 2014; Ferrill et al., 2017a; Ferrill et al., 2017b).

352 The incompetent beds, such as siltstones in the study area experience ductile defor-  
353 mation, e.g., folding or smearing during faulting. The ductile folding appears to form in the  
354 incompetent beds at low strains and accommodates local shearing and more extensive  
355 smearing is then developed when increasing strain offsets the weak/ductile beds. The  
356 progress of folding and smearing can be linked to a relative low fault propagation/slip ratio.  
357 The folding and faulting process is well described by the trishear model (e.g., Erslev, 1991;  
358 Childs et al., 1996a; Childs et al., 1996b; Hardy and Ford, 1997; Childs et al., 2009; Pei  
359 et al., 2014) or the quadrshear model (Welch et al., 2009a; Welch et al., 2009b), where

360 the strain is accommodated by upward and downward propagation of folding and even-  
361 tually faulting into and through the incompetent layer sandwiched between other units  
362 (see also Freitag et al., 2017; Peacock et al., 2017b). At higher offsets continuous faulting  
363 through the incompetent (siltstone) layer, may allow the smearing to become discontinu-  
364 ous which may leave some gouge patches along the slip surface, e.g., F4-4 (Fig. 6) (see  
365 also Welch et al., 2009a; Welch et al., 2009b).

366 Stacked beds define mechanically layered sequences, e.g., interbedded sandstones and  
367 siltstones (Fig. 11a<sub>0</sub>, a<sub>1</sub>), where strength properties have evolved differently during the  
368 burial history. Previous studies describing the structural deformation of layered se-  
369 quences include (e.g. Eisenstadt and De Paor, 1987; Withjack et al., 1990; Peacock and  
370 Sanderson, 1991; McGrath and Davison, 1995; Childs et al., 1996a; Schöpfer et al., 2006;  
371 Ferrill et al., 2017a; Ferrill et al., 2017b; Homberg et al., 2017; Nicol et al., 2017; Bubeck  
372 et al., 2018; Cawood and Bond, 2018; Vasquez et al., 2018). In the examples from the  
373 Lenghu Fold-Thrust Belt, when the mechanically layered sequence of beds are initially  
374 subject to stress, the fractures or small faults appear to form in the competent beds (e.g.,  
375 sandstones in the Lenghu fold-thrust belt) (Fig. 11b<sub>0</sub>, b<sub>1</sub>), whereas the incompetent beds  
376 (e.g., siltstones in the Lenghu fold-thrust belt) are folded or sheared to accommodate the  
377 overall strain (Fig. 11c<sub>0</sub>, c<sub>1</sub>). As the strain increases, the fractures or small faults confined  
378 within the competent beds are considered to grow until they eventually propagate into the  
379 incompetent beds (Peacock and Sanderson, 1991; Childs et al., 1996a; Walsh et al.,  
380 1999; Walsh et al., 2003), where siltstone folding and/or smearing can lead to gouge  
381 forming along the slip surfaces.

382

## 383 **5.2. Thrust fault model**

384 A basic model of fault zone development in the adjacent Junggar Basin was presented  
385 by Liu et al. (2017), where a conceptual model of reverse faults developed in igneous and

386 sedimentary rocks was based on integrating seismic, well logs and drilled cores. However,  
387 this model did not delineate the detailed meso-scale structural features present. Here we  
388 have reviewed the key features of the fault zones mapped in the Lenghu Thrust zone in  
389 [Fig. 12](#) and use this to evaluate the controls on fault zone architecture. The [Fig. 12](#) shows  
390 a fault zone formed in a mechanically layered sequence of beds. The yellow and brown  
391 units represent competent layers (e.g., sandstones) and incompetent layers (e.g., silt-  
392 stones), respectively. The idealised fault zone is composed of a main slip fault, and a  
393 series of fault bound lenses, fault splays and isolated faults that make up the damage  
394 zone ([see also reviews of fault damage zones in Wibberley et al., 2008; Choi et al., 2016;](#)  
395 [Peacock et al., 2017a](#)). The amount of strain accommodated in the fault zones decreases  
396 in the damage zone away from the main slip surface.

397 The majority of the fault throw is located in the most central position of the faulted section  
398 ([Fig. 12](#)), and is often confined by two discrete slip surfaces that are sub-parallel to each  
399 other (e.g., F4-4 in [Fig. 6b](#)). The common occurrence of two dominant slip surfaces was  
400 also recognised by previous studies (e.g., [Childs et al., 1996b; Ferrill and Morris, 2003;](#)  
401 [Loveless et al., 2011; Liu et al., 2017; Nicol et al., 2017; Nicol and Childs, 2018; Xie et al.,](#)  
402 [2018](#)). The fault zone and fault rocks between these two discrete slip surfaces have the  
403 highest strain. The final geometry of the fault zone is dependent on the mechanical stra-  
404 tigraphy of the sequence. For example, the number of faults accommodating the strain  
405 across the central fault zone between the main slip surfaces tends to increase in domains  
406 where more layers and more mechanical contrasts are present (e.g. see F4-4 in [Fig. 5](#)).  
407 In contrast, the incompetent layers (siltstones in this case) are likely to be incorporated  
408 as smears within the high strain zones (e.g. see the smeared grey unit *H* in [Fig. 6](#), and  
409 especially layer *B* and *D* in [Fig 7](#)). The fault damage zones in sections with, what appear  
410 to be, higher mechanical contrasts tend to form domains with increased faulting (e.g. note  
411 faults present in Layers *B* and *D* above the thick sandstone unit in [Fig. 7](#)). The detailed

412 outcrop maps also suggest that the mechanical strength of a layered sequence is scale-  
413 dependent. For example, although sandstone is prone to brittle deformation, a thin sand-  
414 stone layer sandwiched by thick siltstone layers appears to have a limited impact on the  
415 bulk behaviour of the package and is likely to be entrained into the smear zone and follow  
416 the mechanical response of the dominant layers (e.g., the thin yellow sandstone layer  
417 sandwiched between the thick brown siltstone layers, upper section of F4-1, Fig. 9b). The  
418 degree of disruption of entrained sandstone beds therefore appears to depend on the  
419 embedded layer thickness and strength relative to the larger package. Sandstone beds  
420 may form faulted sand boudins, maintaining sand-sand continuity and defining a smear-  
421 ing-like geometry in high strain zones, whereas thin sandstone beds may break down to  
422 form isolated boudins.

423 The damage zones adjacent to the main slip surface (Fig. 12) are characterised by splay  
424 faults, fault bound lenses and folds, where the overall strain is lower than across the main  
425 fault surfaces. The splay faults and fault lenses appear to form within the competent beds  
426 (yellow), and then propagate into and through the incompetent beds (brown). The splay  
427 faults extend into the undeformed or slightly deformed beds, and creates more fault com-  
428 plexity. The short-cut faults that remove local asperities on the developing slip surfaces  
429 can form new fault lenses, which increase the linkage of faults within the damage zone.  
430 The edges of the damage zone, away from the main slip surfaces (Fig. 12), with low  
431 strains are characterised by isolated faults or clusters of small throw faults; although the  
432 detailed linkage to other faults in 3D (out of the plane of exposure) is unknown.

433 The mapped outcrops in the Lenghu fold-thrust belt expose thrust faults with different  
434 amounts of fault throw, ranging from 50 cm (e.g., F4-1) to hundreds of meters (e.g., F4-  
435 4). Accordingly, multiple fault zones, with different individual widths (ranging from tens of  
436 centimetres to 5 meters) are developed across the traverses with a high total throw (see  
437 F4 in Fig. 10b)

438

## 439 **6. Discussion**

440 Previous studies have highlighted that the generation and distribution of fault zone ge-  
441 ometries and fault rocks are affected by several factors, e.g., the fault throw, lithology,  
442 deformation responses and internal fault structure (e.g., Hull, 1988; Blenkinsop, 1989;  
443 Loveless et al., 2011; Torabi and Berg, 2011; Pei et al., 2015; Childs et al., 2017a; Childs  
444 et al., 2017b; Ferrill et al., 2017b; Homberg et al., 2017). Based on the outcrop structures  
445 from the Lenghu fold-thrust belt, the effects of fault throw, bed thickness, host stratigraphy  
446 and mechanical stratigraphy on the thrust fault architecture are discussed here.

447 Large displacements are associated with wider fault zones (see Childs et al., 2009). In  
448 the Lenghu fold-thrust belt, thrust faults (e.g., F4-4 with displacements of > 200 m) form  
449 fault zones of high strain that are > 5 m wide (Fig. 10b), whereas the low strain thrust  
450 faults (e.g., F4-1 with a cumulative displacement of ~ 1.5 m) have ~ 50 cm wide zones of  
451 concentrated deformation (Fig. 10b). This observation concurs with previous studies  
452 (e.g., Otsuki, 1978; Robertson, 1983; Hull, 1988; Evans, 1990; Knott, 1994; Childs et al.,  
453 2009; Bastesen and Braathen, 2010; Davies et al., 2012; Childs et al., 2017a; Childs et  
454 al., 2017b; Ferrill et al., 2017a; Ferrill et al., 2017b), although the detailed relationship  
455 between the evolution of fault zone width (and fault rock width) with fault throw accumu-  
456 lation are still to be clearly defined. The smearing of weak/ductile beds (e.g., siltstones)  
457 are observed along the high strain fault zones in the meso-scale outcrops of thrust faults  
458 (see Fig. 6 and layers in the SW part of 4-3 in Fig. 7). However, large fault throws tend to  
459 destroy the continuity of smears, although thin silt gouges may persist along the important  
460 slip planes (Brown et al., 2003; Childs et al., 2009; Grant, 2017). A number of tools have  
461 been proposed to predict the continuity of siltstone smears in fault zones. Examples of  
462 the tools include: Clay Smear Potential (CSP) (Bouvier et al., 1989; Fulljames et al., 1997),  
463 Shale Smear Factor (SSF) (Lindsay et al., 1993), Shale Gouge Ratio (SGR) (Yielding et

464 al., 1997), Scaled Shale Gouge Ratio (SSGR) (Ciftci et al., 2013) and more complex re-  
465 distributions of smears (e.g., Grant, 2017).

466 The term 'mechanical stratigraphy' in fracture and fault studies has been used to subdi-  
467 vide layered sequences into discrete mechanical units defined by properties such as ten-  
468 sile strength, elastic stiffness, brittleness and fracture mechanics properties (e.g., Corbett  
469 et al., 1987; Tyler and Finley, 1991; Peacock and Sanderson, 1992; Cooke, 1997;  
470 Cosgrove, 1999; Laubach et al., 2009; Ferrill et al., 2012; Delogkos et al., 2017; Ferrill et  
471 al., 2017b; Grant, 2017; Cooke et al., 2018). A mechanical stratigraphy with high hetero-  
472 geneity may increase the complexity of the fault zone architecture in thrust systems (e.g.,  
473 Woodward and Rutherford Jr, 1989; Woodward, 1992; Pfiffner, 1993; Welch et al., 2009b;  
474 Davies et al., 2012; Cawood and Bond, 2018; Pei et al., 2018).

475 For the deformation conditions experienced by the exposed Lenghu fold-thrust belt, the  
476 thrust fault architecture is influenced by the mechanical stratigraphy. We have con-  
477 structed four sets of diagrams to demonstrate fault architecture and strain distribution that  
478 occur in different mechanical settings (Fig. 13a: thick competent layer; Fig. 13b: interbed-  
479 ded thick competent layers and thin incompetent layers; Fig. 13c: interbedded thin com-  
480 petent layers and thick incompetent layers; Fig. 13d: thick incompetent layer). In each  
481 case the competent : incompetent ratio varies (e.g., Ferrill and Morris, 2008; Ferrill et al.,  
482 2017b). Concurring with the previous studies (e.g., Peacock and Sanderson, 1991; Childs  
483 et al., 1996a; Ellis et al., 2004; Schöpfer et al., 2006; Bose et al., 2009; Loveless et al.,  
484 2011; Miller and Mitra, 2011; Yang et al., 2014; Homberg et al., 2017; Vasquez et al.,  
485 2018), stratigraphy dominated by competent layers normally forms a strain zone evolving  
486 from fractures, small faults to through-going faults (Fig. 13a: competent : incompetent  
487 ratio = 100% : 0%), whereas stratigraphy dominated by incompetent layers experienced  
488 folding-dominated deformation in Lenghu (Fig. 13d: competent : incompetent ratio = 0%

489 : 100%). In these two end-member scenarios (Fig. 13a, d), the strain distribution is deter-  
490 mined by the different mechanical properties of the stratigraphy. When the stratigraphy  
491 contains interbedded competent and incompetent layers, the final geometry of a de-  
492 formed sequence is influenced by the mixture as well as the dominant mechanical layers  
493 of the stratigraphy. As illustrated in Fig 13, where the competent layers dominate the  
494 sequence a more brittle deformation behaviour (Fig. 13b: competent/incompetent ratio =  
495 90% : 10%) is expected. Where the incompetent layers dominate the sequence more  
496 ductile deformation features (Fig. 13c: competent : incompetent ratio = 10% : 90%) are  
497 present. In these two intermediate scenarios, the subordinate layers (e.g., incompetent  
498 layers 10% in Fig. 13b and competent layers 10% in Fig. 13c, respectively) will deform  
499 more passively to accommodate the strain distribution determined by the dominant layers  
500 (e.g., competent layers 90% in Fig. 13b and incompetent layers 90% in Fig. 13c, respec-  
501 tively). For example, in F4-1 (see also top-right corner in Fig. 9), as the thin sandstone  
502 layer *I* (3 cm thick) is sandwiched between two thick siltstone layers *H* (8 cm thick) and *J*  
503 (15 cm thick), the overall deformation style is determined by the dominant mechanical  
504 layers *H* and *J*, rather than the subordinate layer *I*. However, the deformation behaviour  
505 of the stacking sequence often also has a scale-independency. Although the sequence  
506 of thin incompetent layers (i.e., *ICL<sub>1</sub>*, *ICL<sub>2</sub>*) sandwiched within thick competent layers (Fig.  
507 14a) can show an overall deformation behaviour similar to that of the sequence domi-  
508 nated by strong layers (Fig. 13a), thin incompetent layers (i.e., *ICL<sub>1</sub>*, *ICL<sub>2</sub>*) may still form  
509 ductile folds at the layer-scale (Fig. 14a). For example, in F4-3 (Fig. 14c), the thin siltstone  
510 layer *B*, sandwiched in between the thick sandstone layers *A* and *C*, shows continuous  
511 smearing; although through-going faults are developed within the sequence dominated  
512 by competent layers. Similarly, the thin competent beds sandwiched within thick incom-  
513 petent layers may accommodate strain at the layer-scale by local faulting (i.e., *ICL<sub>1</sub>*, *ICL<sub>2</sub>*,  
514 Fig. 14b). For example, in F4-1 (Fig. 14d, see also top-right corner in Fig. 9), the thin

515 sandstone layer *I* still illustrates faulting deformation, although the overall deformation  
516 response and strain of *H-I-J* sequence is dominated by folding deformation.  
517 Although the competent : incompetent ratio (Ferrill and Morris, 2008; Ferrill et al., 2017b)  
518 can help understanding the control of mechanical stratigraphy on fault zone architecture,  
519 we also note that (Tyler and Finley, 1991) highlight that variation in the fault zone archi-  
520 tecture is possible for mechanical stratigraphies with identical competent : incompetent  
521 ratios. This reflects the different stacking patterns (e.g. layer thicknesses) possible in a  
522 stratigraphy that shows the same overall ratio. The detailed outcrop studies in the Lenghu  
523 fold-thrust belt enables us to observe variations in the fault architecture that reflects this  
524 situation. For example, the stratigraphy of the outcrop F4-3 (Fig. 7c) has a similar overall  
525 competent : incompetent ratio (68%) to that of the outcrop F4-1 (Fig. 9c) with a ratio of  
526 66%, but F4-3 appears to show a higher mechanical heterogeneity reflected by the more  
527 complex fault array. This is despite the likely impact of the higher strain and overall throw,  
528 in fault F4-3.

529 The field-based outcrop analyses does suggest that high mechanical contrasts produce  
530 wider and complex fault arrays, whereas low mechanical contrasts generate more planar  
531 faults with narrow or absent damage zones. Examples from Lenghu include: a) the  
532 increased folding associated with the more incompetent sequence in the upper section  
533 of fault F4-1 (Fig. 9), and b) the increased fault population and fault lenses in the  
534 incompetent layers above the thick sand in Fault F4-3 (Fig. 7). This agrees with the  
535 published field-based studies (e.g., Loveless et al., 2011; Davies et al., 2012; Ferrill et  
536 al., 2014; Ferrill et al., 2017b; Nicol et al., 2017; Cawood and Bond, 2018).

## 537 **7. Conclusions**

538 The high-resolution, detailed, field observations reported from the Lenghu Thrust Belt  
539 allow the following conclusions on fault geometry:

540 1) A seismically resolvable thrust fault can exhibit multiple structural domains at the meso-  
541 scale and variable complexity related to the fault throw distribution and strain accommo-  
542 dation processes across the fault zone.

543 2) Fault throw distributions and linkages control the strain distribution across the thrust  
544 fault zone, although local folding process contribute important elements in Lenghu espe-  
545 cially where more incompetent beds dominate the stratigraphy. The variation in bed thick-  
546 nesses and mechanical property contrasts are likely to control the initial fault dips and  
547 fault/fracture density. Large fault throws are associated with wide strain accommodation  
548 and damage zones, but the relationship between the development and width of the fault  
549 zone with the throw accumulation cannot be assessed from the outcrops studied.

550 3) Mechanical heterogeneity, induced by different sediment stacking patterns, influences  
551 the fault architecture of the thrust fault zones studied (e.g., the location and generation of  
552 fault lenses, shear smearing, splay faults or fractures).

553

## 554 **Acknowledgements**

555 We would like to thank RDR (Rock Deformation Research Ltd) staff, especially Dr R. K.  
556 Davies, for discussions during the field work. Our colleagues Dr G. Lloyd, Dr J. Imber, Dr  
557 L. Xie and Dr N. Su are thanked for their helpful communications and suggestions on  
558 early drafts of this research. The support from Qinghai Oilfield of PetroChina, Rock De-  
559 formation Research (RDR) and Midland Valley is also highly appreciated. This work has  
560 been financially supported by the National Natural Science Foundation of China (NO.  
561 41872143, NO.41502192), and the Fundamental Research Funds for the Central Univer-  
562 sities (no. 19CX02005A).

563

564 **Figure Captions**

565 **Figure 1.** (a) Structural interpretation on SRTM elevation data of Qaidam basin and (b)  
566 geological map of the northern Qaidam basin (modified after Yin et al., 2008a; Pei et al.,  
567 2017a). The Qaidam basin is an oil-bearing sedimentary basin developed associated with  
568 the uplift of the Tibetan Plateau. A series of NW-SE-trending folds and faults are devel-  
569 oped in the basin. The study area is located in the NW-SE-trending Lenghu fold-thrust  
570 belt in the northern Qaidam basin, where a northeast-directing Lenghu thrust fault ac-  
571 counts for the development of the hanging wall anticline.

572  
573 **Figure 2.** Field-based stratigraphic logging of the study area (modified after Pei et al.,  
574 2017a; Pei et al., 2017b; Pei et al., 2018). The stratigraphy is dominated by middle Neo-  
575 gene sediments, comprising primarily siltstones and sandstones. The lower portion of the  
576 N<sub>2-1</sub> unit is silt-rich fine sandstones with high heterogeneity ( $S_a$ ). The middle portion of the  
577 N<sub>2-1</sub> unit is fine to medium sandstones with low heterogeneity ( $S_b$ ). The top portion of the  
578 N<sub>2-1</sub> unit contains medium to coarse sandstones with medium to high heterogeneity ( $S_c$ ).  
579 The N<sub>2-2</sub> unit is made up of coarse sandstones to conglomerates with medium heteroge-  
580 neity ( $S_d$ ).

581  
582 **Figure 3.** (a) Structural interpretation based on detailed field data integrating high-reso-  
583 lution landsat image (see position in Fig. 1b). The hanging wall anticline, Lenghu thrust  
584 fault zone and minor faults/folds in both the hanging wall and footwall are interpreted. (b)  
585 Enlarged map showing the sites of four representative outcrops (see position in Fig. 3a),  
586 i.e., F1 - F4, used to analyse the detailed fault architecture and its controlling parameters  
587 in the Lenghu thrust-fold belt. The strain distribution of the fault outcrops was evaluated  
588 based on field mapping.

589  
590 **Figure 4.** Detailed outcrop sections of F1 (a), F2 (b) and F3 (c) showing the lateral struc-  
591 tural variation in the fault zone architecture along strike of the Lenghu thrust fault zone  
592 (see position in Fig. 3b) (modified after Pei et al., 2018). The strain distribution of these  
593 three sections are estimated from field observations. The strain distribution across the  
594 fault zone illustrates a similar pattern between the three outcrops (see the estimated  
595 strain curves). The siltstones form vertical domains where they have been smeared into  
596 the fault zone from the hanging wall stratigraphy, while the sandstones are faulted and  
597 deformed by brittle deformation. The bedding within the central fault domains cannot be  
598 identified because of the intense deformation. The shearing into high strain fault zones  
599 generates silt smears and sand inclusions.

600  
601 **Figure 5.** Detailed fault architecture of the outcrop F4 in the Lenghu thrust fault zone (see  
602 position in Fig. 3b): (a) field photo of the fault outcrop F4 and (b) its structural interpreta-  
603 tion; (c) detailed mapping of F4 illustrating the structural domains with different levels of  
604 strain. Note 1: the scale is not even across the field photo because of the perspective,  
605 although an estimated approximate scale is provided. Note 2: the beds dipping in F4-5  
606 looks steeper in the photograph than the real dip because of perspective views.

607  
608 **Figure 6.** (a) Field photo and (b) detailed outcrop map of the high strain domain F4-4 in  
609 the F4 (see detailed position of F4-4 in outcrop F4 in Fig. 5). (c) The F4-4 fault zone  
610 stratigraphy with a competent : incompetent percentage ratio of 58% : 42%. (d) A stere-  
611 ogram of structural features showing the NW-striking thrust faults.

612  
613 **Figure 7.** (a) Field photo and (b) detailed outcrop map of the medium strain domain F4-  
614 3 in the F4 (see detailed position of F4-3 in outcrop F4 in Fig. 5). (c) The F4-3 fault zone

615 stratigraphy with a competent : incompetent percentage ratio of 68% : 32%. (d) A stere-  
616 ogram of structural features showing the NE-directing thrust faults.

617

618 **Figure 8.** (a) Field photo and (b) detailed outcrop map of the low strain domain F4-2 in  
619 the F4 (see detailed position of F4-2 in outcrop F4 in Fig. 5). (c) The F4-2 fault zone  
620 stratigraphy with a competent : incompetent percentage ratio of 55% : 45%. (d) A stere-  
621 ogram of structural features showing the NE-directing thrust faults.

622

623 **Figure 9.** (a) Field photo and (b) detailed outcrop map of the low strain domain F4-1 in  
624 the F4 (see detailed position of F4-1 in outcrop F4 in Fig. 5). (c) The F4-1 fault zone  
625 stratigraphy with a competent : incompetent percentage ratio of 66% : 34%. (d) A stere-  
626 ogram of structural features showing the NE-directing thrust faults together with SW-di-  
627 recting back thrust faults (d).

628

629 **Figure 10.** (a) Field photo of the fault outcrop F4 and its structural interpretation; (b) es-  
630 timated approximate throw and strain distribution cross the fault zone. Note 1: the scale  
631 is not even across the field photo because of perspective, although an estimated approx-  
632 imate scale is provided. Note 2: the beds dipping in F4-5 looks steeper in the photograph  
633 than the real dip because of the perspective views.

634

635 **Figure 11.** Models delineating the fault kinematics for incompetent beds and competent  
636 beds within the interbedded stratigraphy. The central figures demonstrate the kinematics  
637 from the initiation of deformation to a later stage with increasing fault throw ( $a_0 \rightarrow a_1$ ). The  
638 top figures are details capturing the faulting kinematics of a competent layer sandwiched  
639 between two incompetent layers ( $b_0 \rightarrow b_1$ ). The bottom figures are details capturing the

640 faulting kinematics of an incompetent layer sandwiched between two competent layers  
641 ( $c_0 \rightarrow c_1$ ). When the mechanically layered sequence of beds is initially deformed, the frac-  
642 tures or small faults (i.e.,  $f_1$ ,  $f_2$  and  $f_3$ ) are modelled to initially form in the competent beds  
643 *A*, *C* and *E* (e.g., sandstones in the Lenghu fold-thrust belt) whereas the incompetent  
644 beds *B* and *D* (e.g., siltstones in the Lenghu fold-thrust belt) are folded or sheared to  
645 accommodate the overall strain. As the fault zone throw increases, the fractures or small  
646 faults confined within the competent beds will grow until they eventually propagate into  
647 the incompetent beds (e.g.,  $f_2$  within layer *C* in  $b_0$  and  $b_1$ ), forming smearing along the  
648 slip surfaces. A through-going fault will be formed when the propagating faults (e.g.,  $f_1$   
649 and  $f_2$  in  $c_0$  and  $c_1$ ) are linked together. The propagation of small faults from competent  
650 beds into the incompetent beds is well described by the trishear algorithm ([Erslev, 1991](#)).  
651 However, as the incompetent beds are sandwiched by the competent beds ( $c_1$ ), there  
652 may be a divergent trishear zone developed (i.e., in front of the upper tip of  $f_1$  and lower  
653 tip of  $f_2$ ) within the incompetent beds (i.e., *A* and *C* layers) during strain propagation from  
654 both the upper and lower competent beds (i.e., *B* layers). See also the Quadshear model  
655 of [Welch et al. \(2009b\)](#).

656  
657 **Figure 12.** A review of thrust fault zone elements: central through-going faults (TGFs)  
658 and damage zone (DZ). The central through-going faults accommodate a high percent-  
659 age of the fault zone strain, while in the damage zone strain decreases away from the  
660 central fault zone (see the approximate strain distribution profile below the sketch). The  
661 majority of the fault throw is located in the most central position of the faulted section, and  
662 is often defined by two discrete slip surfaces that are sub-parallel to each other. The  
663 damage zone adjacent to the main slip, through-going faults are characterised by splay  
664 faults, fault bound lenses and folds, where the overall strain is lower than across the main  
665 slip surfaces.

666  
667 **Figure 13.** Schematic models delineating the control of stratigraphy on fault architecture  
668 and strain distribution: (a) thick competent layer (competent layers 100%), (b) competent  
669 layers dominated sequence (competent : incompetent ratio = 90% : 10%), (c) incompe-  
670 tent layers dominated sequence (competent : incompetent ratio = 10% : 90%), and (d)  
671 thick incompetent layer (incompetent layers 100%). Stratigraphy dominated by compe-  
672 tent layers normally forms a strain zone evolving from fractures, small faults to through-  
673 going faults, e.g., (a), whereas stratigraphy dominated by incompetent layers often expe-  
674 riences folding-dominated deformation in Lenghu, e.g., (d). See text for detailed discus-  
675 sion.

676  
677 **Figure 14.** Links between schematic models and field observations. (a) Sequences dom-  
678 inated by competent layers: larger scale faulting deformation versus local folding defor-  
679 mation in thin *ICLs* (incompetent layers) (see also Fig. 13b). (b) Sequences dominated  
680 by incompetent layers: larger scale folding deformation versus local faulting deformation  
681 in thin *CLs* (competent layers) (see also Fig. 13c). (c) Portion of F4-3 (see also Fig. 7),  
682 illustrating an example of a thin siltstone layer, *B*, sandwiched between thick sandstone  
683 layers, *A* and *C*, that shows continuous smearing, although through-going faults are de-  
684 veloped. This corresponds to the situation shown in (14a). (d) Portion of F4-1 (see also  
685 Fig. 9), illustrating an example of a thin sandstone layer, *I*, sandwiched between thick  
686 siltstone layers *H* and *J* (corresponding to (14b)), that shows discrete faulting in *I*, with  
687 the faulted sandstone forming an anticline geometry.

688

689

690 **References**

- 691 Bastesen, E., and Braathen, A., 2010, Extensional faults in fine grained carbonates –  
692 analysis of fault core lithology and thickness–displacement relationships: *Journal*  
693 *of Structural Geology*, v. 32, no. 11, p. 1609-1628.
- 694 Blenkinsop, T. G., 1989, Thickness — displacement relationships for deformation zones:  
695 Discussion: *Journal of Structural Geology*, v. 11, no. 8, p. 1051-1053.
- 696 Bose, S., Mandal, N., Mukhopadhyay, D. K., and Mishra, P., 2009, An unstable kinematic  
697 state of the Himalayan tectonic wedge: Evidence from experimental thrust-spacing  
698 patterns: *Journal of Structural Geology*, v. 31, no. 1, p. 83-91.
- 699 Bouvier, J. D., Kaarssijpesteijn, C. H., Kluesner, D. F., Onyejekwe, C. C., and Vanderpal,  
700 R. C., 1989, Three-Dimensional Seismic Interpretation and Fault Sealing  
701 Investigations, Nun River Field, Nigeria: *American Association of Petroleum*  
702 *Geologists Bulletin*, v. 73, no. 11, p. 1397-1414.
- 703 Brown, K. M., Kopf, A., Underwood, M. B., and Weinberger, J. L., 2003, Compositional  
704 and fluid pressure controls on the state of stress on the Nankai subduction thrust:  
705 A weak plate boundary: *Earth and Planetary Science Letters*, v. 214, no. 3, p. 589-  
706 603.
- 707 Bubeck, A., Walker, R. J., Imber, J., and MacLeod, C. J., 2018, Normal fault growth in  
708 layered basaltic rocks: The role of strain rate in fault evolution: *Journal of Structural*  
709 *Geology*, v. 115, p. 103-120.
- 710 Burchfiel, B. C., Deng, Q., Molnar, P., Royden, L., Wang, Y., Zhang, P., and Zhang, W.,  
711 1989, Intracrustal detachment within zones of continental deformation: *Geology*,  
712 v. 17, no. 8, p. 748-752.
- 713 Caine, J. S., Evans, J. P., and Forster, C. B., 1996, Fault zone architecture and  
714 permeability structure: *Geology*, v. 24, no. 11, p. 1025-1028.

715 Cawood, A. J., and Bond, C. E., 2018, 3D mechanical stratigraphy of a deformed multi-  
716 layer: Linking sedimentary architecture and strain partitioning: *Journal of Structural*  
717 *Geology*, v. 106, p. 54-69.

718 Chen, W. P., Chen, C. Y., and Nabelek, J. L., 1999, Present-day deformation of the  
719 Qaidam basin with implications for intra-continental tectonics: *Tectonophysics*, v.  
720 305, no. 1-3, p. 165-181.

721 Chen, Z. Y., Wang, L. Q., Chen, S. P., and Wang, Z. X., 2005, Tectonic model and its  
722 deformation feature of Cenozoic in west section of Lenghu structural belt, northern  
723 margin of Qaidam basin (in Chinese with English abstract): *Xinjiang Petroleum*  
724 *Geology*, v. 26, no. 6, p. 614-617.

725 Childs, C., Holdsworth, R. E., Jackson, C. A.-L., Manzocchi, T., Walsh, J. J., and Yielding,  
726 G., 2017a, Introduction to the geometry and growth of normal faults: *Geological*  
727 *Society*, London, Special Publications, v. 439, p. SP439.423.

728 Childs, C., Manzocchi, T., Nicol, A., Walsh, J. J., Soden, A. M., Conneally, J. C., and  
729 Delogkos, E., 2017b, The relationship between normal drag, relay ramp aspect  
730 ratio and fault zone structure: *Geological Society*, London, Special Publications, v.  
731 439, no. 1, p. 355-372.

732 Childs, C., Manzocchi, T., Walsh, J. J., Bonson, C. G., Nicol, A., and Schöpfer, M. P. J.,  
733 2009, A geometric model of fault zone and fault rock thickness variations: *Journal*  
734 *of Structural Geology*, v. 31, no. 2, p. 117-127.

735 Childs, C., Nicol, A., Walsh, J. J., and Watterson, J., 1996a, Growth of vertically  
736 segmented normal faults: *Journal of Structural Geology*, v. 18, no. 12, p. 1389-  
737 1397.

738 Childs, C., Watterson, J., and Walsh, J. J., 1996b, A model for the structure and  
739 development of fault zones: *Journal of the Geological Society*, v. 153, no. 3, p.  
740 337-340.

741 Choi, J.-H., Edwards, P., Ko, K., and Kim, Y.-S., 2016, Definition and classification of fault  
742 damage zones: A review and a new methodological approach: *Earth-Science*  
743 *Reviews*, v. 152, p. 70-87.

744 Ciftci, N. B., Giger, S. B., and Clennell, M. B., 2013, Three-dimensional structure of  
745 experimentally produced clay smears: Implications for fault seal analysis:  
746 *American Association of Petroleum Geologists Bulletin*, v. 97, no. 5, p. 733-757.

747 Cooke, A. P., Fisher, Q. J., Michie, E. A. H., and Yielding, G., 2018, Investigating the  
748 controls on fault rock distribution in normal faulted shallow burial limestones, Malta,  
749 and the implications for fluid flow: *Journal of Structural Geology*, v. 114, p. 22-42.

750 Cooke, M. L., 1997, Predicting fracture localization in folded strata from mechanical  
751 stratigraphy and fold shape: Case study of east Kaibab Monocline, Utah:  
752 *International Journal of Rock Mechanics and Mining Sciences*, v. 34, no. 3-4, p.  
753 56.e51-56.e12.

754 Corbett, K., Friedman, M., and Spang, J., 1987, Fracture development and mechanical  
755 stratigraphy of Austin Chalk, Texas: *American Association of Petroleum*  
756 *Geologists Bulletin*, v. 71, no. 1, p. 17-28.

757 Cosgrove, J. W., 1999, *Forced folds and fractures: An introduction*: Geological Society,  
758 London, Special Publications, v. 169, no. 1, p. 1-6.

759 Cowgill, E., 2007, Impact of riser reconstructions on estimation of secular variation in  
760 rates of strike-slip faulting: Revisiting the Cherchen River site along the Altyn Tagh  
761 Fault, NW China: *Earth and Planetary Science Letters*, v. 254, no. 3-4, p. 239-255.

762 Cowgill, E., Arrowsmith, J. R., Yin, A., Wang, X. F., and Chen, Z. L., 2004a, The Akato  
763 Tagh bend along the Altyn Tagh fault, northwest Tibet 2: Active deformation and  
764 the importance of transpression and strain hardening within the Altyn Tagh system:  
765 *Geological Society of America Bulletin*, v. 116, no. 11-12, p. 1443-1464.

766 Cowgill, E., Yin, A., Arrowsmith, J. R., Feng, W. X., and Zhang, S. H., 2004b, The Akato  
767 Tagh bend along the Altyn Tagh fault, northwest Tibet 1: Smoothing by vertical-  
768 axis rotation and the effect of topographic stresses on bend-flanking faults:  
769 Geological Society of America Bulletin, v. 116, no. 11-12, p. 1423-1442.

770 Cowgill, E., Yin, A., Feng, W. X., and Qing, Z., 2000, Is the North Altyn fault part of a  
771 strike-slip duplex along the Altyn Tagh fault system?: *Geology*, v. 28, no. 3, p. 255-  
772 258.

773 Cowgill, E., Yin, A., Harrison, T. M., and Wang, X. F., 2003, Reconstruction of the Altyn  
774 Tagh fault based on U-Pb geochronology: Role of back thrusts, mantle sutures,  
775 and heterogeneous crustal strength in forming the Tibetan Plateau: *Journal of*  
776 *Geophysical Research*, v. 108, no. B7, p. 1-28.

777 Craddock, W. H., Kirby, E., Zheng, D. W., and Liu, J. H., 2012, Tectonic setting of  
778 Cretaceous basins on the NE Tibetan Plateau: insights from the Jungong basin:  
779 *Basin Research*, v. 24, no. 1, p. 51-69.

780 Cui, Z. Z., Li, Q. S., Wu, C. D., Yin, Z. X., and Liu, H. B., 1995, The crustal and deep  
781 structure in Golmud-Ejin Qi GGT (in Chinese with English abstract): *Acta*  
782 *Geophysica Sinica*, v. 38, no. 2, p. 28-34.

783 Davatzes, N., and Aydin, A., 2005, Distribution and nature of fault architecture in a layered  
784 sandstone and shale sequence: An example from the Moab fault, Utah: in R.  
785 Sorkhabi and Y. Tsuji, eds., *Faults, fluid flow, and petroleum traps: American*  
786 *Association of Petroleum Geologists Memoir*, v. 85, p. 153-180.

787 Davies, R. K., Knipe, R. J., and Welch, M. J., 2012, The role of vertical mechanical  
788 heterogeneity in predicting fault zone architecture: 3rd EAGE International  
789 Conference on Fault and Top Seals.

790 Delogkos, E., Childs, C., Manzocchi, T., Walsh, J. J., and Pavlides, S., 2017, The role of  
791 bed-parallel slip in the development of complex normal fault zones: *Journal of*  
792 *Structural Geology*, v. 97, p. 199-211.

793 Deng, J., Wu, Z., Yang, J., Zhao, H., Liu, H., Lai, S., and Di, Y., 1995, Crust-mantle  
794 petrological structure and deep processes along the Golmud-Ejin Qi geoscience  
795 section (in Chinese with English abstract): *Acta Geophysica Sinica*, v. 38, no. 2, p.  
796 144-157.

797 Dimmen, V., Rotevatn, A., Peacock, D. C. P., Nixon, C. W., and Nærland, K., 2017,  
798 Quantifying structural controls on fluid flow: Insights from carbonate-hosted fault  
799 damage zones on the Maltese Islands: *Journal of Structural Geology*, v. 101, p.  
800 43-57.

801 Egholm, D. L., Clausen, O. R., Sandiford, M., Kristensen, M. B., and Korstgård, J. A.,  
802 2008, The mechanics of clay smearing along faults: *Geology*, v. 36, no. 10, p. 787-  
803 790.

804 Eisenstadt, G., and De Paor, D. G., 1987, Alternative model of thrust-fault propagation:  
805 *Geology*, v. 15, no. 7, p. 630-633.

806 Ellis, S., Schreurs, G., and Panien, M., 2004, Comparisons between analogue and  
807 numerical models of thrust wedge development: *Journal of Structural Geology*, v.  
808 26, no. 9, p. 1659-1675.

809 Erslev, E. A., 1991, Trishear Fault-Propagation Folding: *Geology*, v. 19, no. 6, p. 617-  
810 620.

811 Evans, J. P., 1990, Thickness-displacement relationships for fault zones: *Journal of*  
812 *Structural Geology*, v. 12, no. 8, p. 1061-1065.

813 Ferrill, D. A., Evans, M. A., McGinnis, R. N., Morris, A. P., Smart, K. J., Wigginton, S. S.,  
814 Gulliver, K. D. H., Lehrmann, D., de Zoeten, E., and Sickmann, Z., 2017a, Fault

815 zone processes in mechanically layered mudrock and chalk: *Journal of Structural*  
816 *Geology*, v. 97, p. 118-143.

817 Ferrill, D. A., McGinnis, R. N., Morris, A. P., Smart, K. J., Sickmann, Z. T., Bentz, M.,  
818 Lehrmann, D., and Evans, M. A., 2014, Control of mechanical stratigraphy on bed-  
819 restricted jointing and normal faulting: Eagle Ford Formation, south-central Texas:  
820 *American Association of Petroleum Geologists Bulletin*, v. 98, no. 11, p. 2477-  
821 2506.

822 Ferrill, D. A., and Morris, A. P., 2003, Dilational normal faults: *Journal of Structural*  
823 *Geology*, v. 25, no. 2, p. 183-196.

824 -, 2008, Fault zone deformation controlled by carbonate mechanical stratigraphy,  
825 Balcones fault system, Texas: *American Association of Petroleum Geologists*  
826 *Bulletin*, v. 92, no. 3, p. 359-380.

827 Ferrill, D. A., Morris, A. P., and McGinnis, R. N., 2012, Extensional fault-propagation  
828 folding in mechanically layered rocks: The case against the frictional drag  
829 mechanism: *Tectonophysics*, v. 576–577, no. 0, p. 78-85.

830 Ferrill, D. A., Morris, A. P., McGinnis, R. N., Smart, K. J., Wigginton, S. S., and Hill, N. J.,  
831 2017b, Mechanical stratigraphy and normal faulting: *Journal of Structural Geology*,  
832 v. 94, p. 275-302.

833 Freitag, U. A., Sanderson, D. J., Lonergan, L., and Bevan, T. G., 2017, Comparison of  
834 upwards splaying and upwards merging segmented normal faults: *Journal of*  
835 *Structural Geology*, v. 100, p. 1-11.

836 Fulljames, J. R., Zijerveld, L. J. J., and Franssen, R. C. M. W., 1997, Fault seal processes:  
837 systematic analysis of fault seals over geological and production time scales, *in*  
838 Møller-Pedersen, P., and Koestler, A. G., eds., *Norwegian Petroleum Society*  
839 *Special Publications*, Volume 7, p. 51-59.

840 Gao, R., Chen, X., and Ding, Q., 1995, Preliminary geodynamic model of Goldmud-Ejin  
841 Qi geoscience transect (in Chinese with English abstract): *Acta Geophysica*  
842 *Sinica*, v. 38, no. 2, p. 14-27.

843 Grant, N. T., 2017, A geometrical model for shale smear: implications for upscaling in  
844 faulted geomodels: *Petroleum Geoscience*, v. 23, no. 1, p. 39-55.

845 Hardy, S., and Ford, M., 1997, Numerical modeling of trishear fault propagation folding:  
846 *Tectonics*, v. 16, no. 5, p. 841-854.

847 Heynekamp, M. R., Goodwin, L. B., Mozley, P. S., and Haneberg, W. C., 1999, Controls  
848 on fault-zone architecture in poorly lithified sediments, Rio Grande Rift, New  
849 Mexico: Implications for fault-zone permeability and fluid flow, *Faults and*  
850 *Subsurface Fluid Flow in the Shallow Crust*. Washington, DC, AGU, Volume 113,  
851 p. 27-49.

852 Homberg, C., Schnyder, J., Roche, V., Leonardi, V., and Benzaggagh, M., 2017, The  
853 brittle and ductile components of displacement along fault zones: *Geological*  
854 *Society, London, Special Publications*, v. 439, no. 1, p. 395-412.

855 Huang, H. C., Huang, Q. H., and Ma, S., 1996, *Geology of Qaidam basin and its*  
856 *petroleum prediction*: Geological Publishing House, Beijing.

857 Hull, J., 1988, Thickness-displacement relationships for deformation zones: *Journal of*  
858 *Structural Geology*, v. 10, no. 4, p. 431-435.

859 Huo, G. M., 1990, *Petroleum geology of China: in Oil fields in Qianghai and Xizang*:  
860 Chinese Petroleum Industry Press, Beijing, v. 14, p. 483.

861 Jolivet, M., Brunel, M., Seward, D., Xu, Z., Yang, J., Malavieille, J., Roger, F., Leyreloup,  
862 A., Arnaud, N., and Wu, C., 2003, Neogene extension and volcanism in the Kunlun  
863 Fault Zone, northern Tibet: New constraints on the age of the Kunlun Fault:  
864 *Tectonics*, v. 22, no. 5, p. 1-23.

865 Knipe, R. J., 1985, Footwall geometry and the rheology of thrust sheets: Journal of  
866 Structural Geology, v. 7, no. 1, p. 1-10.

867 Knott, S., 1994, Fault zone thickness versus displacement in the Permo-Triassic  
868 sandstones of NW England: Journal of the Geological Society, v. 151, no. 1, p. 17-  
869 25.

870 Laubach, S. E., Olson, J. E., and Gross, M. R., 2009, Mechanical and fracture  
871 stratigraphy: American Association of Petroleum Geologists Bulletin, v. 93, no. 11,  
872 p. 1413-1426.

873 Lindanger, M., Gabrielsen, R. H., and Braathen, A., 2007, Analysis of rock lenses in 1046  
874 extensional faults: Norwegian Journal of Geology, v. 87, p. 361-372.

875 Lindsay, N. G., Murphy, F. C., Walsh, J. J., and Watterson, J., 1993, Outcrop Studies of  
876 Shale Smears on Fault Surface, The Geological Modelling of Hydrocarbon  
877 Reservoirs and Outcrop Analogues, Blackwell Publishing Ltd., p. 113-123.

878 Liu, D. L., Fang, X. M., Gao, J. P., Wang, Y. D., Zhang, W. L., Miao, Y. F., Liu, Y. Q., and  
879 Zhang, Y. Z., 2009, Cenozoic Stratigraphy Deformation History in the Central and  
880 Eastern of Qaidam Basin by the Balance Section Restoration and its Implication:  
881 Acta Geologica Sinica-English Edition, v. 83, no. 2, p. 359-371.

882 Liu, Y., Wu, K., Wang, X., Liu, B., Guo, J., and Du, Y., 2017, Architecture of buried reverse  
883 fault zone in the sedimentary basin: A case study from the Hong-Che Fault Zone  
884 of the Junggar Basin: Journal of Structural Geology, v. 105, p. 1-17.

885 Lloyd, G. E., and Knipe, R. J., 1992, Deformation mechanisms accommodating faulting  
886 of quartzite under upper crustal conditions: Journal of Structural Geology, v. 14,  
887 no. 2, p. 127-143.

888 Loveless, S., Bense, V., and Turner, J., 2011, Fault architecture and deformation  
889 processes within poorly lithified rift sediments, Central Greece: Journal of  
890 Structural Geology, v. 33, no. 11, p. 1554-1568.

891 Mao, L., Xiao, A., Zhang, H., Wu, Z., Wang, L., Shen, Y., and Wu, L., 2016, Structural  
892 deformation pattern within the NW Qaidam Basin in the Cenozoic era and its  
893 tectonic implications: *Tectonophysics*, v. 687, p. 78-93.

894 McGrath, A. G., and Davison, I., 1995, Damage zone geometry around fault tips: *Journal*  
895 *of Structural Geology*, v. 17, no. 7, p. 1011-1024.

896 Meng, Q. R., Hu, J. M., and Yang, F. Z., 2001, Timing and magnitude of displacement on  
897 the Altyn Tagh fault: constraints from stratigraphic correlation of adjoining Tarim  
898 and Qaidam basins, NW China: *Terra Nova*, v. 13, no. 2, p. 86-91.

899 Meyer, B., Tapponnier, P., Bourjot, L., Metivier, F., Gaudemer, Y., Peltzer, G., Shunmin,  
900 G., and Zhitai, C., 1998, Crustal thickening in Gansu-Qinghai, lithospheric mantle  
901 subduction, and oblique, strike-slip controlled growth of the Tibet plateau:  
902 *Geophysical Journal International*, v. 135, no. 1, p. 1-47.

903 Miller, J. F., and Mitra, S., 2011, Deformation and secondary faulting associated with  
904 basement-involved compressional and extensional structures: *American*  
905 *Association of Petroleum Geologists Bulletin*, v. 95, no. 4, p. 675-689.

906 Molnar, P., and Tapponnier, P., 1975, Cenozoic Tectonics of Asia - Effects of a  
907 Continental Collision: *Science*, v. 189, no. 4201, p. 419-426.

908 Nicol, A., and Childs, C., 2018, Cataclasis and silt smear on normal faults in weakly  
909 lithified turbidites: *Journal of Structural Geology*, v. 117, p. 44-57.

910 Nicol, A., Childs, C., Walsh, J. J., Manzocchi, T., and Schöpfer, M. P. J., 2017,  
911 Interactions and growth of faults in an outcrop-scale system: *Geological Society*,  
912 London, *Special Publications*, v. 439, no. 1, p. 23-39.

913 Otsuki, K., 1978, On the relationship between the width of shear zone and the  
914 displacement along fault: *Journal of Geological Society of Japan*, v. 84, no. 1, p.  
915 661-669.

916 Pang, X., Li, Y., and Jiang, Z., 2004, Key geological controls on migration and  
917 accumulation for hydrocarbons derived from mature source rocks in Qaidam  
918 Basin: *Journal of Petroleum Science and Engineering*, v. 41, no. 1-3, p. 79-95.

919 Peacock, D. C. P., Dimmen, V., Rotevatn, A., and Sanderson, D. J., 2017a, A broader  
920 classification of damage zones: *Journal of Structural Geology*, v. 102, p. 179-192.

921 Peacock, D. C. P., Nixon, C. W., Rotevatn, A., Sanderson, D. J., and Zuluaga, L. F.,  
922 2017b, Interacting faults: *Journal of Structural Geology*, v. 97, p. 1-22.

923 Peacock, D. C. P., and Sanderson, D. J., 1991, Displacements, segment linkage and  
924 relay ramps in normal fault zones: *Journal of Structural Geology*, v. 13, no. 6, p.  
925 721-733.

926 -, 1992, Effects of layering and anisotropy on fault geometry: *Journal of the Geological*  
927 *Society*, v. 149, no. 5, p. 793-802.

928 Pei, Y., Paton, D. A., and Knipe, R. J., 2014, Defining a 3-dimensional trishear parameter  
929 space to understand the temporal evolution of fault propagation folds: *Journal of*  
930 *Structural Geology*, v. 66, p. 284-297.

931 Pei, Y., Paton, D. A., Knipe, R. J., Lickorish, W. H., Li, A., and Wu, K., 2018, Unravelling  
932 the influence of throw and stratigraphy in controlling sub-seismic fault architecture  
933 of fold-thrust belts: an example from the Qaidam Basin, NE Tibetan Plateau:  
934 *American Association of Petroleum Geologists Bulletin*, v. 102, no. 6, p. 1091-  
935 1117.

936 Pei, Y., Paton, D. A., Knipe, R. J., and Wu, K., 2015, A review of fault sealing behaviour  
937 and its evaluation in siliciclastic rocks: *Earth-Science Reviews*, v. 150, p. 121-138.

938 -, 2017a, Examining fault architecture and strain distribution using geospatial and  
939 geomechanical modelling: An example from the Qaidam basin, NE Tibet: *Marine*  
940 *and Petroleum Geology*, v. 84, p. 1-17.

941 Pei, Y., Paton, D. A., Wu, K., and Xie, L., 2017b, Subsurface structural interpretation by  
942 applying trishear algorithm: An example from the Lenghu5 fold-and-thrust belt,  
943 Qaidam Basin, Northern Tibetan Plateau: *Journal of Asian Earth Sciences*, v. 143,  
944 p. 343-353.

945 Pfiffner, O. A., 1993, The structure of the Helvetic nappes and its relation to the  
946 mechanical stratigraphy: *Journal of Structural Geology*, v. 15, no. 3–5, p. 511-521.

947 Qiu, N. S., 2002, Tectono-thermal evolution of the Qaidam Basin, China: evidence from  
948 Rn and apatite fission track data: *Petroleum Geoscience*, v. 8, no. 3, p. 279-285.

949 Rawling, G. C., and Goodwin, L. B., 2003, Cataclasis and particulate flow in faulted,  
950 poorly lithified sediments: *Journal of Structural Geology*, v. 25, no. 3, p. 317-331.

951 -, 2006, Structural record of the mechanical evolution of mixed zones in faulted poorly  
952 lithified sediments, Rio Grande rift, New Mexico, USA: *Journal of Structural*  
953 *Geology*, v. 28, no. 9, p. 1623-1639.

954 Rieser, A. B., Liu, Y. J., Genser, J., Neubauer, F., Handler, R., Friedl, G., and Ge, X. H.,  
955 2006a, Ar-40/Ar-39 ages of detrital white mica constrain the Cenozoic  
956 development of the intracontinental Qaidam Basin, China: *Geological Society of*  
957 *America Bulletin*, v. 118, no. 11-12, p. 1522-1534.

958 Rieser, A. B., Liu, Y. J., Genser, J., Neubauer, F., Handler, R., and Ge, X. H., 2006b,  
959 Uniform Permian Ar-40/Ar-39 detrital mica ages in the eastern Qaidam Basin (NW  
960 China): where is the source?: *Terra Nova*, v. 18, no. 1, p. 79-87.

961 Robertson, E. C., 1983, Relationship of fault displacement to gouge and breccia  
962 thickness: *Mining Engineering*, v. 35, no. 10, p. 1426-1432.

963 Roche, V., Homberg, C., and Rocher, M., 2012a, Architecture and growth of normal fault  
964 zones in multilayer systems: A 3D field analysis in the South-Eastern Basin,  
965 France: *Journal of Structural Geology*, v. 37, no. 0, p. 19-35.

966 Roche, V., Homberg, C., and Rocher, M., 2012b, Fault displacement profiles in multilayer  
967 systems: from fault restriction to fault propagation: *Terra Nova*, v. 24, no. 6, p. 499-  
968 504.

969 Schöpfer, M. P. J., Childs, C., and Walsh, J. J., 2006, Localisation of normal faults in  
970 multilayer sequences: *Journal of Structural Geology*, v. 28, no. 5, p. 816-833.

971 Seebeck, H., Nicol, A., Walsh, J. J., Childs, C., Beetham, R. D., and Pettinga, J., 2014,  
972 Fluid flow in fault zones from an active rift: *Journal of Structural Geology*, v. 62, no.  
973 0, p. 52-64.

974 Soliva, R., and Benedicto, A., 2004, A linkage criterion for segmented normal faults:  
975 *Journal of Structural Geology*, v. 26, no. 12, p. 2251-2267.

976 Song, T. G., and Wang, X. P., 1993, Structural Styles and Stratigraphic Patterns of  
977 Syndepositional Faults in a Contractional Setting - Examples from Qaidam Basin,  
978 Northwestern China: *American Association of Petroleum Geologists Bulletin*, v. 77,  
979 no. 1, p. 102-117.

980 Sosio De Rosa, S., Shipton, Z. K., Lunn, R. J., Kremer, Y., and Murray, T., 2018, Along-  
981 strike fault core thickness variations of a fault in poorly lithified sediments, Miri  
982 (Malaysia): *Journal of Structural Geology*, v. 116, p. 189-206.

983 Sun, Z. M., Yang, Z. Y., Pei, J. L., Ge, X. H., Wang, X. S., Yang, T. S., Li, W. M., and  
984 Yuan, S. H., 2005, Magnetostratigraphy of Paleogene sediments from northern  
985 Qaidam Basin, China: Implications for tectonic uplift and block rotation in northern  
986 Tibetan plateau: *Earth and Planetary Science Letters*, v. 237, no. 3-4, p. 635-646.

987 Tapponnier, P., Meyer, B., Avouac, J. P., Peltzer, G., Gaudemer, Y., Guo, S. M., Xiang,  
988 H. F., Yin, K. L., Chen, Z. T., Cai, S. H., and Dai, H. G., 1990, Active Thrusting and  
989 Folding in the Qilian-Shan, and Decoupling between Upper Crust and Mantle in  
990 Northeastern Tibet: *Earth and Planetary Science Letters*, v. 97, no. 3-4, p. 382-  
991 403.

- 992 Torabi, A., and Berg, S. S., 2011, Scaling of fault attributes: A review: Marine and  
993 Petroleum Geology, v. 28, no. 8, p. 1444-1460.
- 994 Tyler, N., and Finley, R. J., 1991, Architectural controls on the recovery of hydrocarbons  
995 from sandstone reservoirs: in A. D. Miall and C. N. Tylers, eds., The Three  
996 Dimensional Facies Architecture of Heterogeneous Clastic Sediments and its  
997 Implications for Hydrocarbon Discovery and Recovery. Concepts Sedimentol.  
998 Palontol., v. 3, p. 44-54.
- 999 van der Zee, W., and Urai, J. L., 2005, Processes of normal fault evolution in a siliciclastic  
1000 sequence: a case study from Miri, Sarawak, Malaysia: Journal of Structural  
1001 Geology, v. 27, no. 12, p. 2281-2300.
- 1002 Vasquez, L., Nalpas, T., Ballard, J.-F., Le Carlier De Veslud, C., Simon, B., Dauteuil, O.,  
1003 and Bernard, X. D., 2018, 3D geometries of normal faults in a brittle-ductile  
1004 sedimentary cover: Analogue modelling: Journal of Structural Geology, v. 112, p.  
1005 29-38.
- 1006 Walsh, J. J., Bailey, W. R., Childs, C., Nicol, A., and Bonson, C. G., 2003, Formation of  
1007 segmented normal faults: a 3-D perspective: Journal of Structural Geology, v. 25,  
1008 no. 8, p. 1251-1262.
- 1009 Walsh, J. J., Watterson, J., Bailey, W. R., and Childs, C., 1999, Fault relays, bends and  
1010 branch-lines: Journal of Structural Geology, v. 21, no. 8–9, p. 1019-1026.
- 1011 Wang, B. Q., Wang, Q. H., Chen, H. L., and Xiao, A. C., 2006a, Three-D mensional  
1012 structure modeling and structural analysis of the lenghu area on the northern  
1013 margin of Qaidam basin: Geotectonica et Metallogenia, v. 30, no. 4, p. 430-434.
- 1014 Wang, E., Xu, F. Y., Zhou, J. X., Wan, J. L., and Burchfiel, B. C., 2006b, Eastward  
1015 migration of the Qaidam basin and its implications for Cenozoic evolution of the  
1016 Altyn Tagh fault and associated river systems: Geological Society of America  
1017 Bulletin, v. 118, no. 3-4, p. 349-365.

- 1018 Wang, E. C., and Burchfiel, B. C., 2004, Late cenozoic right-lateral movement along the  
1019 Wenquan fault and associated deformation: Implications for the kinematic history  
1020 of the Qaidam Basin Northeastern Tibetan Plateau: *International Geology Review*,  
1021 v. 46, no. 10, p. 861-879.
- 1022 Welch, M. J., Davies, R. K., Knipe, R. J., and Tueckmantel, C., 2009a, A dynamic model  
1023 for fault nucleation and propagation in a mechanically layered section:  
1024 *Tectonophysics*, v. 474, no. 3–4, p. 473-492.
- 1025 Welch, M. J., Knipe, R. J., Souque, C., and Davies, R. K., 2009b, A Quadshear kinematic  
1026 model for folding and clay smear development in fault zones: *Tectonophysics*, v.  
1027 471, no. 3–4, p. 186-202.
- 1028 Wibberley, C. A. J., Yielding, G., and Di Toro, G., 2008, Recent advances in the  
1029 understanding of fault zone internal structure: a review: *Geological Society*,  
1030 London, *Special Publications*, v. 299, no. 1, p. 5-33.
- 1031 Withjack, M. O., Olson, J., and Peterson, E., 1990, Experimental-Models of Extensional  
1032 Forced Folds: *American Association of Petroleum Geologists Bulletin*, v. 74, no. 7,  
1033 p. 1038-1054.
- 1034 Woodward, N. B., 1992, Deformation styles and geometric evolution of some Idaho-  
1035 Wyoming thrust belt structures: in S. Mitra and G. W. Fisher, eds., *Structural*  
1036 *Geology of Fold and Thrust Belts*, Johns Hopkins University Press, Baltimore, p.  
1037 191-206.
- 1038 Woodward, N. B., and Rutherford Jr, E., 1989, Structural lithic units in external orogenic  
1039 zones: *Tectonophysics*, v. 158, no. 1-4, p. 247-267.
- 1040 Xia, W. C., Zhang, N., Yuan, X. P., Fan, L. S., and Zhang, B. S., 2001, Cenozoic Qaidam  
1041 basin, China: A stronger tectonic inversed, extensional rifted basin: *American*  
1042 *Association of Petroleum Geologists Bulletin*, v. 85, no. 4, p. 715-736.

- 1043 Xie, L., Pei, Y., Li, A., and Wu, K., 2018, Implications of meso- to micro-scale deformation  
1044 for fault sealing capacity: Insights from the Lenghu5 fold-and-thrust belt, Qaidam  
1045 Basin, NE Tibetan Plateau: *Journal of Asian Earth Sciences*, v. 158, p. 336-351.
- 1046 Yang, F., Ma, Z., Xu, T., and Ye, S., 1992, A Tertiary paleomagnetic stratigraphic profile  
1047 in Qaidam Basin (in Chinese with English abstract): *Acta Petrologica Sinica*, v. 13,  
1048 p. 97-101.
- 1049 Yang, Y.-R., Hu, J.-C., and Lin, M.-L., 2014, Evolution of coseismic fault-related folds  
1050 induced by the Chi–Chi earthquake: A case study of the Wufeng site, Central  
1051 Taiwan by using 2D distinct element modeling: *Journal of Asian Earth Sciences*,  
1052 v. 79, Part A, p. 130-143.
- 1053 Yielding, G., Freeman, B., and Needham, D. T., 1997, Quantitative fault seal prediction:  
1054 *American Association of Petroleum Geologists Bulletin*, v. 81, no. 6, p. 897-917.
- 1055 Yin, A., Dang, Y., Zhang, M., McRivette, M. W., Burgess, W. P., and Chen, X., 2007,  
1056 Cenozoic tectonic evolution of Qaidam basin and its surrounding regions (part 2):  
1057 Wedge tectonics in southern Qaidam basin and the Eastern Kunlun Range:  
1058 *Geological Society of America Special Papers*, v. 433, p. 369-390.
- 1059 Yin, A., Dang, Y. Q., Wang, L. C., Jiang, W. M., Zhou, S. P., Chen, X. H., Gehrels, G. E.,  
1060 and McRivette, M. W., 2008a, Cenozoic tectonic evolution of Qaidam basin and  
1061 its surrounding regions (Part 1): The southern Qilian Shan-Nan Shan thrust belt  
1062 and northern Qaidam basin: *Geological Society of America Bulletin*, v. 120, no. 7-  
1063 8, p. 813-846.
- 1064 Yin, A., Dang, Y. Q., Zhang, M., Chen, X. H., and McRivette, M. W., 2008b, Cenozoic  
1065 tectonic evolution of the Qaidam basin and its surrounding regions (Part 3):  
1066 Structural geology, sedimentation, and regional tectonic reconstruction:  
1067 *Geological Society of America Bulletin*, v. 120, no. 7-8, p. 847-876.

1068 Yue, Y. J., Ritts, B. D., Graham, S. A., Wooden, J. L., Gehrels, G. E., and Zhang, Z. C.,  
1069 2004, Slowing extrusion tectonics: lowered estimate of post-Early Miocene slip  
1070 rate for the Altyn Tagh fault: *Earth and Planetary Science Letters*, v. 217, no. 1-2,  
1071 p. 111-122.

1072 Zhou, J. X., Xu, F. Y., Wang, T. C., Cao, A. F., and Yin, C. M., 2006, Cenozoic deformation  
1073 history of the Qaidam Basin, NW China: Results from cross-section restoration  
1074 and implications for Qinghai-Tibet Plateau tectonics: *Earth and Planetary Science*  
1075 *Letters*, v. 243, no. 1-2, p. 195-210.

1076 Zhu, L. D., Wang, C. S., Zheng, H. B., Xiang, F., Yi, H. S., and Liu, D. Z., 2006, Tectonic  
1077 and sedimentary evolution of basins in the northeast of Qinghai-Tibet Plateau and  
1078 their implication for the northward growth of the plateau: *Palaeogeography,*  
1079 *Palaeoclimatology, Palaeoecology*, v. 241, no. 1, p. 49-60.

1080