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1 **Active thrust sheet deformation over multiple rupture cycles:**
2 **a quantitative basis for relating terrace folds to fault slip rates**

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17 **ABSTRACT**

18 Many recent thrust fault earthquakes have involved coseismic surface faulting and folding,
19 revealing the multifaceted nature of active thrust sheet deformation. We integrate records of
20 surface deformation, subsurface structure and geochronology to investigate active surface
21 deformation over multiple rupture cycles across the Southern Junggar Thrust (SJT) in the southern
22 Junggar basin, NW China. Fluvial terrace geometries – extracted from a 1-m digital elevation
23 model – reveal records of surface faulting across a prominent fault scarp. In addition, terraces
24 exhibit progressive folding across fold scarps. Fault and fold scarps are spatially coincident with a
25 surface-emergent SJT splay and subsurface fault bends along the SJT, respectively, constrained by
26 seismic reflection data. We quantify the magnitude of fault slip at depth implied by fold scarps
27 along Holocene-aged terraces. Our method yields results consistent with independent estimates of
28 slip implied by fault scarp relief for the same terraces. Four late Quaternary terrace records are less
29 continuous, preserved only as fold scarps that suggest folding kinematics involving a component
30 of limb rotation. We develop a new method for quantifying fault slip at depth from terrace folds
31 using a mechanical forward modeling approach. Our analysis yields quantitative relations between
32 fold dip and fault slip, allowing us to quantify SJT fault slip from terrace folds from ~250 ka-
33 present. SJT fault slip rate has decelerated from ~7.0 mm/yr in the Late Quaternary to ~1.3 mm/yr
34 throughout the Holocene. These results provide new insight into the kinematics of fault-bend
35 folding for natural structures and define new methods to accurately estimate fault slip and slip rates
36 from terrace folds in active thrust sheets.

37 INTRODUCTION

38 The destructive nature of convergent tectonics is manifest by large magnitude earthquakes
39 that occur both along subduction zones and within fold-and-thrust belts. Contemporary events of
40 this latter type (e.g., 1999 Mw 7.6 Chi-Chi, Taiwan; 2008 Mw 7.9 Wenchuan, China; 2015 M_w
41 7.8 Gorkha, Nepal) have led to tens of thousands of deaths and billions of dollars of damage to
42 infrastructure. These earthquakes have also demonstrated some of the ongoing challenges
43 associated with assessing the hazards posed by active thrust faults. Specifically, surface
44 deformation associated with thrust fault earthquakes is multifaceted, often involving components
45 of coseismic folding as well as surface faulting (e.g., Chen et al., 2007). Many active thrust faults
46 - or portions of these faults – are blind, such that surface deformation is characterized exclusively
47 by folding (e.g., Stein and King, 1984; Shaw and Suppe, 1994; Dolan et al., 2003). However,
48 traditional, geologic methods of inferring fault activity, slip rate, and paleoearthquake magnitudes
49 are based exclusively on characterizations of surface faulting deformation (e.g. Wells and
50 Coppersmith, 1994; Wesnousky, 2006; 2008; Leonard, 2010). These methods prove inadequate,
51 in cases where all or a portion of subsurface fault slip is manifest by folding at the surface. Thus,
52 recent studies have made progress in adapting traditional paleoseismic methods to recover more
53 accurate records of fault activity on blind thrust faults (e.g., Mueller et al., 1999; Pratt et al., 2002;
54 Shaw et al., 2002; Dolan et al., 2003; Leon et al., 2007; 2009). These methods generally require
55 kinematic fault-related folding models in order to quantitatively relate surface folding strains to
56 fault activity.

57 Despite the challenges of constraining deformation in active thrust sheets, coupled faulting
58 and folding deformation accumulated over geologic timescales has been recognized for decades
59 (e.g., Rich, 1934; Dahlstrom, 1970) and their direct relationships are now well-established by fault-

60 related folding theories (e.g. Suppe, 1993; Suppe and Medwedeff, 1990; Hardy and Poblet, 1995;
61 Suppe et al., 2004; Shaw et al., 2005). The fundamental basis for these theories underscores the
62 oft-observed occurrence of folds with faults: folding is driven by slip across fault-bends, at
63 propagating fault tips, and along detachments – reflecting displacement gradients within a thrust
64 sheet (Figure 1). This fault-related folding concept is central to our understanding of how
65 shortening is accommodated in Earth’s brittle crust over geologic time scales. Moreover, it has
66 critical implications for seismic hazards assessment as it describes a range of ways that folding
67 may reflect fault slip at depth. For example, a classic fault-bend fold (Suppe, 1983) predicts that
68 fault slip remains constant as it is transmitted up a planar thrust ramp (Figure 1A). Thus, a measure
69 of surface slip (SS) along an emergent thrust ramp of a fault-bend fold will yield an accurate
70 estimate for the amount of fault slip at depth (SD). However, other classes of fault-related folds
71 form due to fault slip gradients along a thrust ramp. In the case of a simple shear fault-bend fold
72 (Suppe et al., 2004; Hardy and Connors, 2006), slip increases linearly up a planar ramp through
73 the shear interval. In this scenario, measures of surface slip would likely overestimate the
74 displacement on a deeper portion of the thrust ramp (Figure 1B). In contrast, fault-propagation
75 folds (e.g. Suppe and Medwedeff, 1990) consume slip during thrust tip propagation, producing a
76 linearly decreasing slip gradient up a thrust ramp (Figure 1C). If the thrust is surface-emergent,
77 measures of surface slip would likely underestimate estimates of slip, and thus paleoearthquake
78 magnitude or long-term slip rates. Finally, despite the wide utility of fault-related folding theories
79 to characterize natural structures (e.g. Shaw et al., 2005), several analog and mechanical modeling
80 studies have provided insights into natural folding deformation that cannot be described using
81 current kinematic formulations. For example, mechanical models of fault-bend folds have been
82 shown to accommodate shortening involving components of structural growth limb rotation,

83 whereas the kinematic theory predicts folding exclusively by kink-band migration. These
84 examples highlight the importance of properly defining faulting and folding relations when
85 employing surface deformation patterns to infer fault activity at depth along thrust sheets.

86 In this article, we describe new methods to quantitatively relate surface faulting and surface
87 folding strains across active thrust sheets over multiple rupture cycles. Our techniques are based
88 on established fault-related folding concepts and new geomechanical models, which we employ to
89 study earthquake deformation and active fold kinematics across the seismically active Southern
90 Junggar Thrust (SJT) in the southern Junggar fold-and-thrust belt, northwest China. When
91 combined with geochronological constraints, these methods have the ability to elucidate detailed
92 records of fault-related folding from individual ruptures to one hundred thousand year timescales.
93 Using high-resolution digital elevation models, subsurface seismic reflection data, and feldspar
94 luminescence dating methods, we extract detailed records of fluvial terraces deformation and
95 directly relate these to subsurface structure. We quantify SJT fault slip implied by Holocene fold
96 scarps and compare these estimates to independent measures implied by Holocene fault scarp uplift
97 records. We describe how preserved records of surface deformation can be effective tools for
98 evaluating – and informing – interpretations of subsurface structure and folding kinematics.
99 Finally, we define new faulting and folding relations implied by mechanical fault-related fold
100 models to quantify fault slip from measures of terrace uplift and folding patterns. Using these
101 techniques, we define a detailed record of fault slip and slip rate across the SJT extending from the
102 most recent rupture in 1906 through the Late Quaternary. We establish a record of fault slip
103 deceleration on the SJT over this timeframe, yielding one of the the most detailed records of fault
104 slip history of any thrust sheet over a 100 kyr+ timescale.

105

106 STYLES OF ACTIVE THRUST SHEET DEFORMATION

107 Sediments deposited across actively growing structures (i.e. growth stratigraphy) record
108 natural folding kinematics (e.g. Suppe et al., 1992; 1997), cumulative fault slip histories (e.g. Shaw
109 and Suppe; 1994; 1996) and discrete coseismic events (e.g., Dolan et al., 2003; Leon et al., 2009).
110 In a similar vein, terraces that extend across an active fold or fault can be passively deformed and
111 record earthquake deformation from one or several ruptures. This has led to significant
112 advancements in tectonic geomorphology utilizing deformed marine or fluvial terrace geometries
113 to constrain active deformation (e.g. Mueller et al., 1999; Lavé and Avouac, 2000; Thompson et
114 al., 2002; Gold et al., 2006; Scharer et al., 2006; Amos et al., 2007; Hubert-Ferrari et al., 2007;
115 Ishiyama et al., 2007; Yue et al., 2011; Le Béon et al., 2014). These methods utilize terrace fold
116 geometries as records of fold kinematics that can be described by fault-related folding theories, or
117 variants of these existing methods (Figure 2). These models make different predictions for folding
118 of growth strata or terraces that are governed by the kinematics of the underlying structure. For
119 example, fault-bend folds (Suppe, 1983; Suppe et al., 1992; 1997) and certain classes of fault-
120 propagation folds (Suppe and Medwedeff, 1990) grow by kink-band migration, a folding process
121 where folds develop a constant dip and continue to widen with increasing fault slip. These
122 kinematic models predict terrace folds to be localized across fault bends (Figure 2A-B) and above
123 blind thrust tips. In contrast, structures that grow by limb rotation exhibit fold limbs that
124 progressively increase fold dip with increasing fault slip. Limb rotation is a common folding
125 mechanism in the presence of hanging wall shear (Suppe et al., 2004; Hardy and Connors, 2006;
126 Yue et al., 2011) and is predicted across some listric fault geometries (e.g., Seeber and Sorlien,
127 2000; Amos et al., 2007). As a result, fault-related folds growing primarily by limb rotation
128 produce distributed terrace fold signatures (Figure 2C-E).

129 An accurate classification of the deformation style present in a thrust sheet is necessary to
130 confidently relate surface deformation to subsurface fold kinematics and fault slip at depth. In
131 many active thrust sheets, this is not a straightforward assessment: subsurface structure – and the
132 implied folding kinematics – must often be inferred from a combination of surface geology,
133 subsurface geophysical data, and terrace deformation constraints. Structures that grow exclusively
134 by kink-band migration or limb rotation yield distinct patterns of fold dips and limb widths
135 recorded by growth strata or terraces (Figure 2). However, several records of growth strata and
136 terrace geometries across natural structures exhibit components of both kink-band migration and
137 limb rotation (e.g. Dolan et al., 2003; Benesh et al., 2007; Yue et al., 2011), making it difficult to
138 discriminate between competing kinematic fold models. In addition, the ability to resolve modest
139 differences between competing kinematic models (e.g. curved shear fault-bend fold versus listric
140 fault-bend fold; Figure 2 D-E) with natural terraces – subject to incomplete preservation,
141 subsequent dissection and potentially anthropogenic modifications – can prove challenging.
142 Moreover, without independent data on fault slip and slip rate, it generally remains unclear how
143 accurately even the most suitable of these kinematic models can be used to relate surface folding
144 to fault slip at depth. In the following section, we describe the geologic setting of our study area –
145 the southern Junggar basin, NW China –, which provides a unique opportunity to quantify fault
146 slip from independent measures both folding and faulting strains over multiple earthquake cycles.
147 We take advantage of this ideal natural laboratory for developing and applying general methods
148 of quantifying folding across an active thrust sheet and relating it to fault slip and slip rate at depth
149 on active thrust sheets.

150

151 **SOUTHERN JUNGGAR BASIN**

152 **Structural Setting**

153 The southern Junggar basin is the northeastern foreland fold-and-thrust belt of the Tian
154 Shan ranges (Figure 3A). Southern Junggar is characterized by three rows of fault-related folds,
155 which are underlain by surface-emergent and blind thrust faults (Figure 3B). Many of these
156 structures originated as Jurassic-aged rift structures that were subsequently inverted in the Late
157 Jurassic or Early Cretaceous (Guan et al., 2016). These inversion structures localized the
158 development of complex fault related folds involving coeval activity on linked forethrusts and
159 backthrusts, a class of fault-related fold termed a structural wedge (Medwedeff, 1989). Much of
160 the Cenozoic deformation history has been localized on deep-seated detachments within the
161 Jurassic and Cretaceous stratigraphic intervals that ramp up from their detachment levels into the
162 cores of the wedge structures. However, most recently, the active Southern Junggar Thrust (SJT)
163 broke through to the surface in a break-back sense of thrusting sometime in the Quaternary (Guan
164 et al., 2016). Continued activity on the SJT has amplified the emergence of a prominent fold trend
165 in the southern Junggar basin, composed of the Tugulu, Manas and Huoerguosi anticlines (Figure
166 3B), which expose Quaternary and Neogene strata along the flanks of each structure and expose
167 Eocene rocks in the anticlinal cores (e.g. Figure 3C). These anticlines also form structural traps for
168 petroleum fields (Guan et al., 2016), which motivated the collection of 2-D and 3-D seismic
169 reflection data used in this study.

170 **Seismotectonic Setting**

171 Present-day geodetic observations suggest ~11 mm/yr of shortening is accommodated
172 across the central Tian Shan, decreasing to ~5 mm/yr ~86° E in the southern Junggar basin and to
173 ~0 mm/yr at ~90° E longitude (Meade, 2007). Geodetic shortening is consistent with focal
174 mechanism solutions throughout the Tian Shan ranges (Nelson et al., 1987) and the persistence of

175 $M_w \geq 7$ earthquakes across the Tian Shan over the past two centuries (Molnar and Ghose, 2000).
176 Indeed, measureable Quaternary-Holocene fault slip along discrete thrust faults throughout the
177 ranges associated with earthquake deformation accounts for much, if not all, of the total shortening
178 across the Tian Shan (e.g. Avouac et al., 1993; Burbank et al., 1999; Thompson et al., 2002;
179 Hubert-Ferrari et al., 2007).

180 Continued fault activity throughout the Holocene on the SJT is recorded by progressive
181 uplift of fluvial terraces across prominent fault scarps where the SJT is surface-emergent (Avouac
182 et al., 1993; Deng et al., 1996). The SJT is a highly-segmented thrust sheet, exhibiting strike-
183 perpendicular offsets of up to 10 km along the forelimbs of the Tugulu-Manas-Huoerguosi fold
184 row (Figure 3B). Despite this segmentation at the surface, it has been interpreted that all three
185 surface splays of the SJT ruptured coseismically during the most recent rupture, the 1906 M_w 7.4-
186 8.2 Manas, China earthquake (Avouac et al., 1993; Deng et al., 1996). A 3-D fault model of the
187 SJT – constrained by 2- and 3-D seismic reflection data – reveals that, despite these significant
188 lateral segment boundaries at the surface, the three major south-dipping surface splays of the SJT
189 merge at depth along an Eocene detachment horizon as a continuous thrust sheet (Stockmeyer et
190 al., 2014). The SJT extends farther to the south before ramping down below the northern Tian
191 Shan range front, likely extending to the base of the seismogenic crust (Stockmeyer et al., 2014).
192 This 3-D characterization of the SJT suggests it is capable of sourcing $M_w > 8$ earthquakes,
193 consistent with the magnitude estimates of the 1906 rupture.

194 **Fluvial Terrace Records**

195 The Tugulu-Manas-Huoerguosi folds are dissected by an internally drained fluvial system,
196 fed by glacial melt in the northern Tian Shan. Cycles of lateral and vertical incision within several
197 fluvial networks have produced suites of fluvial terraces throughout the basin (e.g. Figure 4A),

198 many of which are preserved across entire fold transects (e.g. Molnar et al., 1994; Poisson and
199 Avouac, 2004). These fluvial terraces serve as passive strain markers, recording faulting
200 deformation where the SJT is surface-emergent as well as surface folding strains. Holocene fault
201 activity along the SJT recorded by progressive uplift of several terrace treads was well-documented
202 in the seminal study of Avouac et al. (1993). These records of surface faulting – recording >15 m
203 of relief in places – were unambiguous during field reconnaissance (Figure 4B). In addition,
204 warping of terrace treads due to distributed surface folding has been documented across the
205 anticlinal cores of the Dushanzi and Tugulu anticlines (Molnar et al. 1994; Poisson and Avouac,
206 2004). These surface strains reflect subtle components of surface folding that can be readily
207 documented. Finally, our field reconnaissance documented abrupt, localized terrace folds in the
208 backlimb of the Tugulu fold (Figure 4C). These terraces exhibit up to hundreds of meters of
209 structural relief, likely reflecting a significant magnitude of fault slip at depth. Thus, we have a
210 unique opportunity to quantify deformation across the entire hanging wall of the surface-emergent
211 SJT, from its Eocene detachment south of the Tugulu backlimb, across the core of the structure
212 and continuing to the prominent fault scarp where the SJT is surface-emergent (Figure 3C). Quartz
213 luminescence geochronological methods have proven well-suited for obtaining absolute age
214 constraints for terraces across the southern Junggar basin, yielding reliable dates of terrace
215 abandonment through the Holocene (e.g. Poisson, 2002; Poisson and Avouac, 2004; Gong et al.,
216 2014). In this study, we apply recently developed methods of feldspar luminescence
217 geochronology (e.g. Brown et al., 2015; Rhodes, 2015) that extend the range of reliable ages for
218 terrace abandonment to the Late Quaternary.

219 **An Ideal Natural Laboratory**

220 The southern Junggar basin presents a unique opportunity to apply quantitative methods of
221 extracting thrust sheet deformation and natural fold kinematics from records of active terrace
222 faulting and folding. Specific aspects of the study area that produce such a unique location include:
223 1) an active thrust sheet that ruptures in large earthquakes, likely $M_w \geq 8$; 2) the availability of
224 high-quality 2- and 3-D seismic reflection data imaging subsurface fault geometries and folding
225 kinematics; 3) several records of both surface faulting and surface folding strains, captured by
226 deformed fluvial terrace records across the entire hanging wall of the active thrust sheet; and 4)
227 the ability to obtain reliable, absolute age constraints of surface strain markers to constrain fault
228 slip rates over >100 kyr timescales.

229

230 SUBSURFACE DEFORMATION

231 The Southern Junggar Thrust (SJT) is thought to be the most active structure in southern
232 Junggar; it most recently ruptured during the 1906 M_w 7.4-8.2 Manas, China earthquake (Avouac
233 et al., 1993; Burchfield et al., 1999). Due to active petroleum exploration and development in the
234 region, the SJT and hanging wall fold geometries are well-constrained by high-quality 2- and 3-D
235 seismic reflection surveys (Stockmeyer et al., 2014; Guan et al., 2016). The SJT is particularly
236 well-imaged in the upper 3-4 km of the crust due to the presence of direct footwall cutoffs,
237 terminating hanging wall axial surfaces, and direct fault plane reflections (Stockmeyer et al.,
238 2014). These data provide tight constraints on the geometry and location of each segment of the
239 SJT. Our interpretation of the SJT in section A-A' (Figure 5) depicts the thrust sheet stepping up
240 from its mid-crustal Eocene detachment (Stockmeyer et al., 2014). This Eocene detachment has a
241 modest dip of $3.4^\circ \pm 1.5^\circ$ south (θ_0). The SJT rises from this detachment across multiple synclinal
242 fault bends, achieving a dip of $27.4^\circ \pm 1.5^\circ$ south (θ_2). To generate this steeper ramp dip, we

243 interpret three principal fault bends that are associated with synclinal axial surfaces in the hanging
244 wall strata. The axial surfaces for the latter two bends interfere in the near-subsurface producing a
245 single axial surface trace representing the transition from the fault segments labeled θ_1 to θ_2 in
246 Figure 5 (e.g. Medwedeff and Suppe, 1997). The relationship of this fault geometry to the hanging
247 wall folds is consistent with classic fault-bend folding theories (Suppe, 1983; Medwedeff & Suppe,
248 1997). Another viable interpretation for this 24° increase in fault dip could invoke a curved fault
249 geometry (Suppe et al., 1997). The well-defined planar geometries for the detachment ($\theta_0=3.4^\circ$)
250 and the thrust ramp beyond the bend ($\theta_2=27.4^\circ$) observed in the 2D and 3D seismic data limit the
251 horizontal extent of this zone of curvature to a maximum dip-parallel distance of ~ 2000 m. In such
252 a case, the axial surfaces accommodating folding in the hanging wall would have a comparable
253 finite width (Suppe et al., 1997). In either case, terrace deformation caused by displacement across
254 these fault bends is expected to occur along – or at least in the vicinity of – surface projections of
255 active synclinal axial surfaces (Figure 2A-B; Shaw et al., 1994). A third interpretation we explored
256 invoked a listric fault-bend fold interpretation (e.g. Figure 2E; Seeber and Sorlien, 2000; Amos et
257 al., 2007). We document why such an interpretation is not viable for the SJT in Appendix A.

258 Farther to the north in section A-A', we interpret the SJT further increases its dip across a
259 series of fault bends associated with synclinal axial surfaces in the hanging wall stratigraphy
260 (Figure 5). We observe direct fault plane reflections indicating that the SJT branches into two fault
261 splays across this series of fault bends. The northern surface splay of the SJT has a strictly planar
262 geometry and is surface-emergent where Avouac et al. (1993) documented a prominent fault scarp
263 in the Taxi He valley (Figure 5). This finding has two primary implications. First, the planar
264 geometry of the SJT across the structural crest of an underlying imbricated structural wedge
265 (Figure 5) implies the SJT is the only active structure at present (Lu et al., 2010; Guan et al., 2016),

266 and thus, all terrace deformation is due to fault-bend folding along the SJT. If the deeper structures
267 were active, the shallow segments of the SJT would be folded where they cross the footwall fold
268 crest. This is the primary evidence to suggest the SJT reflects a period of break-back thrusting
269 regionally across the southern Junggar thrust belt (Guan et al., 2016). Second, as there is only a
270 fault scarp across the northern surface trace of the SJT, the near-surface splays of the thrust sheet
271 appear to have developed in a locally break-forward sequence of thrusting. The lack of any
272 differential uplift across the southern surface splay of the SJT implies it has been inactive since at
273 least the start of the Holocene. In addition, this suggests the black axial surface in Figure 5 is
274 inactive; we should not expect any terrace deformation across the surface projection of this
275 synclinal axis. Thus, our detailed constraints on SJT fault activity reflect a complex evolution of
276 thrusting sequences. Regionally, the SJT reflects break-back thrusting as it truncates older, inactive
277 structures in its footwall. Locally, however, near-surface splays imply a break-forward thrusting
278 sequence. This complex thrusting sequence adds to the structural complexity of the southern
279 Junggar fold-and-thrust belt (Guan et al., 2016). However, our subsurface interpretations yield a
280 rather straightforward expectation for our records of surface deformation: any terrace folding can
281 be attributed to fault slip on the SJT across active (i.e. green) axial surfaces and terrace faulting
282 should be exclusive to the northern surface splay (Figure 5). Thus, records of surface deformation
283 can be used as a rather effective tool to evaluate our subsurface interpretations of fault-bend
284 folding, regional break-back thrusting (Guan et al., 2016) and local break-forward thrusting at
285 Tugulu (Figure 5).

286 Altogether, we interpret the SJT as a series of south-dipping fault ramps that increase in
287 dip from $3.4^\circ \pm 1.5^\circ$ (θ_0) along its Eocene detachment to $44.5^\circ \pm 1.5^\circ$ (θ_4) at the surface (Figure
288 5). The planar geometry of the SJT splays across the crests of the footwall anticlines indicates the

289 deeper structures are inactive. The fault bends along the active segments of the SJT yield active
290 synclinal axial surfaces, which, when projected to the surface, provide locations where surface
291 folding is expected to occur (e.g. Shaw et al., 1994), if our interpretations of fault-bend folding
292 and thrusting sequences are accurate. Similarly, terrace uplift from surface faulting is predicted to
293 be limited to the northern SJT surface trace, which would be consistent with our thrust sequence
294 interpretation and the work of Avouac et al. (1993). In the following section, we assess our
295 subsurface interpretation by comparing terrace deformation to the predictions implied by our
296 subsurface interpretation (e.g. Figure 2A). We then quantify fault slip using terrace folds and
297 compare these to slip estimates implied by the fault scarp record. In this way, we seek to validate
298 the method of using surface fold relief to quantify fault slip by establishing a direct comparison to
299 independent slip constraints from the fault scarp. Moreover, we continue to critically evaluate our
300 subsurface interpretation of fault-bend folding by comparing fault slip gradients across the SJT
301 implied by the terrace deformation to the predictions from fault-bend fold theory (Figure 1A).

302

303 **SURFACE DEFORMATION**

304 **Terrace Mapping with High-Resolution Topographic Data**

305 Preserved terraces along the Taxi He valley have recorded localized and distributed
306 deformation across the SJT (Avouac et al., 1993; Molnar et al., 1994; this study). We acquired a
307 5-m vertical resolution digital elevation model across the Taxi He Valley to correlate terraces
308 across the entire transect of the Tugulu fold (Figure 3C). The vertical resolution was improved to
309 70 cm using 10 differential Global Position System (dGPS) ground truth points. This high-
310 resolution topographic data is capable of precisely defining fault uplift and folding signatures
311 across the entire hanging wall of the SJT over multiple rupture cycles. Based on field observations

312 and various methods of interpreting fluvial terraces (e.g. location, elevation, geometry) we mapped
313 seven distinct terraces in the topography data across the Taxi He valley (Figure 6A). In our study,
314 T6 is the youngest mapped terrace and T0 is the oldest. The youngest of these (T4-T6) are present
315 across the entire transect of the thrust sheet, providing three records of both surface folding and
316 surface faulting. Younger terraces are present in isolated remnant locations throughout the valley,
317 but are too discontinuous to confidently correlate over large distances of non-preservation. One of
318 these terraces, T8, provides a lower age constraint for T6. The older terraces (T0-T3) are less
319 continuous, limited to the southernmost dip domains (θ_0 - θ_2) along the SJT. However, these
320 markers exhibit significant uplift and folding deformation, providing a long record of SJT fault
321 slip activity.

322 In subsequent sections, our structural analyses consider residual terrace profiles, which
323 have had their original depositional gradients removed (Figure 6B-C). A brief description of how
324 we mapped terraces and removed the original depositional gradients is provided in Appendix B.
325 We document our assessment of uncertainties related to measurements used to quantify fault slip
326 (e.g. terrace elevation, fault dip) in Appendix C. We note that the loess cap, which often defines
327 terrace treads in southern Junggar (e.g. Figure 4C), has been completely eroded from our T0
328 terrace, suggesting T0 has undergone at least modest amounts of erosion. Thus, any measure of
329 fault slip implied by our T0 profile reflects a minimum estimate of SJT slip since the time of T0
330 abandonment.

331 **Terrace Geochronology**

332 Ages of terrace abandonment are required in order to obtain rates of surface deformation
333 and associated fault slip rates. Luminescence geochronological methods have proved capable of
334 obtaining reliable absolute age constraints for the lower-elevation terraces across southern

335 Junggar, analogous to our T4-T6 terraces (e.g. Poisson, 2002; Poisson and Avouac, 2004; Lu et
336 al., 2010a; Gong et al., 2014). We employ the recently developed single-grain, post-infrared,
337 infrared stimulated luminescence (p-IR IRSL) methods (Buylaert et al., 2009; Thiel et al., 2011;
338 Brown et al., 2015) to date fluvial deposits in each terrace used for our structural analysis. Fluvial
339 deposits are composed of very fine grain to boulder sized clasts. In most locations, the fluvial
340 deposit is overlain by a light tan loess cap. For each terrace we collect 2-5 samples at least 25 cm
341 below the loess cap by driving a 150 mm aluminum tube into the fluvial deposit and capping the
342 ends of the full tube, shielding the inner 15 cm of sample from exposure to sunlight. Samples for
343 T0-T6, T8 terraces were collected in the backlimb of the Tugulu fold with an additional set of
344 samples collected for T4 near the fault scarp in the forelimb of the fold (Figure 3C).

345 K-feldspar grains were isolated from the sedimentary samples under dim amber light
346 conditions. Samples were wet-sieved to and treated with low-concentration (3%) HCl. The 175-
347 200 μm diameter size fraction was then separated according to density with lithium metatungstate
348 to extract the most K-rich feldspars ($\rho < 2.565 \text{ g/cm}^3$; Rhodes, 2015). Finally, the grains were
349 treated with dilute HF for 10 min to remove the outer surface and enhance grain brightness.

350 All luminescence measurements were performed on a TL-DA-20 Risø automated
351 luminescence reader equipped with a single-grain IR laser and a $^{90}\text{Sr}/^{90}\text{Y}$ beta radiation source
352 (Bøtter-Jensen et al., 2003). Emissions were detected through a Schott BG3-BG39 filter
353 combination. Grains were mounted on aluminum discs, seated within 100 holes per disc.

354 Small (10 g) portions of the bulk sediment were measured with inductively-coupled plasma
355 mass spectrometry (ICP-MS) and inductively-coupled plasma optical emission spectrometry (ICP-
356 OES) to measure the U, Th, and K concentrations. These values were used to determine the annual
357 beta dose-rate following the conversion factors of Adamiec and Aitken (1998). An internal

358 potassium content of 12.5 ± 0.12 wt% was used to calculate the internal dose rate (Huntley and
359 Baril, 1997). The outer edges of sediment taken from sample tubes were oven dried to determine
360 the water content of samples. Cosmic dose-rates were estimated based on overburden depth and
361 geomagnetic latitude after Prescott and Hutton (1994).

362 To avoid problems associated with signal fading in K-feldspar sediments (e.g., Huntley
363 and Lamothe, 2001), we measure both the initial IRSL signal at low temperature and also a
364 subsequent high-temperature, post-IR IRSL signal, which has been shown to be more stable
365 (Buylaert et al., 2009). We measure the p-IR IRSL signal at a temperature of 225 °C (preheat of
366 250 °C for 60 s) to measure the charge population which is both bleachable by sunlight exposure
367 and stable through time (Smedley et al., 2015). Single-aliquot regenerative (SAR) dose-response
368 curves (Murray and Wintle, 2000) were measured for each grain to determine the total radiation
369 dose required to produce the natural luminescence signal (i.e., the equivalent dose, D_e).

370 By dividing the equivalent dose by the natural dose-rate, we calculate an approximate age
371 of that grain. If the grains within a sample show a sufficient degree of internal consistency (i.e.,
372 overdispersion less than about 20 ± 9 %; Arnold and Roberts, 2009) there are interpreted as
373 comprising a single dose-population and an age model (e.g., Central Age Model or Minimum Age
374 Model; Galbraith et al., 1999) is used describe the age of terrace abandonment. However, sediment
375 grains from a single sample often exhibit a range of D_e values. In the case of our samples, none of
376 the 26 samples exhibited enough internal consistency to be interpreted a single, well-bleached
377 population.

378 To reduce the uncertainties in the depositional ages for these terraces, we adopt a Bayesian
379 approach which uses our prior knowledge of terrace depositional order to impose the condition
380 that each uplifted terrace must be the same age or older than the terrace beneath it. The use of

381 stratigraphic order for refining depositional age models is common in archaeological studies
382 (Litton and Buck, 1995) and since the advent of the OxCal software program (Bronk Ramsey,
383 1995) Bayesian statistics are routinely applied in the interpretation of radiocarbon ages. More
384 recently, geologists have begun to incorporate this technique to interpret luminescence ages of
385 samples with definite stratigraphic relationships (Rhodes et al., 2003; Greenbaum et al., 2006;
386 Cunningham and Wallinga, 2012; Brill et al., 2015). While efforts are underway to develop a full
387 incorporation of measurement errors, systematic errors, and dose-rate uncertainties into a Bayesian
388 framework for luminescence studies (e.g., Combès et al., 2015), the use of stratigraphic order as a
389 Bayesian prior applied to the interpretation of single-grain luminescence ages is largely
390 undeveloped.

391 First, for every terrace we construct a summed probability distribution. The natural
392 logarithm of every single-grain age value is set as the mean of a Gaussian distribution, and the
393 relative standard error is used for the standard deviation of this distribution. By adding all single-
394 grain distributions together, we construct our log-transformed probability distribution of all single-
395 grain ages within a given terrace (Figure 7). This distribution represents the depositional age
396 probability for each terrace individually, before considering stratigraphic order. Second, we
397 randomly select one of the terraces (T0-T6, T8). The age of this terrace is sampled from its prior
398 age distribution. From this initially-chosen terrace, we must move stratigraphically up and down
399 until all terraces have been assigned ages. If a sampled terrace age is stratigraphically consistent,
400 the age is accepted; if not (e.g. $T5 > T4$), another age is chosen. This continues until a
401 stratigraphically consistent age is given to each terrace or a pre-determined number of iterations is
402 exceeded. We run 10,000 simulations which are fitted to produce a posterior age distribution for
403 each terrace from all successful model simulations (Figure 7).

404 The posterior age probabilities exhibit modest overlap at the 1σ level (Figure 7) The
 405 posterior procedure described above has an implicitly defined lower-bound for terraces ages of
 406 present-day but does not contain a similar, upper-limit. This yields greater age control for
 407 Holocene aged-terraces (Figure 7). The single-grain ages of older terraces (T0-T3) have higher
 408 standard deviations, and precision remains low even after incorporating stratigraphic constraints.
 409 Moreover, the use of relative standard errors instead of absolute errors produces asymmetric
 410 standard deviations that positively skewed (Figure 7).

411 **Fault Slip Estimates from Surface Deformation**

412 *Surface Faulting*

413 As documented by Avouac et al. (1993), there is a prominent fault scarp delineating the
 414 surface trace of the active SJT splay along the forelimb of the Tugulu anticline. The surface fault
 415 dip slip (u_j) required to produce the observed amount of terrace uplift relative to the footwall
 416 position (h_j) is given by:

$$417 \quad \mathbf{u}_j = \frac{h_j}{\sin \theta_j} \quad (1)$$

418 where θ_j is the dip of the underlying fault segment relative to horizontal, measured in degrees, and
 419 h_j is the total structural relief above dip domain j , given by:

$$420 \quad \mathbf{h}_j = \mathbf{z}_j - \mathbf{z}_{fw} \quad (2)$$

421 where z_x is the elevation of the unfolded terrace within dip domain j , and z_{fw} is the footwall
 422 elevation of the terrace (Figure 8).

423 *Surface Folding*

424 Actively uplifting structures often do not have a preserved record footwall terraces due to
 425 footwall aggradation (Lavé and Avouac, 2000; Yue et al., 2011; Le Béon et al., 2014). Without a
 426 footwall level, estimates of fault slip from surface faulting require assumptions about base level

427 changes and sedimentation rates to estimate the burial depth of the footwall terrace relative to the
 428 present-day stream bed. This method has been shown to yield reasonable estimates of fault slip
 429 when base level changes have been considered thoroughly (e.g. Lavé and Avouac, 2000).
 430 However, the traditional method of quantifying fault slip from surface fault uplift by (1) can be
 431 generalized to yield estimates of fault slip at depth from fold scarps or fault scarps. This method
 432 is independent of base level changes when applied to fold scarps (e.g. Yue et al., 2011; Le Béon
 433 et al., 2014), avoiding additional uncertainties associated with estimates of z_{fw} if a terrace is not
 434 preserved in the footwall (e.g. e.g. Lavé and Avouac, 2000). The structural relief produced across
 435 two dip domains, i and j , provides an estimate of slip by:

$$436 \quad \mathbf{u}_j = \frac{\Delta h_{ji}}{\sin \theta_j - \sin \theta_i} \quad (3)$$

437 where

$$438 \quad \Delta h_{ji} = \mathbf{z}_j - \mathbf{z}_i \quad (4)$$

439 The generalized forms in (3) and (4) reduce to (1) and (2) when dip domain i refers to the footwall
 440 of the fault (i.e. $\theta_i = 0^\circ$). The generalized formula for quantifying fault slip from terrace relief in
 441 (3) is applicable across one or multiple fault bends across a thrust sheet; $j-i$ need not equal 1. Thus,
 442 if a thrust sheet has several fault bends, such as the SJT (Figure 5), (3) may yield several estimates
 443 of fault slip.

444 We have precise constraints on the footwall positions of the Holocene terraces, T4-T6
 445 (Figure 6B), but the Quaternary terraces, T0-T3, are only preserved as fold scarps (Figure 6C). In
 446 the following section, we test the accuracy of (3) for estimating magnitudes of fault slip from only
 447 fold scarp relief by directly comparing it to measures of fault slip implied by the fault scarps using
 448 (1).

449

450 **INTEGRATED RECORDS OF ACTIVE THRUST SHEET DEFORMATION**451 **Holocene Fault Activity**452 *Fault Scarp Estimates of Fault Slip*

453 Structural relief of the T4 terrace across the Taxi He fault scarp suggests $\sim 15 \text{ m} \pm 1.2 \text{ m}$ of
454 vertical throw on the SJT (Figure 6B) since it was abandoned in the early Holocene (Figure 7).
455 The progressive decrease in structural relief with decreasing terrace age implies a record of
456 multiple rupture events on the SJT throughout the Holocene. We use (1) to calculate total fault slip
457 on the SJT since the time of terrace abandonment for each Holocene terrace and our constraints of
458 subsurface fault dip to (Table 2). This surface faulting record suggests at least $21.4 \text{ m} \pm 2.4 \text{ m}$ of
459 fault slip on the SJT during the Holocene.

460 *Fold Scarp Estimates of Fault Slip*

461 We calculate the fault slip required to produce the measured structural relief across all
462 possible combinations of dip domains for the T4-T6 using (3). As discussed above, our
463 interpretation of the SJT geometry and its hanging wall fold reflects fault-bend folding (Suppe,
464 1983). For our case of \sim parallel hanging wall strata and underlying fault dip, fault-bend folding
465 predicts no change in slip across a synclinal fault bend (Suppe, 1983). Therefore, we should expect
466 a single magnitude of fault slip to explain all of our measures of structural relief and change in
467 fault dip used in (3) for a given terrace. In Figure 9A, we plot structural relief versus change in
468 fault geometry and apply a linear regression to each terrace dataset that runs through the origin,
469 reflecting no relief for no slip. The slope of each best-fit function yields the magnitude of slip that
470 best describes the terrace fold scarps and fault dip data. The low variance between the linear
471 models and the data implies no change in fault slip across the entire hanging wall of the SJT among

472 the fold scarps (Figure 9A), indicating that a single magnitude of fault slip can readily explain all
473 of the observed fold scarps for each Holocene terraces (T4-T6).

474 The fold scarps preserved in the T5 record yield consistent fault slip values across dip
475 domains $x=0, 3$ and 4 (Figure 9A). We note that the uplift preserved across the T5 fold scarps
476 corresponding to dip domains 1 and 2 is less than the relief preserved for T6 in the same dip
477 domains (Figure 6B). As T5 is older than T6 in both an absolute (Figure 7) and relative (Figure
478 6A) sense, T5 must have experienced at least as much fault slip as T6. However, the regions where
479 relief is greatest suggests T5 has been deformed by more SJT fault slip than T6 (Figure 6B),
480 consistent with the result from the fault scarp data (Table 2). This suggests some of the uplift
481 experienced by T5 has been removed in dip domains 1 and 2. Potential mechanisms to remove
482 terrace fold relief may require lateral erosion, perhaps slake-driven lateral incision (Johnson and
483 Finnegan, 2015), or, if the Taxi He was transporting sufficiently erosive bedload at that time,
484 downstream sweep erosion (Cook et al., 2014). Whatever the mechanism may have been, the
485 consistency of fault slip suggested by all of the slip measures by T4 and T6 as well as the T5 data
486 used in Figure 9A suggest the two depressed uplift signals in the T5 profile are likely
487 underestimating total SJT fault slip.

488 When we compare the magnitudes of fault slip derived using (1) and (3) using the fault
489 scarp and fold scarp data, respectively, the results are indistinguishable (Figure 9B). This is further
490 consistency with our fault-bend folding interpretation for the hanging wall of the SJT. A linear
491 regression to these data suggest a fairly constant Holocene slip rate on the SJT of 1.2-1.3 mm/yr
492 (Figure 9B).

493 We have established that quantifying fault slip from terrace folds can accurately reflect
494 total fault slip at depth (Figure 9). We suggest this provides confidence for using folding recorded

495 by growth strata or terraces to quantify fault slip on blind thrust sheets (e.g. Dolan et al., 2003;
496 Benesh et al., 2007). When possible, seismic hazards assessments should employ this method using
497 as many different measures of fold relief as available in order to evaluate the potential for spatial
498 gradients in slip along an active thrust sheet (e.g. Figure 1). In our case, a fault-bend fold, we can
499 state confidently that a single measure of fault slip anywhere in the hanging wall would have been
500 yielded an accurate measure of fault slip at depth. Yet, we could not have stated this with
501 confidence if we only used a single fold scarp in our analysis. We only validate the lack of slip
502 variation by producing a complete record of surface folding and surface faulting deformation
503 across the entire SJT in our study area.

504 **Quaternary Fault Activity**

505 The T0-T3 terraces provide a record of Late Quaternary surface folding across the Tugulu
506 backlimb (Figure 6C; 7). While the Holocene terraces would only record a few earthquakes
507 equivalent to the 1906 Manas, China event, these older terraces provide long-term records of uplift
508 due to fold growth and fault activity on the SJT – likely the products of hundreds of 1906-
509 equivalent ruptures. Given the discontinuous nature of these older terraces, they do not record fault
510 offset. Therefore, we use (3) to constrain the fault slip required to produce the observed fold relief
511 for T0-T3 (Table 3). The z_0 elevation – the residual elevation above the detachment – for both T2
512 and T3 is preserved in our terrace records (Figure 6C). To estimate z_0 for T1 and T0, we assume
513 the rate of incision implied from T2 to T3 has been constant since the abandonment of T0.
514 Although we do not have evidence for a constant incision rate from ~250-100 ka, this method
515 should yield a reasonable approximation for the structural relief developed before T1
516 abandonment. As described previously, the magnitude of fault slip from the T0 profile is likely a
517 minimum constraint, given the evidence for erosion. Our calculations from (3) suggest a minimum

518 of ~525 m of fault slip on the SJT over the past ~250 kyr (Table 3). Before we discuss the long-
519 term slip rate history on the SJT implied by our terrace data, we discuss the folding kinematics
520 implied by the T0-T3 terrace geometries (Figure 6B), which appear to deviate from the predictions
521 of kinematic fault-bend fold theories (Figure 2A-B). In doing so, we attempt to develop a method
522 for quantifying fault slip from terrace fold dips, which, if successful, will provide a more accurate
523 estimate for fault slip implied by the T0 terrace profile.

524 *Quaternary Terrace Fold Kinematics*

525 The Quaternary terraces preserved across the backlimb of the Tugulu fold exhibit a fanning
526 of limb dips, with older terraces dipping more steeply than younger terraces (Figure 6C). Where
527 preserved, these terraces acquire their dips over a region of finite width, coincident with synclinal
528 axial surfaces that reflect the SJT increasing its dip from 3.4° to 27.4°. The variable limb dips
529 exhibited by these Quaternary terrace folds are remarkably planar. These observations suggest T0-
530 T3 folds have developed – at least in part – by limb rotation. Limb rotation is a folding mechanism
531 that describes fold limbs which progressively increase their dip with increasing fault slip. Fault-
532 bend folding theories (Suppe, 1983; Suppe et al., 1997) predict these structures grow exclusively
533 by kink-band migration (Figure 2A-B). Kink-band migration is a folding mechanism whereby
534 folds acquire a constant dip after passing over a fault bend – instantaneously (Figure 2A) or over
535 some region of finite width (Figure 2B) – and widen at this constant dip with increasing fault slip.

536 Observations of progressive limb rotation across fault-related folds have led to the
537 development of numerous fault-related fold variants based in part on the original fault-bend fold
538 theory. These commonly invoke an axial surface zone of some finite width (e.g. Erslev, 1986;
539 Suppe et al., 1997; Seeber and Sorlien, 2000), and may invoke additional folding mechanisms that
540 involve limb rotation, such as trishear (Erslev, 1993; Allmendinger, 1998; Cristallini and

541 Allmendinger, 2002; Brandenburg, 2013). Simple and pure shear fault-bend folding models
542 describe structures that grow by a combination of kink-band migration and limb rotation (Suppe
543 et al., 2004; Hardy and Connors, 2006).

544 More recently, studies have explored the possibility that structures may deviate from the
545 strict kinematics of fault-bend folding theory under certain conditions (Benesh et al., 2007;
546 Benesh, 2010). These studies have employed mechanical forward models using the discrete
547 element modeling (DEM) technique. These models readily produce fault-bend folds that grow by
548 a combination of kink-band migration and limb rotation – referred to herein as hybrid folding– as
549 strata are displaced across a discrete fault bend (Benesh et al., 2007; Benesh, 2010). This behavior
550 offers the prospect of reconciling our observations that Holocene slip on the SJT is consistent with
551 fault-bend folding kinematic predictions of slip magnitudes across the entire hanging wall (Figure
552 1A, 5, 9B) while the fanning of limb dips in the Quaternary terrace record implies a component of
553 folding by limb rotation (Figure 6C).

554

555 **A MECHANICAL MODEL OF THRUST SHEET DEFORMATION**

556 **Model Description**

557 Following the work of Benesh et al. (2007) and others (e.g., Strayer et al., 2004; Benesh,
558 2010; Hughes and Shaw, 2015; Morgan, 2015), we produced a mechanical model of deformation
559 within a thrust sheet using a discrete element model (DEM) to help guide our interpretations of
560 folding kinematics for the hanging wall of the SJT, including the T0-T3 terraces. The DEM method
561 is able to replicate natural brittle-plastic deformation processes such as folding, frictional sliding,
562 fracture growth, and the influence of mechanical stratigraphy (e.g., Cundall and Strack, 1979;
563 Morgan, 1999; Strayer et al., 2004) that likely influence the manner of deformation during natural

564 fault-related folding. We created our model using the 2-D Particle Flow Code (PFC) numerical
565 modeling package, which describes granular behavior of linear elastic particles with frictional
566 contacts. The code employs a method by which circular balls interact at an infinitesimally small
567 contact. These contacts can replicate both shear and tensional bonding between particles. If bonds
568 are broken, balls will interact and can slide, governed by Coulomb frictional sliding behavior. In
569 addition, physical rock properties such as density, elastic moduli, and friction can be prescribed.
570 Moreover, forces are implemented to models, such as gravity and translating boundary walls.
571 Translating walls are often employed as displacement boundary conditions to drive deformation.
572 For a more detailed description of the DEM method and PFC code applied to studies of active
573 deformation and folding kinematics, we direct the reader to Benesh (2010); Hughes et al. (2014);
574 and Morgan (2015).

575 We define a 24° dip change along the fault in our mechanical model to replicate folding of
576 the T0-T3 Quaternary terraces across the SJT, where they are preserved (e.g. Figure 5, 6C). The
577 model includes a 12 km long detachment that steps up to a thrust ramp dipping 24° (Figure 10A).
578 We deposit pre-growth strata to the hanging wall of our fault model in 500 m thick layers,
579 following the same settling procedure of Benesh et al. (2007), allowing each layer to reach a state
580 of static equilibrium following deposition. Between pre-growth layers, we deposit 125 m thick
581 sections that have smaller ball radii, no friction and lack bonding. These weak layers are employed
582 to promote flexural slip during deformation, which enables the structure to deform in a manner
583 consistent with fault-bend folding (Suppe, 1983; Benesh, 2010). We deposit seven layers of pre-
584 growth and six flexural slip surfaces (Figure 10A). A boundary condition is applied to the leftmost
585 boundary wall to translate along the detachment fault at a constant rate of 1 m/s. After each 250 m
586 interval of fault slip, we deposit a layer of growth strata to a thickness that is 100 m higher than

587 the mean elevation of the structural crest. Growth strata aid in recording the kinematics of the fold
588 growth and also serve to limit effects such as slumping and minor extension that can develop at
589 the top of the hanging wall. The material properties prescribed for our model are summarized in
590 Table 4.

591 There are many similarities between our mechanical model result and kinematic fault-bend
592 fold theory (Suppe, 1983). In the final state of deformation (Figure 10B), pre-growth strata parallel
593 the underlying thrust ramp, which is the kinematic prediction for our initial model geometry. As a
594 result, slip on the fault ramp is generally constant and consistent with the structural relief across
595 the fold in its hanging wall. This behavior further validates (3) to calculate slip on the SJT from
596 the fold scarp relief of deformed terraces. In the growth strata of our model, we observe a
597 narrowing upward growth triangle (Figure 10B), which is diagnostic of fold growth by kink-band
598 migration - the mechanism invoked by fault-bend folding theory (Suppe et al., 1992; Shaw and
599 Suppe, 1994). However, we observe additional details that reflect important departures from the
600 kinematic expectations, consistent with similar studies (Benesh et al., 2007). Most notably, there
601 is a shallowing upward of limb dips in growth strata, suggesting the hanging wall has deformed
602 by a component of limb rotation. Moreover, we observe a distributed zone of folding that has
603 developed to accommodate fault slip across the discrete bend in the thrust sheet at depth. This
604 results in a much wider region of folding than generally is described by the kinematic theory.

605 Our mechanical fault-bend fold model accommodates shortening during structural growth
606 in part by limb rotation (Figure 10B). Thus, the fanning of dips exhibited by T0-T3 (Figure 6C)
607 remains consistent with fault-bend folding when stresses and mechanical stratigraphy are
608 considered. To quantify how bed dips evolve in the model, we record fold dip and total slip
609 experienced for each bed in both growth and pre-growth sections following each 250 m slip

610 interval. For each strata type, we calculate the average dip for a given amount of fault slip (Figure
611 11A). We find that both pre-growth and growth layers develop their dips incrementally (Benesh,
612 2010), reflecting a component of fold growth by limb rotation throughout the hanging wall of our
613 mechanical fault-bend fold model (Figure 11A). This pattern of dip evolution was a robust feature
614 for growth and pre-growth strata in all of the models we tested. We find that these relationships
615 are generalized by a second-order polynomial functions that passes through the origin, reflecting
616 zero slip and dip (Figure 11A). The precise nature the dip evolution – governed by the two
617 constants in the functional form – will vary as a function of layer strength, thickness, and the
618 spacing of flexural slip surfaces. However, all of the models we tested – in addition to those of
619 Benesh et al. (2007) and Benesh (2010) – involve a component of fault-bend folding by limb
620 rotation in both growth and pre-growth strata, similar to the implied kinematics of the T0-T6
621 terraces in our study area (Figure 5, 6, 9).

622 **Deriving Fault Slip from Terrace Dips**

623 The pre-growth strata generally develop folds much faster than growth strata in this DEM
624 approach (Benesh et al., 2007). In addition, variations in mechanical stratigraphy of a DEM model
625 can yield changes in the precise form the quadratic dip-slip functional relation described above.
626 This variability presents a challenge for determining the appropriate way to relate bed dips to fault
627 slip in natural structures, given that we generally lack precise knowledge of these mechanical
628 properties. Thus, we suggest an approach that employs fitting a second-order polynomial function
629 to data from the natural structure. Specifically, terraces that preserve both limb dip and structural
630 relief can be used directly in this fitting procedure. For the SJT, this information is available for
631 the T1-T4 terraces (Figure 6). We omit T0 from the fitting procedure due to the potential it has
632 undergone significant erosion, as described above. In addition, we supplement our natural terrace

633 dataset with an upper constraint on the critical slip value required to produce the maximum
634 allowable dip, which in our model and the SJT is limited by the ramp dip. The critical slip for the
635 SJT is constrained by pre-growth fault offset across the SJT to be ~2800 m (Guan et al., 2016;
636 their Figure 4). Thus, the Tugulu pre-growth strata require no more than ~2800 m of fault slip to
637 achieve their maximum dip. By incorporating this critical slip and maximum pre-growth dip
638 relation, along with the other direct constraints from terraces that preserve both dip and uplift, we
639 suggest that it's possible to develop a robust relationship between terrace dip and slip.

640 We note that growth strata may have a different critical slip than pre-growth, as discussed
641 above (Figure 11A). However, terraces are merely passive strain markers. Thus, it seems
642 reasonable that they will be governed by the dip-slip relation of whichever stratigraphic interval
643 they reside within. In our case, the SJT has incised into the pre-growth strata, leaving behind
644 terraces within the Tugulu pre-growth section. Thus, we suggest the pre-growth critical slip value
645 serves as an effective constraint for our terrace data. Our work here, as well as that of Benesh
646 (2010), consistently found that growth layers acquire fold dips more gradually than pre-growth.
647 Thus, magnitudes of fault slip we define by the functional form derived using the pre-growth
648 critical slip value will yield a minimum slip estimate for the terrace data. This reflects uncertainty
649 in how the mechanical stratigraphy of the fluvial deposits overlying the pre-growth may fold
650 precisely. Regardless of this effect, it's reasonable to suggest the pre-growth critical slip is not
651 greater than the critical slip for the terrace folds.

652 We define a dip-slip relationship for the Quaternary folds in the backlimb of the Tugulu
653 structure. The constraints for this relationship include dip and slip for the T1-T4 terraces, the pre-
654 growth strata, and the origin, with the origin reflecting no dip for zero fault slip. The functional
655 form of the 2nd-order polynomial describing the terrace dip-slip relation yields a tight fit to the

656 data, suggesting it is a viable path to describe the history of fold growth for the terrace data. In
657 addition, this dip-slip relation confirms our observation that the slip derived from the T0 structural
658 relief will underestimate total slip. However, we can use the observed T0 dip magnitude to estimate
659 the total amount of slip that has occurred on the SJT since the time of T0 abandonment (Figure
660 11B). Finally, the tight fit to the terrace data using the pre-growth critical slip magnitude implies
661 that this is a reliable measure for the critical slip for our terrace folds.

662 We conclude the slip estimates from uplift of Holocene terraces (T4-6) – which are
663 consistent with kinematic fault-bend fold theory (Suppe, 1983) – can be reconciled with the
664 fanning of limb dips in Quaternary terraces (T0-T3) – which deviate from kinematic fault-bend
665 fold theory (Suppe, 1983) – through a mechanical fault-bend fold model that grows by a
666 combination of limb rotation and kink-band migration (Figure 11B). We do not advocate that any
667 specific mechanical model can be used to uniquely define the dip-slip relation for a specific natural
668 structure. In contrast, we suggest that the general functional form of this relationship can be
669 effectively described by a second-order polynomial relation that fits through the origin. This offers
670 a generalized approach by which limited data from natural folds – surface folds or buried growth
671 strata– may be used to develop a quantitative relation between fold geometry and fault slip at depth
672 (Figure 11).

673

674 **250 KYR RECORD OF ACTIVE THRUST SHEET DEFORMATION**

675 Based on our analysis of the kinematics governing the dip-slip relation for the hanging wall
676 of the SJT, the slip estimates derived from (3) for the T4-T6 terraces, and our new terrace
677 geochronology (Figure 7), we have developed a detailed history fault slip rate on the SJT (Figure
678 12). Specifically, the mean slip rate for the SJT has decelerated from a maximum of ~7.0 mm/yr

679 in the Late Quaternary, to a mean slip rate of ~1.3 mm/yr throughout the Holocene (Figure 9; 12).
680 We formally evaluate this conclusion of a decelerating SJT slip rate from the Late Quaternary to
681 the Holocene by performing an f-test on the functional forms fit to the terrace data that considers
682 uncertainties in our estimates of fault slip as well as the terrace age uncertainties (Appendix C). In
683 this assessment, a 2nd-order polynomial function fits our terrace data more accurately than a
684 constant slip rate (i.e. linear) function fit to all of the data (Supplemental Figure C1). Thus,
685 although the actual SJT slip rates may differ from the preferred values reported here within the
686 range of our uncertainties, our conclusion of a decelerating slip rate from the Late Quaternary to
687 the Holocene remains robust.

688 Our preferred Holocene slip rate represents ~25% of the geodetically measured shortening
689 across the Tian Shan range front at the 86° latitude of our studied area (Meade, 2007). Thus, the
690 SJT currently serves as a principal structure for accommodating shortening across the eastern Tian
691 Shan in. A faster slip rate on the SJT in the Late Quaternary implies: 1) the regional shortening
692 rate has decreased over the past 250 kyr, 2) deformation formerly accommodated on the SJT has
693 shifted to structures toward the hinterland, within the Tian Shan ranges, or 3) a combination of 1
694 and 2. Moreover, the dynamic history of SJT slip rate suggests that single measures of fault slip
695 rate for active thrust sheets may not be adequate to properly characterize past or present-day slip
696 rates. Thus, in addition to considering spatial slip gradients in thrust sheets (Figure 1), adequate
697 seismic hazards studies should consider temporal variations as well (Figure 12).

698

699 CONCLUSIONS

700 Through a unique case study integrating deformed fluvial terraces, feldspar luminescence
701 geochronology, and structural analysis facilitated by seismic reflection data and mechanical

702 forward models, we have developed a new method of extracting detailed histories of fault slip and
703 slip rate from folds in thrust sheets. By combining kinematic and mechanical modeling methods,
704 we developed quantitative relationships between fold relief, fold limb dip, and slip that enabled us
705 to extract a ~250 kyr history of deformation and fault activity on the SJT from measures of terrace
706 fold dip and uplift. These methods can be readily employed in regions of active convergent
707 tectonics to delineate active thrust faults, growing folds, and, thus, understand their histories of
708 deformation over multi-rupture timescales. Moreover, methods that consider more complete
709 records of deformation over multiple rupture cycles provide unique insights into the mechanisms
710 of natural fold growth in relation to thrust faulting. With proper consideration of the potential for
711 spatiotemporal fault slip variations (e.g. Figure 1, 12), hazards assessments can provide more
712 accurate details of fault activity, paleoearthquake magnitudes, and slip rates to better reduce the
713 risk to life and property in active thrust belts.

714

715

716 **APPENDICES**

717 **Appendix A: Evaluating Alternative SJT Kinematic Models**

718 We present our preferred interpretation of the SJT fault bend from its Eocene detachment
719 ($\theta_0=3.4^\circ$) to a steeper planar ramp dip ($\theta_2=27.4^\circ$) in Figure 5. In this interpretation, we follow
720 classic fault-bend folding (Suppe, 1983; Medwedeff and Suppe, 1997) where folding occurs across
721 an instantaneous change in fault dip and axial surfaces bisect the hanging wall syncline fold. An
722 equally permissible interpretation allows for a curved-hinge fault bend fold (e.g. Suppe et al.,
723 1997) that progressively increases the fault dip over a ~2,100 m zone of finite width. A third
724 possibility is a listric fault-bend fold (Seeber and Sorlien, 2000; Amos et al., 2007). This possibility
725 has important implications on the expected folding kinematics as listric fault-bend folds develop

726 by limb rotation (Figure 2E) whereas either of the viable fault-bend fold models deform by kink-
727 band migration (Figure 2A-B).

728 In listric fault-bend fold kinematic model (Seeber and Sorlien, 2000), entry and exit axial
729 surfaces are oriented perpendicular to the entry (e.g. $\theta_0=3.4^\circ$) and exit (e.g. $\theta_2=27.4^\circ$) thrust fault
730 dips. These axial surfaces meet at a point in the hanging wall of the thrust sheet, defining the origin
731 and radius of a circle (Seeber and Sorlien, 2000). From our interpretation of the SJT and hanging
732 wall fold, this solution defines a 4,500 m radius of curvature. The origin of the circle is located in
733 the backlimb of the Tugulu fold, in the vicinity of where we have observed a distinct fanning of
734 terrace fold dips (Figure 4B). However, the origin of the defined circle is ~1,200 m above sea level.
735 The absolute elevations of these terraces south of the backlimb fold limb are ~1,000-1,100 m.
736 Thus, terrace folding would be forced to occur over a very narrow horizontal distance. In this
737 kinematic model, portions of terraces above the planar ramp beyond the region of fault curvature
738 (θ_2), terraces would be rigidly uplifted and would not undergo folding by limb rotation (Seeber
739 and Sorlien, 2000; Amos et al., 2007; Hu et al., 2015). In contrast, we observe Quaternary terraces
740 (T0-T3) folded across the entire extent of the θ_2 fault ramp. We note that the width of the T3 fold
741 limb is ~1.8 km whereas the width of the T4 fold limb is ~900 m. Thus, in this interpretation, the
742 T3 terrace would have experienced significantly more slip than T4 equating to ~1-2 orders of
743 magnitude more fault slip than suggested by the structural relief (Table 3). Based on this analysis,
744 we conclude that a listric fault-bend fold kinematic model (Seeber and Sorlien, 2000; Amos et al.,
745 2007; Hu et al., 2015) is not consistent our integrated surface and subsurface data constraints. We
746 note that in the absence of our subsurface data, the listric fault-bend fold model may be permissible
747 because we would not have independent constraints on the width of the fault curvature (e.g. Amos
748 et al., 2007; Hu et al., 2015). However, as we show with our mechanical model, fault-bend folding

749 is consistent with both the surface and subsurface data constraints for this thrust sheet. This
750 highlights the importance of subsurface data constraints to develop accurate kinematic models of
751 fold growth; the occurrence of progressive limb rotation in growth strata or terrace folds may be
752 consistent with a fault-bend fold solution (e.g. Dolan et al., 2003; Benesh et al., 2007; Leon et al.,
753 2007; 2009).

754

755 **Appendix B: Terrace Profile Extraction Procedure**

756 **Terrace Mapping**

757 We mapped terraces across the Tugulu anticline along the Taxi He valley using the 1-m
758 digital elevation model data set. For the young river terraces along the active stream channel, we
759 mapped the top of terrace treads by extracting linear profiles along several transects of terrace
760 segments. Only the T4 terrace was fully continuous across one side of the Taxi He (Figure 3),
761 requiring the T5 and T6 terraces to involve profiles from both sides of the river valley. We assumed
762 that a terrace tread directly across a river valley (perpendicular to the flow direction) within <70cm
763 change in elevation was considered a terrace of equal age. We found the terraces interpreted for
764 T5 and T6 had elevation changes that were negligible when compared to the natural variability of
765 these terrace elevations (~35 cm). Interpretations of discontinuous Quaternary terraces (Figure 4C)
766 required mapping of a loess cap contact with the fluvial deposits beneath, marking the top of the
767 terrace tread. These features were readily identifiable in the field and DEM, facilitating relatively
768 straightforward mapping procedures. However, given their discontinuous state, these features
769 required iterative quality control both internally when mapping with the topographic data, as well
770 as confirmation in the field. This procedure included comparison of terrace elevation, dip,
771 lithology wherever two terrace remnants were discontinuous. This was particularly important in

772 places where we were required to jump correlate terraces across the Taxi or Tugulu He (Figure
773 3C).

774 **Correcting for Depositional Gradient**

775 In order to quantify tectonic deformation, the original depositional gradient should be
776 estimated to properly assess uplift and fold dips. This procedure can be difficult without some
777 constraint on the undeformed geometry of a terrace (e.g. Finnegan, 2013). The continuity of
778 terraces in southern Junggar allow us to make reasonable assumptions on their depositional
779 gradients. The raw terrace profiles for T4-T6 terraces to the south of any axial surfaces likely
780 represent their depositional gradient as there are no known structures that would have warped or
781 folded these terraces immediately south of Tugulu (Figure 3C). Each of these terraces parallel the
782 present-day Taxi He channel where they overlie the underlying detachment dip domain, indicating
783 the Taxi He has maintained a relatively constant gradient since the deposition of T4 (Figure 6A).
784 We remove this regional dip of 1.1° to reorient terrace elevations relative to the Taxi He. In this
785 reference frame (Figure 6B), any significant deviations from negligible dip may indicate structural
786 relief due to fault slip on the SJT. The T0-T3 terraces are farther removed from the present-day
787 Taxi He channel and mimic a paleo-trajectory significantly different than the Holocene Taxi He
788 meandering (Figure 3C). The azimuths of these terraces more closely resemble a presently dry
789 streambed that is adjacent to these terraces – which we refer to as the Tugulu He –, west of the
790 Taxi He (Figure 3C). T0 and T1 are not preserved outside of the Tugulu fold limb, whereas T2
791 and T3 can be mapped south of the fold over a distance that sufficiently constrains their original
792 depositional gradients (Figure 3C). The T2 and T3 terraces have an undeformed dip of 1.3° above
793 the underlying detachment, parallel to the gradient of the Tugulu He (Figure 6A). Given the
794 apparently long-term steady river gradients from the Taxi and Tugulu systems, we assume T1 and

795 T0 had the same 1.3° depositional gradient. We remove this gradient and produce residual terrace
796 profiles relative to the Tugulu He for T0-T3 (Figure 6C). All subsequent structural analysis is
797 conducted using these residual terrace profiles. We document our assessment of uncertainties
798 related to the vertical position of terrace interpretations in Appendix C.

799

800 **Appendix C: Uncertainties in Slip and Slip Rate Calculations**

801 **Fault Slip Uncertainty**

802 We use structural relief measured in fluvial terrace profiles to quantify total fault slip along
803 the SJT since the times of terrace abandonment. We apply a 1.2 m uncertainty for the all of the
804 terrace elevation data associated with variations in the gravel veneer thickness and the resolution
805 limits of the topographic dataset (70 cm). For Quaternary terraces, we add an additional ± 1.5 m
806 uncertainty due to horizontal measurement error when interpreting terraces to account the potential
807 for steep gradients ($\sim 35^\circ$ in places) at loess-gravel contacts, along which these older terraces were
808 mapped. These uncertainties encompass those related to selecting a single elevation to represent
809 the position of a natural terrace tread (e.g. natural variations). Dip measurements along the SJT
810 fault geometry were estimated to be $\sim 1.5^\circ$ by considering the range of hanging wall reflector and
811 thrust dip orientations permissible while still producing a viable cross-section across the entire A-
812 A' section that is consistent with fault-bend folding (Suppe, 1983).

813 **Slip Rate Uncertainty**

814 The mean values of the terrace data across the Tugulu anticline indicate a maximum slip
815 rate of ~ 7.0 mm/yr at ~ 250 ka that has since decreased to a constant rate of ~ 1.3 mm/yr throughout
816 the Holocene. We assess our conclusion of a decelerating SJT slip rate with a straightforward f-
817 test simulation that considers terrace age uncertainties as well as fault slip uncertainties. For each
818 simulation, fit two functions to these data: 1st- and 2nd-order polynomials that both run through the
819 origin (e.g. Supplemental Figure 1A). For both functions we evaluate the model residuals:

$$820 \quad \chi^2 = \sum_i \frac{r_i^2}{\sigma_i^2}$$

821 where r_i are the slip residuals (e.g. Supplemental Figure 1B) and σ_i are the 1-sigma slip
822 uncertainties. When χ^2 for the 2nd-order polynomial fit is less than that for the 1st-order polynomial

823 fit to the data, a decelerating slip rate is considered to have passed our f-test. We run 5000
824 simulations that randomly draw from the terrace age distributions and perform the f-test for each
825 simulation. All 5000 2nd-order polynomial fits pass this f-test. Thus, a decelerating slip rate is a
826 more robust description of our terrace data than a linear slip rate model to describe the same data.

827 We further evaluate how well the 2nd-order polynomials describe the terrace data relative
828 to linear slip rate models by evaluating the modified Akaike Information Criterion (AICc):

829

$$830 \quad AICc = 2k - 2 \ln L + \frac{2k(k+1)}{n-k-1}$$

831

832 where k is the number of parameters in the model, L is the maximum of the likelihood function
833 for the studied model and n is the sample size. AIC can be used to evaluate the amount of
834 information lost by a describing a dataset. The modified form used here (AICc) incorporates a
835 penalty to avoid over-fitting to small datasets. The 2nd-order polynomial functions systematically
836 reduce the amount of lost information (lower AICc) relative to the constant slip rate functions
837 (Supplemental Figure 2). This indicates that the decreasing slip rate models described by the 2nd-
838 order polynomial functions to our terrace data and uncertainties are consistently a better fit than a
839 linear function to the same data.

840

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847

848 **REFERENCES**

- 849 Adamiec, G., Aitken, M., 1998. Dose-rate conversion factors: update. *Ancient TL*, v. 16, pp. 37-
850 50.
- 851
- 852 Amos, C. B., Burbank, D.W., Nobes, D. C., and Read, S.A.L., 2007, Geomorphic constraints on
853 listric faulting: implications for active deformation in the Mackenzie Basin, South Island,
854 New Zealand: *Journal of Geophysical Research*, v. 112, B03S11, 24 pp.
- 855
- 856 Arnold, L.J., Roberts, R.G., 2009, Stochastic modelling of multi-grain equivalent dose (D_e)
857 distributions: Implications for OSL dating of sediment mixtures: *Quaternary Geochronology*,
858 v. 4, pp. 204-230.
- 859
- 860 Avouac, J.P., Tapponnier, P., Bai, M., You, H., Wang, G., 1993, Active thrusting and folding
861 along the northern Tien Shan and late Cenozoic rotation of the Tarim relative to Dzungaria
862 and Kazakhstan: *Journal of Geophysical Research*, v. 98, no. B4, p. 6755-6804.
- 863
- 864 Benesh, N.P., 2010. The mechanics of fault-bend folding and tear-fault systems in the Niger
865 Delta: PhD Dissertation, Harvard University, 124 pp.
- 866
- 867 Benesh, N.P., Plesch, A., Shaw, J.H. and Frost, E.K., 2007, Investigation of growth fault bend
868 folding using discrete element modeling: Implications for signatures of active folding above
869 blind thrust faults: *Journal of Geophysical Research: Solid Earth*, v. 112(B3).
- 870
- 871 Bøtter-Jensen, L., C. E. Andersen, G. A. T. Duller, A. S. and Murray, 2003, Developments in
872 radiation, stimulation and observation facilities in luminescence measurements: *Radiation*
873 *Measurements*, v. 37, p. 535-541.
- 874
- 875 Brandenburg, J.P., 2013. Trishear for curved faults. *Journal of Structural Geology*, v. 53, p. 80-
876 94.
- 877

- 878 Brown, N.D., Rhodes, E.J., Antinao, J.L. and McDonald, E.V., 2015. Single-grain post-IR IRSL
879 signals of K-feldspars from alluvial fan deposits in Baja California Sur, Mexico. *Quaternary*
880 *International*, 362, pp.132-138.
881
- 882 Burchfiel, B.C., Brown, E.T., Deng, Q., Feng, X., Li, J., Molnar, P., Shi, J., Wu, Z., You, H.,
883 1999, Crustal shortening on the margins of the Tien Shan, Xinjiang, China: *International*
884 *Geology Review*, v. 41, no. 8, p. 665-700.
885
- 886 Buylaert, J.P., Murray, A.S., Thomsen, K.J., Jain, M., 2009. Testing the potential of an elevated
887 temperature IRSL signal from K-feldspar. *Radiation Measurements* 44, 560-565.
888
- 889 Charreau, J., J-P. Avouac, Y. Chen, S. Dominguez and S. Gilder (2008), Miocene to present
890 kinematics of fault-bend folding across the Huerguosi anticline, northern Tianshan (China),
891 derived from structural, seismic, and magnetostratigraphic data, *Geology*, 36, p. 871-874.
892
- 893 Chen, Y.-G., Lai, K.-Y., Lee, Y.-H., Suppe, J., Chen, W.-S., Lin, Y.-N. N., Wang, Y., Hung, J.-
894 H., Kuo, Y.-T., 2007, Coseismic fold scarps and their kinematic behavior in the 1999 Chi-
895 Chi earthquake Taiwan: *Journal of Geophysical Research*, vol. 112, B03S02, 15 pp.
896
- 897 Cook, K.L., Turowski, J.M. and Hovius, N., 2014, River gorge eradication by downstream sweep
898 erosion: *Nature Geoscience*, 7(9), pp.682-686.
899
- 900 Cristallini, E.O. and Allmendinger, R.W., 2002. Backlimb trishear: a kinematic model for curved
901 folds developed over angular fault bends. *Journal of Structural Geology*, 24(2), pp.289-295.
902
- 903 Cundall, P.A. and Strack, O.D., 1979. A discrete numerical model for granular assemblies.
904 *Geotechnique*, 29(1), pp.47-65.
905
- 906 Dahlstrom, C.D., 1970, Structural geology in the eastern margin of the Canadian Rocky
907 Mountains: *Bulletin of Canadian Petroleum Geology*, v. 18(3), pp.332-406.
908
- 909 Dolan, J.F., Christofferson, S., Shaw, J.H., 2003, Recognition of paleoearthquakes on the Puente
910 Hills blind thrust fault, Los Angeles, California: *Science*, v. 300, p. 115-118.
911
- 912 Erslev, E.A., 1991, Trishear fault propagation folding: *Geology*, v. 19, p. 617-620.
913
- 914 Finnegan, N. J., 2013, Interpretation and downstream correlation of bedrock river terrace treads
915 created from propagating knickpoints: *Journal of Geophysical Research: Earth Surface*, v.
916 118(1), p.54-64.
917
- 918 Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H. and Olley, J.M., 1999. Optical dating
919 of single and multiple grains of quartz from jinnium rock shelter, northern australia: part i,
920 experimental design and statistical models*. *Archaeometry*, 41(2), pp.339-364.
921

- 922 Gold, R.D., Cowgill, E., Wang, X.F. and Chen, X.H., 2006. Application of trishear fault-
923 propagation folding to active reverse faults: examples from the Dalong Fault, Gansu
924 Province, NW China. *Journal of Structural Geology*, 28(2), pp.200-219.
925
- 926 Gong, Z., Li, S. H., & Li, B., 2014, The evolution of a terrace sequence along the Manas River in
927 the northern foreland basin of Tian Shan, China, as inferred from optical dating:
928 *Geomorphology*, v. 213, p. 201-212.
929
- 930 Guan, S., Stockmeyer, J. M., Shaw, J.H., Plesch, A. and Zhang, J., 2016, Structural inversion,
931 imbricate wedging, and out-of-sequence thrusting in the southern Junggar fold-and-thrust
932 belt, northern Tian Shan, China: AAPG Bulletin, in press, DOI:10.1306/04041615023.
933
- 934 Hardy, S. and C. D. Connors, 2006, Short note: a velocity description of shear fault-bend
935 folding: *Journal of Structural Geology*, v. 28, no. 3, p. 536-543.
936
- 937 Hardy, S. and Poblet, J., 1994, Geometric and numerical model of progressive limb rotation in
938 detachment folds: *Geology*, v. 22(4), p. 371-374.
939
- 940 Hu, X., B. Pan, E. Kirby, H. Gao, Z. Hu, B. Cao, H. Geng, Q. Li, and G. Zhang, 2015, Rates and
941 kinematics of active shortening along the eastern Qilian Shan, China, inferred from deformed
942 fluvial terraces: *Tectonics*, v. 34(12), p. 2478–2493
943
- 944 Hubert-Ferrari, A., Suppe, J., Gonzalez-Mieres, R., Wang, X., 2007, Mechanisms of active
945 folding of the landscape (southern Tian Shan, China): *Journal of Geophysical Research*, v.
946 112, B03S09, 39 pp.
947
- 948 Hughes, A.N. and Shaw, J.H., 2014, Fault displacement-distance relationships as indicators of
949 contractional fault-related folding style: AAPG bulletin, v. 98(2), p.227-251.
950
- 951 Hughes, A.N. and Shaw, J.H., 2015. Insights into the mechanics of fault-propagation folding
952 styles. *Geological Society of America Bulletin*, 127(11-12), pp.1752-1765.
953
- 954 Hughes, A.N., Benesh, N.P. and Shaw, J.H., 2014. Factors that control the development of fault-
955 bend versus fault-propagation folds: Insights from mechanical models based on the discrete
956 element method (DEM). *Journal of Structural Geology*, 68, pp.121-141.
957
- 958 Huntley, D.J., Baril, M., 1997. The K content of the K-feldspar being measured in optical dating
959 or in thermoluminescence dating. *Ancient TL*, v. 15, pp. 11-13.
960
- 961 Huntley, D.J., Lamothe, M., 2001. Ubiquity of anomalous fading in K-feldspars and the
962 measurement and correction for it in optical dating. *Canadian Journal of Earth Science*, 38,
963 pp. 1093-1106.
964
- 965 Ishiyama, T., Mueller, K., Sato, H., & Togo, M. (2007). Coseismic fault-related fold model,
966 growth structure, and the historic multisegment blind thrust earthquake on the basement-
967 involved Yoro thrust, central Japan. *J. Geophys. Res.*, 112(B3), 22 pp.

- 968
969 Johnson, K.N. and Finnegan, N.J., 2015. A lithologic control on active meandering in bedrock
970 channels. *Geological Society of America Bulletin*, 127(11-12), pp.1766-1776.
971
- 972 Lavé, J., and Avouac, J.P., 2000, Active folding of fluvial terraces across the Siwaliks Hills,
973 Himalayas of central Nepal: *Journal of Geophysical Research*, v. 105, no. B3, p. 5735-5770.
974
- 975 Le Béon, M., Suppe, J., Jaiswal, M.K., Chen, Y.G. and Ustaszewski, M.E., 2014. Deciphering
976 cumulative fault slip vectors from fold scarps: Relationships between long-term and
977 coseismic deformations in central Western Taiwan. *Journal of Geophysical Research: Solid*
978 *Earth*, 119(7), pp.5943-5978.
979
- 980 Leon, L.A., Christofferson, S.A., Dolan, J.F., Shaw, J.H. and Pratt, T.L., 2007, Earthquake-by-
981 earthquake fold growth above the Puente Hills blind thrust fault, Los Angeles, California:
982 implications for fold kinematics and seismic hazard: *Journal of Geophysical Research: Solid*
983 *Earth*, v. 112(B3).
984
- 985 Leon, L.A., Dolan, J.F., Shaw, J.H. and Pratt, T.L., 2009, Evidence for large Holocene
986 earthquakes on the Compton thrust fault, Los Angeles, California: *Journal of Geophysical*
987 *Research: Solid Earth*, 114(B12).
988
- 989 Leonard, M. (2010), Earthquake fault scaling: self-consistent relating of rupture length, width,
990 average displacement, and moment release, *Bull. Seismol. Soc. Am.*, 100, 1971-1988,
991 doi:10.1785/0120090189.
992
- 993 Lu, H., Burbank, D. W., Li, Y., & Liu, Y. (2010). Late Cenozoic structural and stratigraphic
994 evolution of the northern Chinese Tian Shan foreland. *Basin Research*, 22(3), 249-269.
995
- 996 Medwedeff, D. A., 1989, Growth fault-bend folding at southeast Lost Hills, San Joaquin Valley,
997 California: *AAPG Bulletin*, v. 73(1), p. 54-67.
998
- 999 Medwedeff, D.A. and Suppe, J., 1997. Multibend fault-bend folding. *Journal of Structural*
1000 *Geology*, 19(3), pp.279-292.
1001
- 1002 Molnar, P., Brown, E.T., Burchfiel, B.C., Deng, Q., Feng, X., Li, J., Raisbeck, G.M., Shi, J., Wu,
1003 Z., Yiou, F., You, H., 1994, Quaternary Climate Change and the Formation of River Terraces
1004 across Growing Anticlines on the North Flank of the Tien Shan, China: *The Journal of*
1005 *Geology*, v. 102, p. 583-602.
1006
- 1007 Molnar, P. and Ghose, S., 2000. Seismic moments of major earthquakes and the rate of
1008 shortening across the Tien Shan. *Geophysical Research Letters*, 27(16), pp.2377-2380.
1009
- 1010 Morgan, J.K., 1999. Numerical simulations of granular shear zones using the distinct element
1011 method: 2. Effects of particle size distribution and interparticle friction on mechanical
1012 behavior. *Journal of Geophysical Research: Solid Earth*, 104(B2), pp.2721-2732.
1013

- 1014 Morgan, J.K., 2015. Effects of cohesion on the structural and mechanical evolution of fold and
1015 thrust belts and contractional wedges: Discrete element simulations. *Journal of Geophysical*
1016 *Research: Solid Earth*, 120(5), pp.3870-3896.
- 1017
- 1018 Mueller, K., J. Champion, M. Guccione, and K. Kelson, , 1999, Fault slip rates in the modern
1019 New Madrid seismic zone. *Science*, v. 286(5442), p.1135-1138.
- 1020
- 1021 Murray, A.S. and Wintle, A.G., 2000, Luminescence dating of quartz using an improved single-
1022 aliquot regenerative-dose protocol: *Radiation Measurements*, v. 32, p. 57-73.
- 1023
- 1024 Nelson, M.R., McCaffrey, R., Molnar, P., 1987, Source parameters for 11 earthquakes in the
1025 Tien Shan, Central Asia, determined by P and SH waveform inversion: *Journal of*
1026 *Geophysical Research*, v. 92, no. B12, p. 12629-12648.
- 1027
- 1028 Poisson, B., 2002. *Impact du climat et de la tectonique sur l'évolution géomorphologique d'un*
1029 *piémont-Exemple du piémont Nord du Tian Shan depuis la fin du Pléistocène* (Doctoral
1030 dissertation, Université Paris Sud-Paris XI).
- 1031
- 1032 Poisson, B. and Avouac, J.P., 2004, Holocene hydrological changes inferred from alluvial stream
1033 entrenchment in north Tian Shan (Northwestern China): *The Journal of Geology*, v. 112, p.
1034 231-249.
- 1035
- 1036 Pratt, T. L., Shaw, J. H., Dolan, J. F., Christofferson, S., Williams, R. A., Odum, J. K., Plesch,
1037 A., 2002, Shallow folding imaged above the Puente Hills blind-thrust fault, Los Angeles,
1038 California: *Geophysical Research Letters*, v. 29, p. 18-1 to 18-4.
- 1039
- 1040 Prescott, J., Hutton, J., 1994. Cosmic ray contributions to dose rates for luminescence and ESR
1041 dating: large depths and long-term time variations. *Radiation Measurements*, v. 23, pp. 497-
1042 500.
- 1043
- 1044 Rhodes, E.J., 2015. Dating sediments using potassium feldspar single-grain IRSL: Initial
1045 methodological considerations. *Quaternary International*, 362, pp.14-22.
- 1046
- 1047 Rich, J.L., 1934, Mechanics of low-angle overthrust faulting as illustrated by Cumberland thrust
1048 block, Virginia, Kentucky, and Tennessee: *AAPG Bulletin*, v. 18(12), pp.1584-1596.
- 1049
- 1050 Scharer, K.M., Burbank, D.W., Chen, J., Weldon, R.J., 2006, Kinematic models of fluvial
1051 terraces over active detachment folds: constraints on the growth mechanisms of the Kashi-
1052 Atushi fold system, Chinese Tian Shan: *Geological Society of America Bulletin*, v. 118, no.
1053 7-8, p. 1006-1021.
- 1054
- 1055 Seeber, L. and Sorlien, C.C., 2000. Listric thrusts in the western Transverse Ranges, California.
1056 *Geological Society of America Bulletin*, 112(7), pp.1067-1079.
- 1057
- 1058 Shaw, J.H., Connors, C., Suppe, J., eds., 2005, Seismic interpretation of contractional fault-
1059 related folds: An AAPG seismic atlas, *AAPG Studies in Geology* 53, 156 pp.

- 1060
1061 Shaw, J.H., F. Bilotti, and P. Brennan, 1999, Patterns of imbricate thrusting: Geological Society
1062 of America Bulletin, v. 111, p. 1140-1154.
1063
1064 Shaw, J.H. and J. Suppe, 1994, Active faulting and growth folding in the eastern Santa Barbara
1065 channel, California: Geological Society of America Bulletin, v. 100, no. 5, p. 607-626.
1066
1067 Shaw, J.H. and J. Suppe, 1996, Earthquake hazards of active blind-thrust faults under the central
1068 Los Angeles basin, California: Journal of Geophysical Research: Solid Earth, 101(B4), p.
1069 8623-8642.
1070
1071 Shaw, J.H., Hook, S.C. and Suppe, J., 1994. Structural trend analysis by axial surface mapping.
1072 *AAPG bulletin*, 78(5), pp.700-721.
1073
1074 Shaw, J.H., Plesch, A., Dolan, J.F., Pratt, T., Fiore, P., 2002, Puente Hills blind thrust system,
1075 Los Angeles basin, California: Bulletin of the Seismological Society of America, v. 92, p.
1076 2946-2960.
1077
1078 Smedley, R.K., Duller, G.A.T., Roberts, H.M., 2015. Bleaching of the post-IR IRSL signal from
1079 individual grains of K-feldspar: Implications for single-grain dating. *Radiation*
1080 *Measurements*, v. 79, pp. 33-42.
1081
1082 Stein, R.S., and King, G.C.P., 1984, Seismic potential revealed by surface folding: 1983
1083 Coalinga, California, earthquake: *Science*, v. 224, no. 4651, p. 869-872.
1084
1085 Stockmeyer, J. M., J. H. Shaw, and G. Shuwei, 2014, Seismic hazards of multisegment thrust-
1086 fault ruptures: insights from the 1906 Mw 7.4-8.2 Manas, China, Earthquake, *Seis. Res. Lett.*,
1087 v. 85, p. 801-808, doi: 10.1785/0220140026.
1088
1089 Strayer, L.M., Erickson, S.G. and Suppe, J., 2004. Influence of growth strata on the evolution of
1090 fault-related folds—distinct-element models.
1091
1092 Suppe, J., 1983, Geometry and kinematics of fault-bend folding: *American Journal of Science*, v.
1093 283, p. 684-721.
1094
1095 Suppe, J. and Medwedeff, D.A., 1990, Geometry and kinematics of fault-propagation folding:
1096 *Eclogae Geologicae Helvetiae*, v. 83, no. 3, p. 409-454.
1097
1098 Suppe, J., C. D. Connors, and Y. Zhang, 2004, Shear fault-bend folding, in: McClay, K.R., ed.,
1099 Thrust tectonics and hydrocarbon systems: *AAPG Memoir* 82, p. 303-323.
1100
1101 Suppe, J., F. Sabat, J. Muñoz, J. Poblet, E. Roca, and J. Vergés, 1997, Bed-by-bed fold growth
1102 by kink-band migration: Saint Llorenç de Morunys, eastern Pyrenees: *Journal of Structural*
1103 *Geology*, v. 19, no. 3-4, p. 443-461.
1104

- 1105 Suppe, J., G. T. Chou, and S. C. Hook, 1992, Rates of folding and faulting determined from
1106 growth strata, in K. R. McClay ed., Thrust tectonics: Springer, p. 105- 121.
1107
- 1108 Thiel, C., Buylaert, J.-P., Murray, A.S., Terhorst, B., Hofer, I., Tsukamoto, S., Frechen, M.,
1109 2011. Quaternary International 234, 23-31.
1110
- 1111 Thompson, C.T., Weldon, R.J., Rubin, C.M., Abdrakhmatov, K., Molnar, P., Berger, G.W.,
1112 2002, Late Quaternary slip rates across the central Tien Shan, Kyrgyzstan, central Asia:
1113 Journal of Geophysical Research, v. 107, no. B9, p. ETC 7-1–7-32.
1114
- 1115 Wells, D.L., and K.J. Coppersmith (1994), New empirical relationships among magnitude,
1116 rupture length, rupture width, rupture area, and surface displacement, *Bull. Seismol. Soc.*
1117 *Am.*, 94, 974-1002.
1118
- 1119 Yue, L.F., Suppe, J. and Hung, J.H., 2011, Two contrasting kinematic styles of active folding
1120 above thrust ramps, Western Taiwan: in Thrust Fault Related Folding (eds. McClay et al).
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1123 TABLES

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Table 1. Dosimetry data for individual samples and single-grain post-IR IRSL depositional ages for terraces.

Unit	Field code	% K	Th (ppm)	U (ppm)	Depth (m)	Latitude (°N)	Longitude (°E)	Elevation (m.a.s.l.)	Total dose rate (Gy/ka)	Terrace age (ka)
T8	TGL-T8-OSL10	2.0 ± 0.1	4.9 ± 0.2	1.38 ± 0.07	1.63	44.070	86.341	822	3.411 ± 0.171	
T8	TGL-T8-OSL11	2.0 ± 0.1	4.4 ± 0.2	1.44 ± 0.07	1.98	44.070	86.341	822	3.382 ± 0.171	4.0 ^{+3.2} / _{-1.8}
T8	TGL-T8-OSL12	1.5 ± 0.1	5.9 ± 0.3	1.61 ± 0.08	2.57	44.070	86.341	822	3.033 ± 0.139	
T6	TGL-T6-OSL7	2.2 ± 0.1	4.6 ± 0.2	1.45 ± 0.07	0.30	44.072	86.338	864	3.636 ± 0.190	
T6	TGL-T6-OSL8	2.0 ± 0.1	6.3 ± 0.3	1.80 ± 0.09	0.46	44.072	86.338	864	3.638 ± 0.177	5.6 ^{+4.1} / _{-2.4}
T6	TGL-T6-OSL9	1.9 ± 0.1	4.1 ± 0.2	1.44 ± 0.07	0.73	44.072	86.338	864	3.299 ± 0.164	
T5	TGL-T5-OSL4	2.1 ± 0.1	5.7 ± 0.3	1.96 ± 0.10	0.70	44.072	86.338	872	3.723 ± 0.183	
T5	TGL-T5-OSL5	1.9 ± 0.1	4.3 ± 0.2	1.67 ± 0.08	1.15	44.072	86.338	872	3.355 ± 0.165	9.4 ^{+5.1} / _{-3.3}
T5	TGL-T5-OSL6	2.1 ± 0.1	4.6 ± 0.2	1.59 ± 0.08	1.52	44.072	86.338	872	3.538 ± 0.179	
T4	TGL-T4-OSL1	2.7 ± 0.1	6.1 ± 0.3	1.90 ± 0.10	0.65	44.065	86.335	894	4.312 ± 0.227	
T4	TGL-T4-OSL2	1.9 ± 0.1	4.8 ± 0.2	1.61 ± 0.08	1.30	44.065	86.335	894	3.372 ± 0.165	
T4	TGL-T4-OSL3	2.0 ± 0.1	5.5 ± 0.3	1.70 ± 0.09	2.75	44.065	86.335	894	3.501 ± 0.173	17.5 ^{+13.4} / _{-7.6}
T4	TGL-T4-OSL13	2.0 ± 0.1	3.9 ± 0.2	1.50 ± 0.08	1.25	44.114	86.354	777	3.391 ± 0.170	
T4	TGL-T4-OSL14	1.8 ± 0.1	4.1 ± 0.2	1.51 ± 0.08	1.60	44.114	86.354	777	3.206 ± 0.156	
T3	TGL-T3-OSL15	2.1 ± 0.1	5.9 ± 0.3	2.99 ± 0.15	0.80	44.071	86.328	959	3.956 ± 0.188	
T3	TGL-T3-OSL16	2.1 ± 0.1	8.6 ± 0.4	2.78 ± 0.14	1.60	44.071	86.328	959	3.879 ± 0.180	46.3 ^{+23.6} / _{-15.6}
T3	TGL-T3-OSL17	2.0 ± 0.1	5.4 ± 0.3	1.85 ± 0.09	2.40	44.071	86.328	959	3.529 ± 0.174	
T2	TGL-T2-OSL19	1.5 ± 0.1	4.9 ± 0.2	2.40 ± 0.12	0.80	44.065	86.318	996	3.192 ± 0.143	
T2	TGL-T2-OSL20	2.2 ± 0.1	6.0 ± 0.3	2.35 ± 0.12	1.40	44.065	86.318	996	3.903 ± 0.192	106.4 ^{+76.6} / _{-44.5}
T2	TGL-T2-OSL21	2.1 ± 0.1	5.5 ± 0.3	2.17 ± 0.11	2.05	44.065	86.318	996	3.743 ± 0.184	
T1	TGL-T1-OSL23	2.2 ± 0.1	4.9 ± 0.2	1.71 ± 0.09	0.65	44.067	86.314	1084	3.753 ± 0.190	
T1	TGL-T1-OSL24	2.0 ± 0.1	5.8 ± 0.3	2.21 ± 0.11	1.30	44.067	86.314	1084	3.649 ± 0.176	182.1 ^{+39.2} / _{-32.3}
T1	TGL-T1-OSL25	2.1 ± 0.1	5.7 ± 0.3	2.28 ± 0.11	1.75	44.067	86.314	1084	3.769 ± 0.184	
T0	TGL-T0-OSL15	1.9 ± 0.1	5.2 ± 0.3	1.91 ± 0.10	0.69	44.069	86.309	1102	3.496 ± 0.168	
T0	TGL-T0-OSL16	1.9 ± 0.1	6.4 ± 0.3	2.27 ± 0.11	1.05	44.069	86.309	1102	3.652 ± 0.172	236.7 ^{+45.9} / _{-38.5}
T0	TGL-T0-OSL17	1.7 ± 0.1	5.8 ± 0.3	2.02 ± 0.10	0.77	44.069	86.309	1102	3.370 ± 0.156	

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1130TABLE 2. SJT FAULT SLIP FROM
HOLOCENE FAULT SCARPS

	T4	T5	T6
Age (ka)	17.50	9.40	5.60
z_4 (m)	61.80	50.02	35.13
z_{fw} (m)	46.83	41.52	29.72
h_4 (m)	14.97	8.50	5.41
θ_4 (°)	44.50	44.50	44.50
u_4 (m)	21.4	12.1	7.7

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1135TABLE 3. SJT FAULT SLIP FROM
QUATERNARY FOLD SCARPS

	T0	T1	T2	T3
Age (ka)	256.7	182.1	106.4	46.3
z_2 (m)	271.30	234.47	104.97	19.19
z_0 (m)	66.04	49.26	26.16	7.44
Δh_2 (m)	205.26	185.21	78.81	11.75
$\sin(\theta_2) - \sin(\theta_0)$	0.40	0.40	0.40	0.40
u_4 (m)	512.0	462.0	197.1	29.31

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1140TABLE 4. PHYSICAL PROPERTIES OF THE
MECHANICAL FAULT-BEND FOLD

Property	Pre-growth strata	Flexural slip surfaces	Growth strata	Fault surfaces	Boundary wall
Density (kg/m ³)	2500	2500	2500	n/a	n/a
Ball radii (m) [†]	30-40	22.5-30	22.5-30	n/a	n/a
k_n (N/m)	$6.0 \cdot 10^9$	$6.0 \cdot 10^9$	$6.0 \cdot 10^9$	$6.6 \cdot 10^9$	$6.6 \cdot 10^9$
k_s (N/m)	$6.0 \cdot 10^9$	$6.0 \cdot 10^9$	$6.0 \cdot 10^9$	n/a	n/a
μ [§]	0.30	0.00	0.30	0.10	0.45
E (GPa)	3.0	3.0	3.0	3.3	3.3
σ_c (MPa) [#]	10	0	10	n/a	n/a
τ_c (MPa) [#]	600	0	600	n/a	n/a
Layer thickness (m)	500	125	~250	n/a	n/a

[†]Randomly generated from a uniform distribution bounded by prescribed range.[§]Contact friction.[#]Contact bond strength; selected from a Gaussian distribution with a prescribed mean.

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1143 **FIGURE CAPTIONS**

1144 Figure 1: Fault-related fold models and their corresponding distance-displacement plots (Hughes
1145 and Shaw, 2014), including measures of surface slip (SS) and fault slip at depth (SD). A) Fault-
1146 bend folds (Suppe, 1983) predict constant fault slip up a thrust ramp. The absence of folding
1147 through this zone reflects the constant slip at depth along the thrust ramp. B) Simple shear fault-
1148 bend folds (Suppe et al., 2004) produce a wide, gentle fold limb above the pre-growth shear
1149 interval, where slip increases linearly up the thrust ramp. Note the lack of a fold limb outside of
1150 the shear interval, near the structural crest, where slip is constant. C) Fault propagation folds
1151 consume fault slip during fault tip propagation. The resultant slip gradient decreases linearly up a
1152 thrust ramp. In this latter case, SS can drastically underestimate SD. See text for details. Figure is
1153 modified from Hughes and Shaw (2014).

1154

1155 Figure 2: Kinematic models of terrace deformation. A) Classic fault-bend folding (Suppe, 1983)
1156 localizes folding across fault bends. Terrace folds develop by kink-band migration. B) Curved
1157 hinge fault-bend folds (Suppe et al., 1997) produce fold scarps due to differential uplift that is
1158 localized through the curved fault bend. Terrace folds grow by kink-band migration. C) Simple
1159 shear fault bend folds (Suppe et al., 2004) produce two dip panels of different magnitudes. More
1160 intense folding occurs across the fault bend by kink-band migration. Outboard of this zone across
1161 the pre-growth shear interval, more distributed folding occurs by limb rotation. D) Simple shear
1162 curved hinge fault-bend folds (Suppe et al., 2004) produce folds of similar styles as described in
1163 C but differ only due to kink-band migration across a curved fault zone of finite width, as described
1164 in B. E) Listric fault-related folds (Seeber and Sorlien, 2000; Amos et al., 2007) exhibit distributed

1165 folding by limb rotation across a listric fault ramp. In E, the region undergoing limb rotation is
1166 localized to the listric fault segment. See text for details.

1167

1168 Figure 3: A) Western China and major tectonic provinces. Black box outlines the southern Junggar
1169 basin. Imagery from Google Earth. B) False-color Landsat imagery of the southern Junggar basin
1170 study area. Imagery is displayed with bands 7-5-1 (R-G-B). C) Geologic map of surface geology
1171 and mapped terraces along the Taxi He valley, across the Tugulu anticline, mapped in the digital
1172 elevation model. Section A-A' is shown in Figure 5.

1173

1174 Figure 4: Field observations of fluvial terraces. A) Terraces are preserved across the entire extent
1175 of the Taxi He. B) A prominent fault scarp marks the surface-emergent SJT along the entire
1176 forelimb of each structure in southern Junggar (Avouac et al., 1993). This provides a record of
1177 surface faulting deformation. C) Older, discontinuous terraces in the backlimb of Tugulu provide
1178 the ability to quantify surface folding deformation from terrace geometries. Here, terrace treads
1179 are marked by the contact between the fluvial deposits below and loess cap above.

1180

1181 Figure 5: Structural interpretation of the SJT fault geometry and hanging wall fold structure across
1182 section A-A'. The geometry of the interpreted fault and hanging wall folds are consistent with a
1183 fault-bend fold (Suppe, 1983). Projecting axial surfaces (green dashes) to the Earth's surface
1184 provide a straightforward method for relating surface deformation observations to subsurface
1185 structure (e.g. Shaw et al., 1994). See text for details. Satellite imagery and digital elevation model
1186 are displayed at 3:1 vertical exaggeration. Seismic data is displayed at 1:1.

1187

1188 Figure 6: A) Raw terrace profiles used for structural analysis. T0 is the oldest mapped terrace; T6
1189 is the youngest. B) Residual profiles of the Holocene terraces (T4-T6) exhibit abrupt uplift and
1190 folding across several active axial surfaces implied by our structural interpretation (Figure 5).
1191 Little to no folding is apparent between fault bends. This structural relief is restored across the
1192 fault scarp. C) Residual profiles of the Quaternary terraces (T0-T3) are preserved across the
1193 southern-most SJT synclinal fault bends. However, they record tens to hundreds of meters of
1194 structural relief, developed by surface folding. See text for details. See Appendix B for details on
1195 terrace mapping and removing depositional gradients.

1196

1197 Figure 7: Terrace geochronology across the Taxi He valley. A Bayesian model assuming
1198 stratigraphic consistency of terraces is used to produce the posterior age distributions. See text for
1199 details.

1200

1201 Figure 8: Schematic diagram illustrating the different measures of fold scarp relief used to estimate
1202 fault slip since the time of terrace abandonment.

1203

1204 Figure 9: A) Fault slip estimates from Holocene terrace fold scarps across the Tugulu structure
1205 from (3). The slope of the best-fit linear regression line yields an estimate of total fault slip
1206 experienced by that terrace. The goodness of fit of each regression to the terrace folding data
1207 implies a single magnitude of fault slip readily explains all of the fold scarp deformation. B)
1208 Estimates of Holocene fault slip and slip rates from terrace faulting and terrace folding are
1209 indistinguishable. See text for details.

1210

1211 Figure 10: Mechanical model of a fault-bend fold (Benesh et al., 2007; Benesh, 2010). A) Set-up
1212 of the model geometry. Note the change in fault dip is consistent with the dip change across the
1213 southern most fault bends of the SJT. Model parameters are summarized in Table 4. B) Final result
1214 of the mechanical model after 3000 m of fault slip. Noteworthy observations include 1) pre-growth
1215 strata that parallel the fault ramp, consistent with kinematic prediction; 2) an upward narrowing
1216 growth fold triangle, which indicates folding by kink-band migration, consistent with the
1217 kinematic predictions; 3) uplift and folding is consistently initiated before reaching the fault bend,
1218 which is not predicted by the kinematic theory; and 4) a fanning of limb dips, indicating folding
1219 by limb rotation, which is not predicted by classic fault-bend folding theories.

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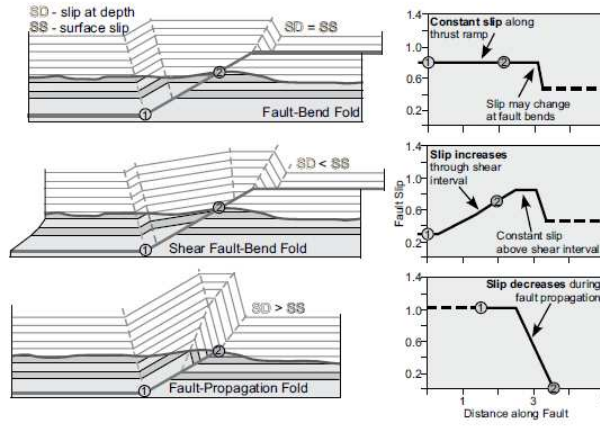
1221 Figure 11: A) Dip-slip relations for growth and pre-growth strata in the DEM model. The form of
1222 this relation is generalized as a 2nd-order polynomial function that goes through the origin. The
1223 constants of the functional form are sensitive to mechanical stratigraphy, grain size, thickness, and
1224 other natural heterogeneities. B) Estimates of fault slip versus the observed fault-dip for T1-T4
1225 and the pre-growth constraint for the critical slip required to develop the maximum hanging wall
1226 fold dip (Guan et al., 2016; their Figure 4). The slip for T0 can be estimated directly from this
1227 functional form. See text for discussion. Fault slip magnitudes for T1-T4 are from Tables 2 and 3.

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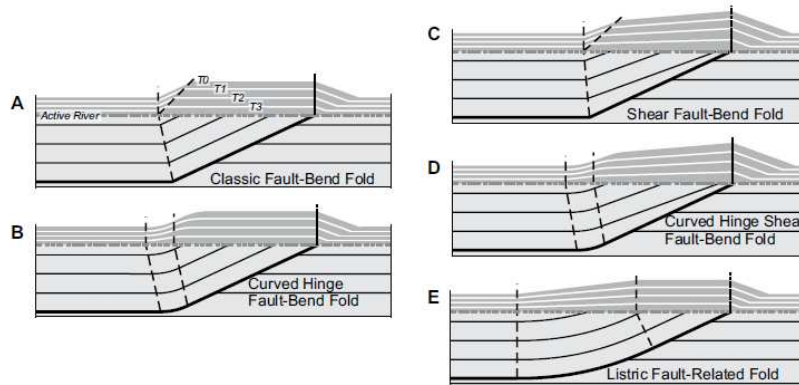
1229 Figure 12: Slip rate history for the SJT from 250 ka to present. SJT slip rate has decelerated
1230 considerably from the Late Quaternary (~7.0 mm/yr) to Holocene (~1.3 mm/yr). See text for
1231 details.

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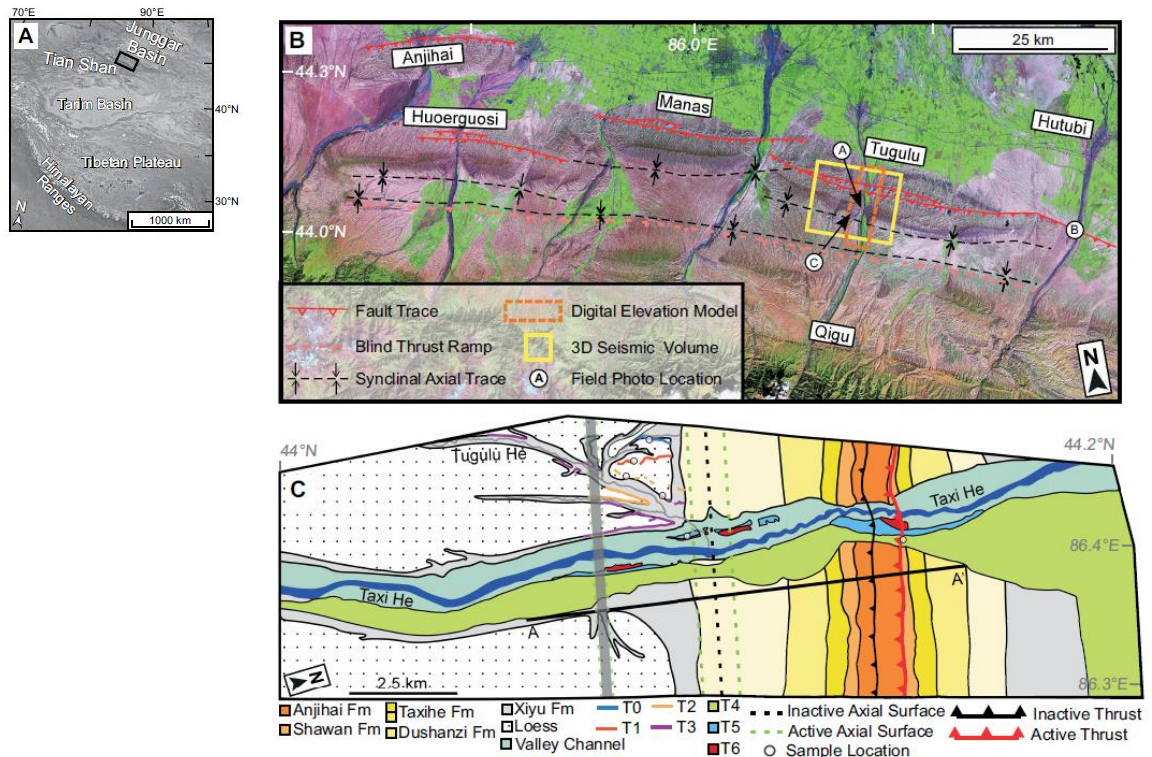
1233 Fig. 1



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1246 Fig. 3



1256 Fig. 4

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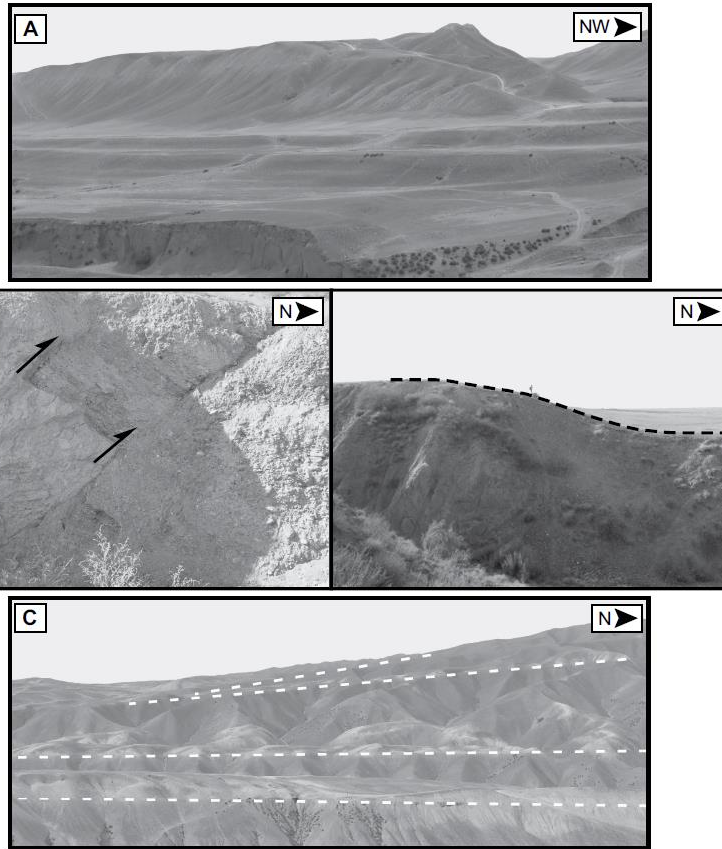
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1269 Fig. 5

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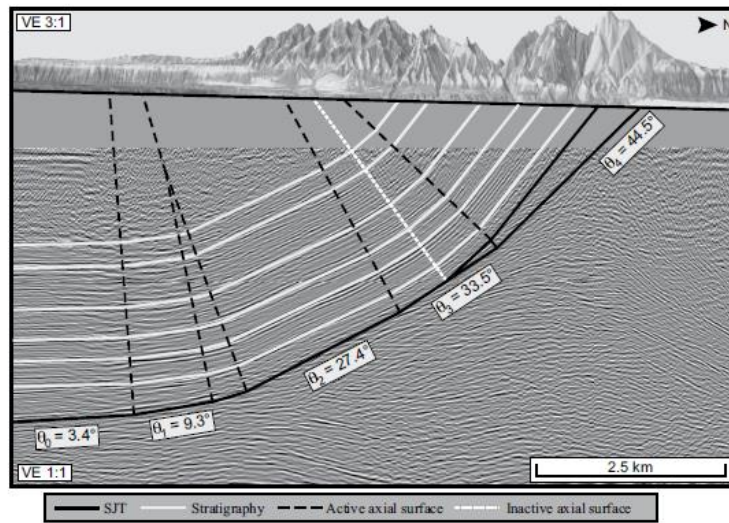
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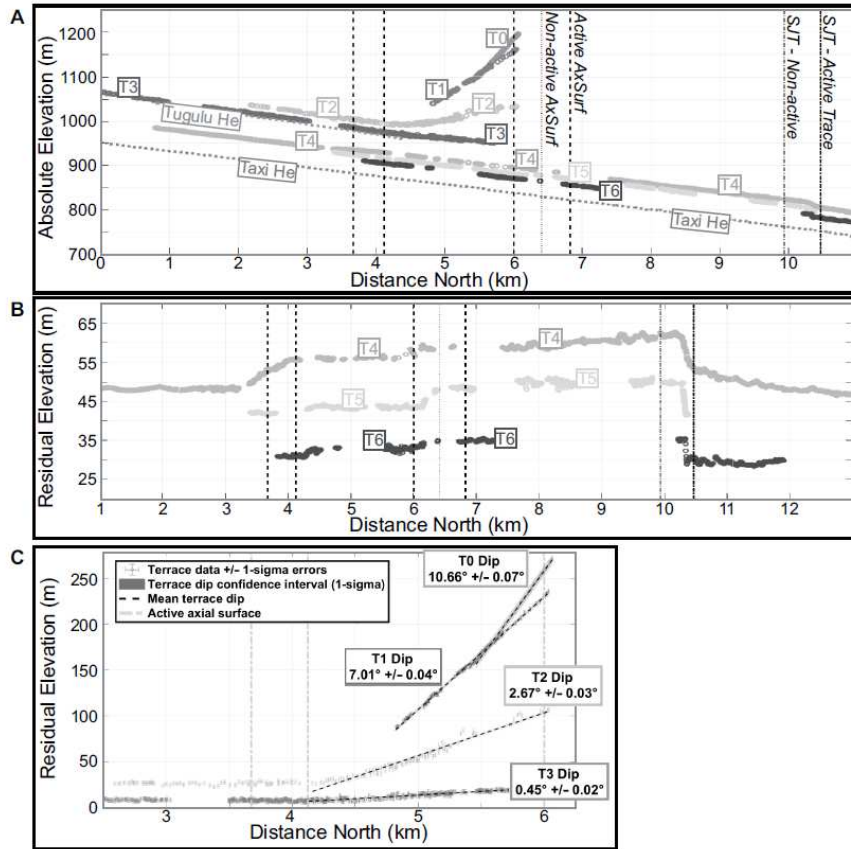
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1279 Fig. 6



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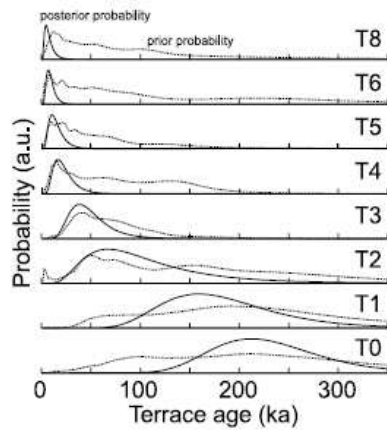
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1291 Fig. 7



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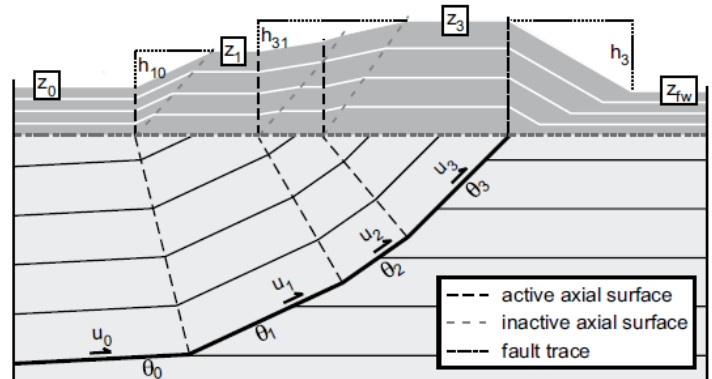
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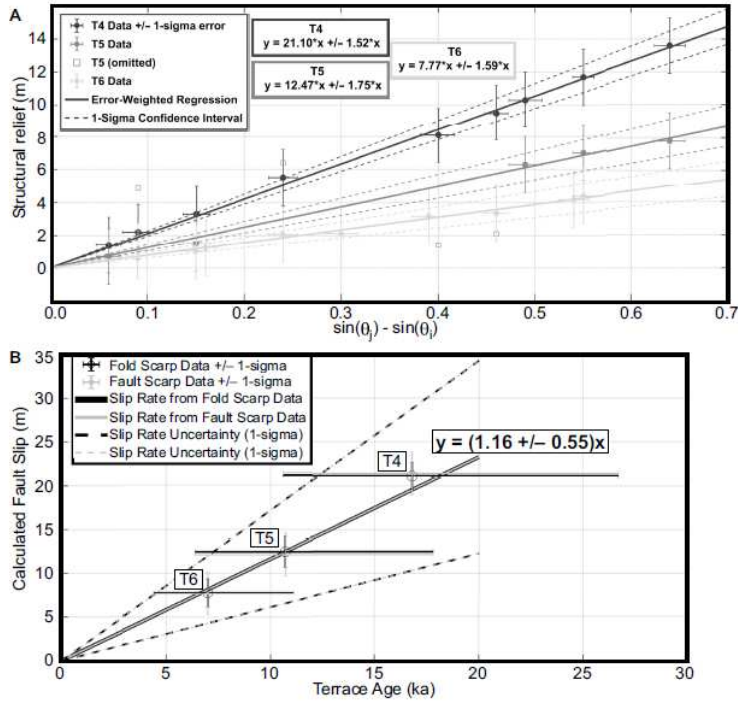
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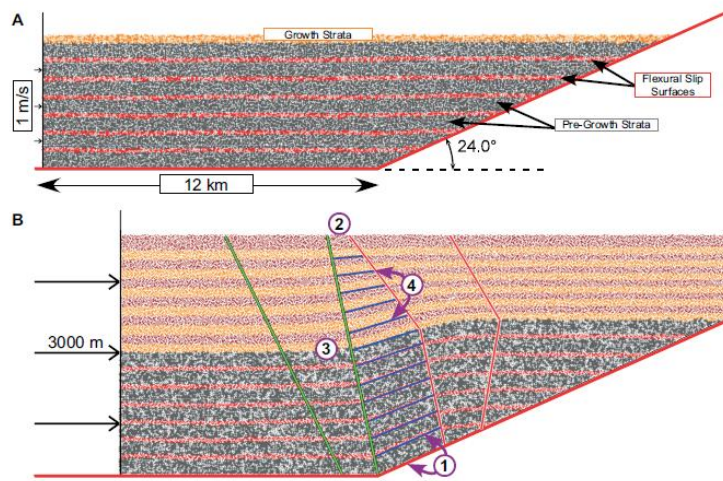
Fig. 8



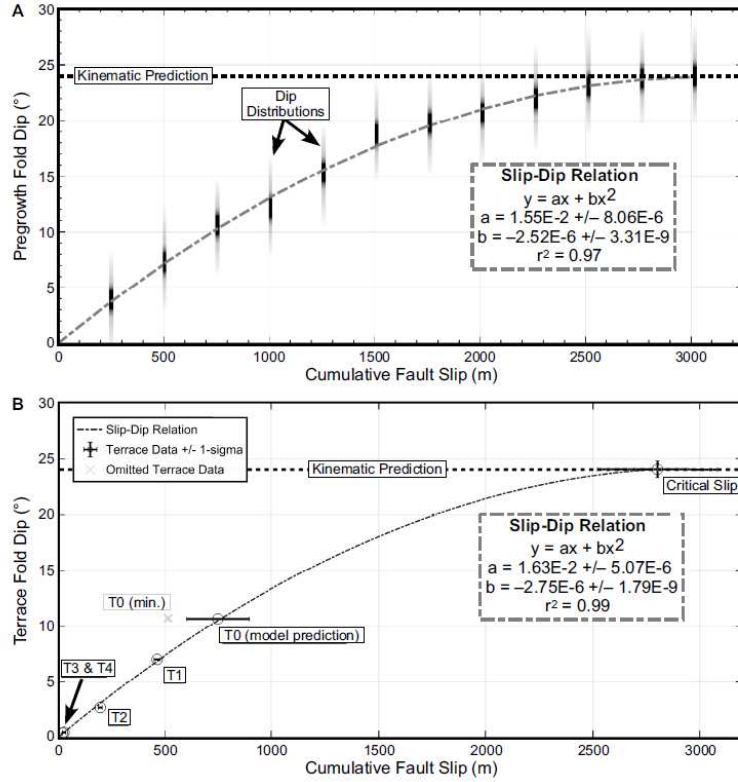
1302 Fig. 9



1312 Fig. 10



1325 Fig. 11



1336 Fig. 12

