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# Large-scale displacement along the Altyn Tagh Fault (North Tibet) since its Eocene initiation: Insight from detrital zircon U–Pb geochronology and subsurface data

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1 **Large-scale displacement along the Altyn Tagh Fault (North Tibet) since its**  
2 **Eocene initiation: insight from detrital zircon U-Pb geochronology and**  
3 **subsurface data**

4

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15

16 **Abstract**

17 Marking the northern boundary of the Tibetan plateau, the Altyn Tagh fault plays  
18 a crucial role in accommodating the Cenozoic crustal deformation affecting the  
19 plateau. However, its initiation time and amount of offset are still controversial  
20 despite being key information for the understanding of Tibet evolution. In this study,  
21 we present 1122 single LA-ICP-MS detrital zircon U-Pb ages obtained from 11  
22 Mesozoic to Cenozoic sandstone samples, collected along two sections in the  
23 northwestern Qaidam basin (Eboliang and Huatugou). These data are combined with  
24 new 3D seismic reflection profiles to demonstrate that: (1) From the Paleocene to  
25 early Eocene, the Eboliang section was approximately located near the present  
26 position of Anxi,  $360 \pm 40$  km southwest from its current location along the Altyn  
27 Tagh fault, and sediments were mainly derived from the Altyn Tagh Range. At the  
28 same period, the Huatugou section was approximately located near the present  
29 position of Tula, ca. 360 km southwest from its current location along the Altyn Tagh  
30 fault, and the Eastern Kunlun Range represented a significant sediment source. (2)  
31 Left-lateral strike-slip movement along the Altyn Tagh fault initiated during the  
32 early-middle Eocene, resulting in northeastward displacement of the two sections. (3)  
33 By early Miocene, the intensive deformation within the Altyn Tagh Range and  
34 northwestern Qaidam basin strongly modified the drainage system, preventing the  
35 materials derived from the Altyn Tagh Range to reach the Eboliang and the Huatugou  
36 sections. The post-Oligocene clastic material in the western Qaidam basin is generally

37 derived from local sources and recycling of the deformed Paleocene to Oligocene  
38 strata. From these data, we suggest enhanced tectonic activity within the Altyn Tagh  
39 Range and northwestern Qaidam basin since Miocene time, and propose an  
40 early-middle Eocene initiation of left-lateral strike-slip faulting leading to a  $360 \pm 40$   
41 km offset along the Altyn Tagh fault.

42 **Keywords:** Detrital zircon U-Pb geochronology, Cenozoic tectonics, North Tibet,  
43 Altyn Tagh fault, Qaidam basin.

44

## 45 **1. Introduction**

46 Two competing end-member mechanisms have been proposed to explain the  
47 accommodation of the ongoing convergence between India and Eurasia since the early  
48 Eocene collision: (1) a homogeneous crustal thickening of the Tibetan plateau (e.g.  
49 England and Houseman, 1989; Searle, 1996); and (2) an eastward extrusion of the  
50 Tibetan plateau and southeast Asia away from the indenting Indian plate (Molnar and  
51 Tapponnier, 1975; Peltzer and Tapponnier, 1988; Avouac and Tapponnier, 1993;  
52 Tapponnier, et al., 2001). The second model requires large-scale displacement along  
53 lithospheric strike-slip fault zones to allow extrusion of the Tibetan crust (e.g. Searle,  
54 1996; Tapponnier, et al., 2001). Marking the northern boundary of the Tibetan plateau  
55 (Fig. 1), the lithospheric-scale left-lateral strike-slip Altyn Tagh fault (ATF) plays a  
56 crucial role in accommodating the crustal deformation and appears to be an ideal field  
57 laboratory for ascertaining the dynamics of plateau formation (Molnar and

58 Tapponnier, 1975; Wittlinger et al., 1998; Jolivet et al., 1999, 2001; Yin and Harrison,  
59 2000; Yin et al., 2002; Searle et al., 2011). Understanding the kinematic pattern of the  
60 ATF, especially the exact Cenozoic initiation time and the amount of Cenozoic offset,  
61 is of major importance for unraveling the crustal accommodation processes within the  
62 plateau since the India-Eurasian collision and for deciphering the growth history of  
63 the entire Tibetan plateau.

64 Several authors proposed that a large scale Jurassic basement cooling event  
65 associated to tectonic exhumation affected a corridor along the ATF (e.g. Delville et  
66 al., 2001; Sobel et al., 2001; Wang et al., 2005). In addition, many researchers  
67 consider that deformation along the ATF initiated after the late Mesozoic, during the  
68 early Cenozoic, or even during the Neogene (e.g. Tapponnier et al., 1986; Jolivet et al.,  
69 1999; Chen et al., 2001; Jolivet et al., 2001; Yin et al., 2002; Wang et al., 2006a; Wu  
70 et al., 2012a, 2012b; Zhang et al., 2012, 2014a). Similarly, estimations of the total  
71 displacement along the ATF vary widely from ~1200 km to less than 90 km (e.g.  
72 Tapponnier et al., 1986; Wang, 1997; CSBS, 1992; Ritts and Biffi, 2000; Yin and  
73 Harrison, 2000; Yang et al., 2001; Yue et al., 2001; Chen et al., 2002; Yin et al., 2002;  
74 Cowgill et al., 2003; Gehrels et al., 2003a, 2003b; Darby et al., 2005; Yue et al., 2005;  
75 Searle et al., 2011; Cheng et al., 2015a). These tremendous discrepancies may be  
76 partially attributed to the immense size and extent of the Altyn Tagh Range, making it  
77 difficult to locate ideal piercing points to estimate the total displacement along the  
78 ATF. Furthermore, due to strong Cenozoic deformation, continuous Mesozoic to  
79 Cenozoic stratigraphic sections necessary to estimate the time of initiation of

80 left-lateral slip movement are seldom preserved (e.g. Yin and Harrison, 2000; Cheng  
81 et al., 2015a).

82 Detrital zircon analysis of a continuous, well dated stratigraphic succession has  
83 become a powerful tool for unraveling source to sink relationships and constraining  
84 the tectonic and topographic evolution of an area (e.g. Fedo et al., 2003; Thomas,  
85 2011; Gehrels, 2014). To bring more constraints on the kinematic evolution of the  
86 ATF, we conducted an integrated analysis on two Jurassic to Pleistocene sedimentary  
87 sections in the western part of the Qaidam basin, adjacent to the ATF (Fig. 2). We  
88 then combined the detrital zircon U-Pb geochronology data obtained from these  
89 sections with high-quality subsurface data, including newly acquired seismic profiles  
90 and drill core sandstone samples.

## 91 **2. Geological Background**

### 92 *2.1 Altyn Tagh Range*

93 The Altyn Tagh Range is located along the northern edge of the Tibetan plateau,  
94 separating the Tarim basin to the northwest from the Tibetan plateau and the Qaidam  
95 basin to the south (Figs. 1 and 2). The bedrock of the Altyn Tagh Range mainly  
96 consists of Precambrian igneous and metamorphic rocks and Paleozoic igneous and  
97 sedimentary rocks (e.g. Sobel and Arnaud, 1999; Yin et al., 2002). It has been shown  
98 that the Altyn Tagh Range experienced multiple-stage deformation and tectonic  
99 exhumation from the Jurassic to the Holocene (Tapponnier et al., 1986; Jolivet et al.,  
100 1999; Yue and Liou, 1999; Chen et al., 2001; Delville et al., 2001; Jolivet et al., 2001;

101 Sobel et al., 2001; Yin et al., 2002; Wang et al., 2005, 2006a; Zhang et al., 2012).  
102 Within this range, the over 1600 km long ENE-trending ATF links the western  
103 Kunlun thrust belt to the southwest and the Qilian Shan thrust belt to the northeast  
104 (Fig. 1; Burchfiel et al., 1989; Wang, 1997; Yue and Liou, 1999; Yin and Harrison,  
105 2000; Yin et al., 2002). Although Mesozoic shearing occurred in the Altyn Tagh  
106 Range, the growth of the northern Tibetan plateau is largely influenced by Cenozoic  
107 sinistral strike-slip faulting along the ATF (Tapponnier et al., 1986, 2001; Arnaud et  
108 al., 2003; Wang et al., 2005; Li et al., 2006; Liu et al., 2007). As previously  
109 mentioned, the estimation of the total displacement along the fault remains heavily  
110 debated, varying from about 1200 km to less than 90 km (e.g. CSBS, 1992; Ritts and  
111 Biffi, 2000; Yang et al., 2001; Chen et al., 2002; Cowgill et al., 2003; Gehrels et al.,  
112 2003a, 2003b; Yue et al., 2005; Cheng et al., 2015a).

## 113 2.2 *Qaidam basin*

114 The rhomb-shaped Qaidam basin is the largest petroliferous basin within the  
115 entire Tibetan plateau (Figs. 1 and 2). Geomorphologically, the basin is surrounded by  
116 the Altyn Tagh Range to the northwest, the Qilian Shan to the northeast and the  
117 Eastern Kunlun Range to the south. Geological mapping and petroleum exploration  
118 revealed that the Qaidam basin is filled with Mesozoic to Cenozoic clastic sediments  
119 unconformably overlying a poorly documented basement (Xia et al., 2001; Meng and  
120 Fang, 2008; Yin et al., 2008a, 2008b; Zhang et al., 2013a). The Mesozoic strata,  
121 especially the Jurassic and lower Cretaceous sequences, are mainly distributed along  
122 the foreland of both the Altyn Tagh Range and the Qilian Shan (Ritts et al., 1999; Wu

123 et al., 2011), while the Cenozoic series are generally deposited over the entire basin  
124 (Yin et al., 2008b). The Cenozoic sedimentation pattern is largely controlled by a  
125 succession of depocenters consistently located along the long axis of the basin and  
126 gradually migrating eastward since Eocene times, indicating the gradual uplift of the  
127 Altyn Tagh Range (Fig. 1; Song and Wang, 1993; Qiu, 2002; Sun et al., 2005; Wang  
128 et al., 2006a; Yin et al., 2008b). Using magnetostratigraphy, palynology and  
129 paleontology, the Mesozoic-Cenozoic strata have been precisely subdivided into 11  
130 chronostratigraphically constrained units (Fig. 3; Huo, 1990; QBGMR, 1991; Yang et  
131 al., 1992; Huang et al., 1996; Xia et al., 2001; Qiu, 2002; Deng et al., 2004a, 2004b;  
132 Sun et al., 2005; Zhang, 2006; Zhao et al., 2006; Fang et al., 2007; Sun et al., 2007;  
133 Yin et al., 2008b; Gao et al., 2009; Pei et al., 2009; Lu and Xiong, 2009; Ke et al.,  
134 2013). These units are: (1) the Dameigou Formation,  $J_{1+2d}$ ; (2) the Caishiling  
135 Formation,  $J_{3c}$ ; (3) the Quanyagou Formation,  $Kq$ ; (4) the Lulehe Formation,  
136  $E_{1+2l}$ , >53.5 - 43.8 Ma (Yang et al., 1992; Zhang, 2006; Ke et al., 2013); (5) the lower  
137 Xiaganchaigou Formation,  $E_3^1xg$ , 43.8 - 37.8 Ma (Zhang, 2006; Sun et al., 2007; Pei  
138 et al., 2009); (6) the upper Xiaganchaigou Formation,  $E_3^2xg$ , 37.8 - 35.5 Ma (Sun et  
139 al., 2005; Sun, 2007; Pei et al., 2009); (7) the Shangganchaigou Formation,  $N_{1sg}$ , 35.5  
140 - 22.0 Ma (Sun et al., 2005; Lu and Xiong, 2009); (8) the Xiayoushashan Formation,  
141  $N_2^1xy$ , 22.0 - 15.3 Ma (Fang et al., 2007; Lu and Xiong, 2009); (9) the  
142 Shangyoushashan Formation,  $N_2^2sy$ , 15.3 - 8.1 Ma (Fang et al., 2007); (10) the  
143 Shizigou Formation,  $N_2^3s$ , 8.1 - 2.5 Ma (Fang et al., 2007); (11) the Quaternary  
144 deposits, including the Qigequan Formation ( $Q_{1q}$ ) and the Dabuxun-Yanqiao

145 Formation (Q<sub>2d</sub>), 2.5 - 0.01 Ma (Fang et al., 2007; Yin et al., 2008b). Effective elastic  
146 thickness calculation implies that the mechanical strength of the Qaidam crust is  
147 exceptionally strong compared to the rest of the Tibetan plateau (Braitenberg et al.,  
148 2003). Based on balanced cross section results, Zhou et al. (2006) proposed that the  
149 Qaidam basin experienced an average of 10% of NE-SW shortening during the  
150 Cenozoic, whereas Yin et al. (2008b) suggested that the shortening strain across the  
151 basin decreases systematically eastward from ca. 48% in the west, to ca. 11% in the  
152 center, and <1% in the east.

### 153 **3. Stratigraphy and sedimentary characteristics of the studied sections**

154 In this study, the Eboliang and Huatugou sections, situated along the eastern and  
155 central segments of the ATF, have been chosen for their exceptional preservation and  
156 exposure of the Jurassic to Pleistocene sedimentary series (Figs. 2 and 3). In order to  
157 give a continuous description of the Jurassic to Quaternary sediment evolution of the  
158 northwestern Qaidam basin, we constructed the Eboliang and Huatugou sections  
159 based on the lithologies, sediment facies and paleocurrent directions obtained from  
160 fieldwork, drill-core and literature data as summarized in the Figure 3 and in the text  
161 below. The stratigraphy of the Huatugou and Eboliang sections has already been  
162 established by previous field geological studies which give age constrains based on  
163 fossil assemblages, distinctive lithology feature, magnetostratigraphy, palynology and  
164 paleontology (e.g. XBGRM, 1993; HGSI, 2003; IGSQP, 2004). Consequently, we  
165 follow the previous division of formations.

166 *3.1 Eboliang section*

167 The Eboliang section is located along the southern flank of the Altyn Tagh Range  
168 (Fig. 2). The upper Jurassic-Cretaceous strata are missing, and the Paleogene deposits  
169 rest unconformably on lower - middle Jurassic series. Except for the absence of the  
170 Paleocene Lulehe Formation, the Cenozoic sequence is complete and exceptionally  
171 well exposed.

172 High-quality seismic profiles and drill core data reveal that the base of the  
173 Eboliang section is formed by the lower to middle Jurassic Dameigou Formation  
174 ( $J_{1+2d}$ ), resting unconformably on the basement rocks (Yin et al., 2008). This Jurassic  
175 sequence generally contains a succession of three well-developed fining upward  
176 cycles. Each cycle characteristically begins with medium- to coarse-grained sandstone  
177 deposits (Fig. 4A), fining upwards to silty mudstone. The sequence, as in general for  
178 the Qaidam basin, is considered to represent shore shallow lacustrine facies at the  
179 base, evolving into flood plain sediments upward (Ritts et al., 1999; Ritts and Biffi,  
180 2000; Wu et al., 2011; Jian et al., 2013). Trough and planar cross-stratification and  
181 clast imbrication from those Jurassic fluvial strata indicates northward paleoflows  
182 (Fig. 3; Ritts and Biffi, 2000).

183 The entire upper Jurassic and Cretaceous sequence is missing and the Paleocene  
184 Lulehe Formation ( $E_{1+2l}$ ) unconformably overlies the lower and middle Jurassic  
185 series (Wu et al., 2011). The strata are composed of dark brown mudstone (Fig. 4B)  
186 and sandy mudstone intercalated with gray siltstone at the base, evolving towards  
187 brown pebbly sandstone intercalated with conglomerates and gypsum-salt layers in

188 the middle and upper parts of the section. The Lulehe Formation is generally  
189 interpreted as braided river and alluvial fan depositional environments (Zhuang et al.,  
190 2011; Jian et al., 2013; Song et al., 2013). Based on heavy mineral contents,  
191 calculated zircon-tourmaline-rutile (ZTR) indices, and the heavy mineral assemblages  
192 from drill-core samples from a large number of oil wells in the Eboliang section, Fu et  
193 al. (2013) suggested that during the deposition of the Paleocene-early Eocene Lulehe  
194 Formation, the material deposited in the Eboliang area was derived from the north,  
195 probably from the Altyn Tagh Range.

196 The Eocene to Oligocene strata of the Xiaganchaigou Formation unconformably  
197 rest on the Lulehe Formation. The strata are mainly composed of grey and brown  
198 sandstone (Fig. 4C) and conglomerate at the bottom corresponding to alluvial facies  
199 deposits (Zhuang et al., 2011; Jian et al., 2013; Wang et al., 2013) and contain a  
200 succession of fining upward cycles. The middle part of the Xiaganchaigou Formation  
201 is dominated by brownish red mudstone and sandy mudstone intercalated with gray  
202 calcareous mudstone and marlstone. The upper part of the Xiaganchaigou Formation,  
203 however, is dominated by variegated mudstone intercalated with thin-layers of sandy  
204 conglomerate, sandstone and limestone, generally associated to a lacustrine  
205 depositional environment (Zhuang et al., 2011; Jian et al., 2013; Wang et al., 2013).  
206 Conglomerate fabrics in the Eboliang area show north-directed or south-directed  
207 bilateral paleoflows, suggesting a low-energy lacustrine-offshore environment at the  
208 time (Fig. 3; Wu et al., 2012b).

209 The Oligocene Shangganchaigou Formation ( $N_{1sg}$ ), conformably rests on the

210 Xiaganchaigou Formation. It consists of brownish red, gray siltstone, grey mudstone,  
211 sandy mudstone and siltstone, intercalated with gray sandstone and marlstone (Fig.  
212 4D) mostly corresponding to lacustrine sediment facies (Zhuang et al., 2011; Jian et  
213 al., 2013; Wang et al., 2013). Paleocurrents measured from the conglomerate fabrics  
214 become dominantly south-directed away from the Altyn Tagh Range (Fig. 3; Wu et al.,  
215 2012b).

216 The early Miocene Xiayoushashan Formation ( $N_2^1xy$ ) conformably lies on the  
217 Shangganchaigou Formation. The lower part of the formation is composed of gray  
218 and brownish red mudstone and sandy mudstone intercalated with gray siltstone,  
219 grayish yellow sandstone and grayish brown marlstone. It evolves upwards to gray  
220 mudstone, argillaceous sandstone and argillaceous siltstone intercalated with grey  
221 siltstone, brownish red mudstone and gray marlstone (Fig. 4E). The early Miocene  
222 sequence in the north Qaidam basin is generally considered as deposited in a fluvial to  
223 marginal lacustrine environment (Zhuang et al., 2011; Jian et al., 2013; Wang et al.,  
224 2013). Conglomerate fabrics in the section suggest south-directed paleocurrents  
225 during the early Miocene (Fig. 3; Wu et al., 2012b).

226 The late Miocene Shangyoushashan Formation ( $N_2^2sy$ ) conformably rests on the  
227 Xiayoushashan Formation. The deposits are mainly composed of grey mudstone and  
228 sandy mudstone intercalated with grey argillaceous sandstone, argillaceous siltstone,  
229 grayish yellow marlstone and some limited gray sandy limestone corresponding again  
230 to a fluvial to marginal lacustrine environment (Zhuang et al., 2011; Jian et al., 2013;  
231 Wang et al., 2013). Paleocurrent measurements from the sandstone layers around the

232 Eboliang area indicate southwest-directed paleoflows (Fig. 3; Wu et al., 2012b).

233 The Pliocene Shizigou Formation ( $N_2^3s$ ) generally conformably and locally  
234 unconformably rests on the Shangyoushashan Formation. The series are composed of  
235 gray mudstone and silty mudstone intercalated with brown siltstone, pebbly sandstone  
236 and gypsum-salt layers. They are generally interpreted as deposited in a marginal  
237 lacustrine to alluvial fan environment (Fig. 4F; Zhuang et al., 2011; Heermance et al.,  
238 2013; Jian et al., 2013; Wang et al., 2013). Trough cross-bedding within the strata  
239 suggests generally southwestward paleoflows during the Pliocene (Fig. 3; Heermance  
240 et al., 2013).

241 Finally, the Pleistocene sequence, dominated by the Qigequan Formation ( $Q_{1q}$ ),  
242 unconformably overlies the Shizigou Formation. The sediments are characterized by  
243 brown sandstone, pebbly sandstone and conglomerate intercalated with gypsum layers,  
244 corresponding to fluvial to evaporitic lacustrine facies (Heermance et al., 2013; Jian  
245 et al., 2013). Well-developed cross-beddings within the strata show primarily  
246 southward unidirectional paleocurrents (Fig. 3; Heermance et al., 2013).

### 247 *3.2 Huatugou section*

248 The Huatugou section is located in the northernmost part of the prominent  
249 Yingxiongling uplift structure (Fig. 2). Except again for the Paleocene Lulehe  
250 Formation, the whole Mesozoic-Cenozoic sequence is well exposed (Figs. 2 and 3).

251 Subsurface data reveal that the Jurassic clastic coal-bearing strata rest  
252 unconformably on the Altyn Tagh Range basement (Xia et al., 2001; Yin et al., 2008).  
253 The Dameigou Formation ( $J_{1+2d}$ ) is dominated by a set of sandstone beds interbedded

254 with conglomerate, siltstone and mudstone (Ritts et al., 1999; Ritts and Biffi, 2000).  
255 The sediment facies vary from fluvial to shallow lake deposits (Ritts and Biffi, 2000).  
256 Trough and planar cross-stratification as well as clast imbrication within the strata  
257 indicate northward paleoflows during the Jurassic (Fig. 3; Ritts and Biffi, 2000).

258 Based on the subsurface data (core and seismic profile data), the Paleocene to  
259 early Eocene Lulehe Formation ( $E_{1+2l}$ ) is dominated by successions of purple-red  
260 conglomerate interbedded with sandstone at the base, evolving upward towards grey  
261 sandstone, siltstone and sandy mudstone. The sediment facies vary from fluvial to  
262 shallow lake deposits upward and basinward (Fu et al., 2013; Li et al., 2015). Heavy  
263 mineral contents in surface samples, calculated zircon-tourmaline-rutile (ZTR) indices,  
264 and the heavy mineral assemblages from the drill-core samples from a large number  
265 of oil wells in the Huatugou area suggest that during the deposition of the  
266 Paleocene-early Eocene Lulehe Formation, the material deposited in that area was  
267 mainly derived from the southwest, probably from the Eastern Kunlun Range (Fu et  
268 al., 2013; Li et al., 2015).

269 The middle Eocene lower Xiaganchaigou Formation ( $E_3^1xg$ ) is mainly composed  
270 of grey-green, brownish-red sandstone and pebbly sandstone at the base, evolving  
271 upward towards brown red sandstone and siltstone (Fig. 4G). The sediment facies  
272 vary from fluvial to shallow lacustrine deposits upward (Zhuang et al., 2011; Wu et al.,  
273 2012a, 2012b). Paleocurrents measurements based on pebble imbrication and  
274 cross-stratification in the fluvial sandstone layers indicate NE-directed paleoflows  
275 (Fig. 3; Meng and Fang, 2008).

276 The late Eocene upper Xiaganchaigou Formation ( $E_3^2xg$ ) rests conformably on the  
277 lower Xiaganchaigou Formation. This sequence is dominated by successions of  
278 grey-green, brownish-red mudstone and carbonaceous siltstone, intercalated with  
279 argillaceous siltstone and marlstone (Fig. 4H). The sediment facies vary upward from  
280 braided river to shallow lake deposits (Wu et al., 2012a, 2012b). Clast imbrications  
281 within the fluvial strata suggest that paleocurrents were directed towards the south  
282 during the deposition of the upper Xiaganchaigou Formation. (Fig. 3; Wu et al.,  
283 2012a).

284 The Oligocene Shangganchaigou Formation ( $N_1sg$ ), conformably resting on the  
285 upper Xiaganchaigou Formation, is mainly composed of greyish-green carbonaceous  
286 mudstone and sandstone interbedded with grey-white mudstone. This series is  
287 dominated by deltaic to shallow lake facies deposits (Wu et al., 2012a, 2012b).  
288 Reported paleocurrents from clast imbrications are generally directed towards the  
289 south (Fig. 3; Wu et al., 2012a).

290 The Xiayoushashan Formation ( $N_2^1xy$ ), conformable with the Shangganchaigou  
291 Formation, is mainly composed of yellowish-brown, pebbly sandstone, sandstone and  
292 argillaceous siltstone with intercalations of limestone. The facies vary from shallow  
293 lake to fluvial deposits (Wu et al., 2012a, 2012b). Clast imbrications within the  
294 sequences suggest generally southwestward paleoflows during the early Miocene.

295 The Shangyoushashan Formation ( $N_2^2sy$ ), resting unconformably on the  
296 Xiayoushashan Formation (Wang et al., 2010), mainly consists of yellow pebbly  
297 sandstone, sandstone and silty mudstone. The sediment facies is dominated by

298 shallow lake, alluvial plain and braided river deposits (Wu et al., 2012a, 2012b). Clast  
299 imbrication as well as trough (and lesser planar) cross-stratification within the layers  
300 in the section suggest generally northwestward paleoflows (Zhuang et al., 2011).

301 The Shizigou Formation ( $N_2^3s$ ), again lying unconformably on the  
302 Shangyoushashan Formation, is mainly composed of earth-yellow sandstone and silty  
303 mudstone corresponding to fluvial facies sediments (Wu et al., 2012a, 2012b).  
304 Paleocurrents from clast imbrications indicate generally south-directed paleoflows  
305 away from the Altyn Tagh Range during the deposition of the Shizigou Formation  
306 (Fig. 3; Zhuang et al., 2011).

307 The Qigequan ( $Q_{1q}$ ) and Dabuxun-Yanqiao ( $Q_2$ ) formations, unconformably  
308 overly the Shizigou Formation, and mainly consists of grey and brown sandstone and  
309 conglomerate corresponding to flood plain and alluvial facies deposits.

#### 310 **4. Methods and analytical procedures**

##### 311 *4.1 Detrital zircon geochronology*

312 Detrital zircon U-Pb geochronology has rapidly developed into a very powerful  
313 tool for determining sediment provenances (e.g. Fedo, et al., 2003; Thomas, 2011; Liu  
314 et al., 2013; Yang et al., 2013; Gehrels et al., 2014; Cheng et al., 2015a). By  
315 systematically comparing the detrital zircon U-Pb age spectrum obtained from  
316 sedimentary sequences in basins with the known ages of potential source terranes, it is  
317 possible to describe the source to sink relations through time within a given area and  
318 to reconstruct the landscape evolution of the region (e.g. Fedo, et al., 2003; Gehrels et

319 al., 2011; Thomas, 2011; Liu et al., 2013; Yang et al., 2013; Gehrels et al., 2014;  
320 Yang et al., 2014; Cheng et al., 2015a). In the Eboliang section, eight samples were  
321 collected, ranging in age from Jurassic to Pleistocene (Fig. 2), and including three  
322 samples from drill cores. In the Huatugou section, three core samples were obtained  
323 from drill wells, ranging in age from Paleocene to Oligocene. In order to derive a  
324 continuous Jurassic to Pleistocene source to sink relation between the Altyn Tagh  
325 Range and the western Qaidam basin, we also integrated six published detrital zircon  
326 U-Pb dating results obtained on samples collected from the Huatugou section (Cheng  
327 et al., 2015a, 2016). The major petrological characteristics of all the samples are  
328 described in Table 1.

329 Zircon grains for U-Pb age dating were concentrated from each sample following  
330 the standard procedures outlined in Liu et al. (2013). This work was conducted at the  
331 Chengxin Geology Service Co. Ltd, Langfang, Hebei Province, China. Individual  
332 zircon crystals (generally more than 200 grains) were mounted in epoxy resin without  
333 handpicking to avoid sampling bias. Samples were then polished to obtain a smooth  
334 flat internal surface. Reflected and transmitted light as well as cathodoluminescence  
335 (CL) images were made to reveal internal heterogeneities and allow choosing  
336 potential internal targets for isotopic dating. U-Pb analysis was performed on an  
337 Agilent 7500a ICP-MS connected to an American New Wave UP 193 SS 193 nm  
338 Excimer laser ablation system at the China University of Geosciences, Beijing. All  
339 samples were analyzed using a laser spot size of 36  $\mu\text{m}$  and a frequency of 10 Hz.  
340 Two standards (Black et al., 2003; Qi et al., 2005) were analyzed every 10 to 20

341 grains, to correct for instrument fluctuations and determine fractionation factors.  
342 Zircons Qinghu and 91500 (Wiedenbeck et al., 1995) were the monitoring standards.  
343 For elemental concentration analysis, NIST610 was the external standard, and  $^{29}\text{Si}$   
344 was the internal standard. Meanwhile, NIST612 and NIST614 were used as  
345 monitoring standards. The GLITTER 4.4 software was used to calculate the U-Pb  
346 isotope ratios and element contents (China University of Geosciences, Lab. of Prof.  
347 Y.S. Liu, Beijing, China). The U-Pb ages obtained were checked for discordance by  
348 plotting the analyses on concordia diagrams using the Isoplot 3.0 software (Ludwig,  
349 2003). The common-Pb correction followed the method described by Andersen  
350 (2002). Ages younger than ca. 1000 Ma are based on common Pb-corrected  $^{206}\text{Pb}/^{238}\text{U}$   
351 ratios, whereas ages older than ca. 1000 Ma are based on common Pb-corrected  
352  $^{207}\text{Pb}/^{206}\text{Pb}$  ratios. For ICP-MS analyses, those ages with discordance degree >10%  
353 were excluded from analysis (e.g. Gehrels et al., 2003a; Yang et al., 2013; Liu et al.,  
354 2015). A more complete description of the sample separation methods and analytical  
355 procedures is given in Yuan et al. (2004).

#### 356 *4.2 Seismic profile*

357 Extensive petroleum exploration of the Qaidam basin in recent years has provided  
358 abundant subsurface data, including high-quality seismic profiles and drill core data.  
359 In this study, we integrated two 3D seismic blocks and two 2D seismic profiles (A-A',  
360 B-B', CC' and DD', see locations in Figs. 1 and 2) with our surface field investigation  
361 to describe the tectonic history of the western Qaidam basin. Seismic data were  
362 interpreted using the SMT Kingdom software.

## 363 5. U–Pb geochronology results of detrital zircons

364 In general, about 90% of the zircon crystals are characterized by relatively  
365 distinct oscillatory zoning in CL images and relative high Th/U ratios, indicating a  
366 magmatic origin (Corfu et al., 2003; Hanchar and Rudnick, 1995; Hoskin and Black,  
367 2000). The detrital zircons U-Pb ages vary widely between 2956 Ma and 57. Except  
368 for a single Cenozoic U-Pb age in sample EBLE, the detrital zircons U-Pb ages can be  
369 statistically subdivided into three groups of Precambrian (spanning from ca. 2.8 Ga to  
370 550 Ma), early to middle Paleozoic (peaks at 460~400 Ma) and late Paleozoic to  
371 Mesozoic (peaks at ca. 260~240 Ma). Representative CL images of typical zircon  
372 grains are presented in Figure 5. U-Pb isotopic ages with errors and related raw data  
373 are listed in full in Appendix A. The statistical U–Pb geochronology data for each of  
374 the samples are listed in Table 1 and a detailed description of the zircons analyzed in  
375 each sample is given in Appendix B. Concordia plots for the eleven samples are  
376 shown in Figure 6. The zircon age spectrum of the samples from the Eboliang and  
377 Huatugou sections are shown in Figures 7 and 8, respectively. In the following, major  
378 age groups and their corresponding peak ages have been established from visual  
379 inspection of the detrital zircon U-Pb age probability plots for all the samples. Age  
380 peaks are considered major when including at least 20% of the total number of data  
381 spread over less than 250 Ma, whereas a minor peak refers to populations representing  
382 less than 20% of the total number of data distributed over more than 300 Ma.

383 **6. Discussion**

384 *6.1 Geochronological characteristics of potential sources for the sedimentary rocks in*  
385 *the western Qaidam basin*

386 The Altyn Tagh Range, the Qilian Shan, as well as the Eastern Kunlun Range are  
387 all potential source regions likely to provide zircons to the Qaidam basin (e.g.  
388 Métivier et al., 1998; Xia et al., 2001; Meng and Fang, 2008; Yin et al., 2007, 2008a,  
389 2008b). In order to better constrain the provenance area of the samples collected in the  
390 western Qaidam basin (Fig. 9A), we compiled the zircon U-Pb ages available on  
391 basement rocks of the Altyn Tagh Range (Fig. 9B), the Qilian Shan (Fig. 9C) and the  
392 Eastern Kunlun Range (Fig. 8D).

393 *6.1.1 Altyn Tagh Range*

394 In the Altyn Tagh Range, the basement mainly consists of Archean and  
395 Proterozoic rocks with Archean zircon U-Pb ages ranging from ~3.6 Ga to ~2.6 Ga  
396 (Lu and Yuan, 2003; Lu et al., 2008; Long et al., 2014; Zhang et al., 2014b and  
397 references therein), and Proterozoic zircon U-Pb ages ranging from ~2.4 Ga to ~650  
398 Ma (Gehrels et al., 2003a, 2003b; Wang et al., 2006b; Lu et al., 2008 and references  
399 therein; Zhang et al., 2011; Wang et al., 2013). A few scattered Neoproterozoic  
400 intrusions are exposed, with a large, distinctive early Neoproterozoic intrusion (ca.  
401 850 Ma to ca. 1000 Ma in age) exposed west of the Xorkol basin (Fig. 9A). Wang et  
402 al. (2013) recently reported a mean crystallization age of ~910 Ma for the basement  
403 rocks near the Anxi area, in the western part of the Altyn Tagh Range (Fig. 9A).

404 Paleozoic intrusions with ages spanning from ~550 Ma to ~400 Ma are widely  
405 distributed (Jolivet et al., 1999; Sobel and Arnaud, 1999; Zhang et al., 2001; Cowgill  
406 et al., 2003; Gehrels et al., 2003a; Chen et al., 2004; Yue et al., 2004a, 2005; Yang et  
407 al., 2006; Wang et al., 2014b and references therein). Finally a few Permian igneous  
408 rocks are exposed along the central part of the Altyn Tagh Range, with zircon U-Pb  
409 ages ranging between ~300 Ma and ~260 Ma (Fig. 9A; Cowgill et al., 2003; Gehrels  
410 et al., 2003a; Gehrels et al., 2003b; Wu et al., 2014).

#### 411 6.1.2 *Qilian Shan*

412 Zircon U-Pb ages from the North Qaidam and South Qilian Shan terranes mainly  
413 group between 2700 to 1100 Ma, 550 to 400 Ma, and 300 to 200 Ma (Fig. 9B; Yang  
414 and Song, 2002; Cowgill et al., 2003; Gehrels et al., 2003a, 2003b; Yue et al., 2005;  
415 Shi et al., 2006; Song et al., 2014 and references therein). The North Qilian Shan  
416 basement mainly consists of early Paleozoic marine strata associated with a series of  
417 Ordovician volcanics and Silurian granitic plutons (Bovet et al., 2009; Xiao et al.,  
418 2009; Song et al., 2014 and references therein). These granitoid intrusions yielded  
419 U-Pb zircon ages ranging from ca. 550 to ca. 440 Ma (Wu et al., 2001; Gehrels et al.,  
420 2003a, 2003b; Yue et al., 2005; Song et al., 2014 and references therein). Finally, the  
421 central Qilian Shan basement is composed of Mesoproterozoic to Neoproterozoic  
422 marine sequences intruded by early Paleozoic plutons, with detrital and plutonic  
423 zircon ages comprised between 2333 to 874 Ma and 442 to 424 Ma respectively (Guo  
424 and Li, 1999; Lu, 2002; Yue et al., 2005; Bovet et al., 2009; Song et al., 2014 and  
425 references therein). The Qilian Shan basement was affected by a Devonian phase of

426 metamorphism (400-360 Ma), with a metamorphic peak at 440-423 Ma within the  
427 north Qaidam ultrahigh pressure belt (Yang et al., 2001, Yang and Song, 2002; Song  
428 et al., 2006; Yang et al., 2006; Song et al., 2014 and references therein). Finally,  
429 sporadically distributed late Permian to early Triassic granitoids are exposed along the  
430 western edge of the South Qilian Shan terrane, yielding zircon U-Pb ages ranging  
431 from ca. 270 Ma to ca. 230 Ma (Fig. 9A and 9C; Yang and Song, 2002; Wu et al.,  
432 2009; Dong et al., 2014, 2015).

### 433 *6.1.3 Eastern Kunlun Range*

434 Within the Eastern Kunlun Range, Proterozoic ages are rare (Fig. 9A and 9D).  
435 Several early Paleozoic intrusions with U-Pb zircon ages ranging from ca. 500 Ma to  
436 400 Ma have been reported by previous studies (Fig. 9C; Cowgill et al., 2003; IGSQP,  
437 2004; Dai et al., 2013; Li et al. 2013). Late Paleozoic - early Mesozoic granitoids (ca.  
438 300 Ma to ca. 200 Ma), corresponding to the magmatism associated to the  
439 Permo-Triassic closure of the Paleo-Tethys Ocean and to the post-collision  
440 magmatism that followed the docking of the Qiangtang Block, are extensively  
441 distributed (Fig. 9A; e.g. Roger et al., 2003, 2008, 2010; Liu et al., 2006; Li et al.,  
442 2013; Jolivet et al., 2015; Chen et al., 2015). Finally, a few Cretaceous ages have been  
443 obtained from the Tula Uplift in the western reach of the Eastern Kunlun Range (Figs.  
444 2A and 9A; Robinson et al., 2003; Cheng et al., 2015a) and some Miocene to  
445 Quaternary volcanism occurred in the southwestern part of the range (Jolivet et al.,  
446 2003).

447 6.2 Provenance analyses of the Mesozoic-Cenozoic strata in the western Qaidam  
448 basin

449 6.2.1 Eboliang section

450 On a first order analysis, the detrital zircon U-Pb age spectrum obtained from the  
451 eight samples collected on the Eboliang section are largely similar (Fig. 7), suggesting  
452 that the provenance area was largely homogeneous through time. However,  
453 second-order variations in age cluster proportions among those samples record source  
454 changes during basin filling. In general, the detrital zircons U-Pb ages can be  
455 statistically subdivided into three major groups of Precambrian (spanning from ca. 2.8  
456 Ga to 550 Ma), early to middle Paleozoic (peaks at 460~400 Ma) and late Paleozoic  
457 to Mesozoic (peaks at ca. 260~240 Ma) (Fig. 7). Aside from these major groups, the  
458 restricted early Neoproterozoic age group spanning from ca. 850 to ca. 1100 Ma with  
459 a peak age around 911 Ma (for example in sample E123, Lulehe Formation)  
460 represents the contribution from a distinctive source in the Altyn Tagh Range that will  
461 be discussed in details below.

462 Based on isopachs distribution, the Jurassic depocenter was situated farther  
463 south of the Eboliang section, which rules out any contribution from the Eastern  
464 Kunlun Range in the Jurassic sediments from that section (Fig. 9A; also see Fig. 3b in  
465 Meng et al., 2001). We thus consider that the paleocurrents in the northwestern  
466 Qaidam basin (Ritts and Biffi, 2000) probably provided sediments from mixed  
467 sources both in the Qilian Shan and Altyn Tagh Range. Based on  $^{40}\text{Ar}/^{39}\text{Ar}$   
468 thermochronology as well as zircon and apatite fission track analysis, previous

469 researches have reported Jurassic exhumation in the Altyn Tagh Range (Delville et al.,  
470 2001; Jolivet et al., 2001; Sobel et al., 2001; Wang et al., 2005). The detrital zircon  
471 age distribution of the Jurassic sediments in the Eboliang section (sample E122, Fig.  
472 7D), is very similar to that of the Cenozoic samples, including early to middle  
473 Paleozoic zircons (peaks at 422 Ma; 56 % of total), late Paleozoic to Mesozoic zircons  
474 (peaks at ca. 253 Ma; 20 % of total) and a few Precambrian zircon (15 % of total).  
475 This similarity suggests that the source of the material deposited in the Eboliang  
476 region has been largely stable since the early Jurassic including both Permian  
477 granitoids and Ordovician to Devonian basement from either or both the Altyn Tagh  
478 Range and the Qilian Shan (Figs. 7A and 9).

479 The Paleogene depocenters of the Qaidam basin were consistently located south  
480 of the Eboliang section (see Fig. 12A in Yin et al., 2008b), again excluding material  
481 contribution from the Eastern Kunlun Range (Fig. 9A; Meng and Fang, 2008; Yin et  
482 al., 2008b; Mao et al., 2014). Paleocurrent directions obtained from conglomerate  
483 fabrics (clast imbrications) as well as heavy mineral assemblages suggest that the  
484 Paleogene clastic materials deposited in the northwestern Qaidam basin mainly  
485 derived from the Qilian Shan to the northeast and the Altyn Tagh Range to the north  
486 (Fig. 7; Wu et al., 2011; Fu et al., 2013; Jian et al., 2013). The age spectrum obtained  
487 from the three Paleogene samples (E123, EBLE, and E22) are characterized by early  
488 to middle Paleozoic zircons (peaks at ca. 414 to ca. 461 Ma; 20 % ~ 43 % of total),  
489 late Paleozoic to early Mesozoic zircons (peaks at ca. 246 Ma to ca. 255 Ma; 20 % ~  
490 23 % of total), and a progressively increasing proportion of Precambrian zircons

491 (from 23 % to 37 %).

492 The age spectrum of sample E123 displays a distinctive early Neoproterozoic age  
493 group (Fig. 7B; 1100 Ma to 850 Ma; peak at 911 Ma). The oscillatory zoning in CL  
494 images and the relatively high Th/U ratios (over 0.1, average value 0.3) of those early  
495 Neoproterozoic zircons in sample E123 indicate a clear magmatic origin (Fig. 10;  
496 Hanchar and Rudnick, 1995; Hoskin and Black, 2000; Corfu et al., 2003). As shown  
497 in Figure 9A, the early Neoproterozoic sources are few and small in the Altyn Tagh  
498 Range and Qilian Shan, but for a large magmatic complex north of the Anxi area.  
499 Wang et al. (2013) recently reported a mean zircon U-Pb crystallization age of ~910  
500 Ma for these intrusions, consistent with the 911 Ma peak age in the Paleocene to early  
501 Eocene sample E123 (Fig. 9A). The enriched early Neoproterozoic zircon age groups  
502 (ca. 1100 to ca. 850 Ma) in sample E123 that accounts for over 20% of the total  
503 analysis represents a major difference from the age spectrum of the Jurassic and  
504 post-Paleocene samples. We suggest that this group indicates that the extensive early  
505 Neoproterozoic intrusion north of the Anxi area (Fig. 9A) formed a potential source for  
506 the Paleocene to early Eocene strata in the Eboliang section. According to the isopach  
507 map of the Paleocene to early Eocene Lulehe Formation provided by Yin et al.  
508 (2008b), the main depocenter was located south of the Eboliang section and the strata  
509 in the Eboliang section generally thicken southwards and westwards (Fig. 8). In  
510 addition, a sub-depocenter developed in the western Qaidam basin close to the early  
511 Neoproterozoic basement rocks in the Altyn Tagh Range (see Fig. 12A in Yin et al.,  
512 2008b). If the Eboliang section had been continuously situated in roughly the same

513 region as it occupies today (Fig. 2), the clastic materials derived from the early  
514 Neoproterozoic basement would thus not have been transported to the northwestern  
515 Qaidam basin. In addition, the few Neoproterozoic intrusions in the central and  
516 northern Qilian Shan region are not only far away from the Eboliang section, but also  
517 completely obstructed by the Paleocene uplift of the northern Qaidam thrust belt,  
518 clearly revealed by the seismic profiles in the southwestern flank of the Qilian Shan  
519 (Yin et al., 2008a). Based on these results combined with the generally south-directed  
520 paleoflows reported from the northern Qaidam basin (e.g. Fu et al., 2013; Jian et al.,  
521 2013) and the largely accepted hundreds of kilometers of Cenozoic offset along the  
522 lithospheric ATF (e.g. Wittlinger et al., 1998; Wang et al., 2006a; Yu et al., 2014;  
523 Cheng et al., 2015a, 2015b), we conclude that the Eboliang section must have been  
524 located much closer to the present day position of Anxi (Figs. 1 and 2). The single  
525 Paleogene zircon age observed in sample EBLE (Fig. 7C) is difficult to interpret since  
526 no Cenozoic magmatism has been reported in the Qaidam basin, Altyn Tagh Range or  
527 Qilian Shan. Our preferred interpretation is that this 57 Ma zircon was derived from  
528 the Cenozoic volcanic ash emitted from the volcanic centers exposed along the  
529 northern edge of the Qiangtang Block (e.g. Jolivet et al., 2003; Ding et al., 2007;  
530 Staisch et al., 2015).

531 The post-Oligocene depocenters are all located in the center of the Qaidam basin,  
532 south of the Eboliang section (Fig. 8; Meng and Fang, 2008; Yin et al., 2008b; Mao et  
533 al., 2014). This again excludes the possibility that the Neogene Eboliang sediments  
534 issued from the Eastern Kunlun Range to the south. Consistently, the generally

535 south-directed paleocurrents indicate that the sources of the post-Oligocene sediments  
536 in the Eboliang section were to the north, probably in the Altyn Tagh Range and the  
537 Qilian Shan (Wu et al., 2012b). However, the paleoflows changed from south-directed  
538 during the early Miocene, to generally southwest-directed during the Pliocene (Fig. 7).  
539 Unidirectional, south-directed paleocurrents prevail during the Quaternary (Fig. 7).  
540 Although Miocene to Quaternary strata are still dominated by early to middle  
541 Paleozoic zircons (peaks at ca. 444 Ma to ca. 401 Ma; 45 % ~ 48 % of total) and late  
542 Paleozoic to Mesozoic zircons (peaks at ca. 258 Ma to ca. 242 Ma; 39 % ~ 50 % of  
543 total), Precambrian zircons become scarce (3% ~ 9 % of total), especially in Pliocene  
544 and Quaternary strata (Fig. 7F, 7G and 7H). As shown in the 3D seismic profile (Fig.  
545 11), growth strata that developed during the deposition of the early Miocene series  
546 most probably indicate intense tectonic deformation along the adjacent ATF. Based on  
547 sediment facies studies and provenance analysis of the Oligocene to Miocene strata in  
548 the Xorkol basin, Ritts et al. (2004) concluded that the Oligocene to early Miocene  
549 sequence coarsens upwards from low-energy playa and alluvial mudflat deposits to  
550 proximal alluvial fan deposits, again supporting early Miocene deformation within the  
551 Altyn Tagh Range. A similar transition has been observed in the Oligocene to  
552 Miocene strata along the northern flank of the Altyn Tagh Range (Yue et al., 2004a).  
553 In addition, Miocene deformation within the Altyn Tagh Range has been clearly  
554 registered by thermochronology and paleomagnetism data (e.g. Jolivet et al., 1999;  
555 Chen et al., 2001; Jolivet et al., 2001; Wang et al., 2006; Liu et al., 2007; Lu et al.,  
556 2014). We thus propose that the disappearance of the Precambrian zircon in the

557 post-Oligocene strata is linked to a major change in drainage pattern within the Altyn  
558 Tagh Range. The early Miocene deformation along the ATF led to the growth of a  
559 prominent topographic barrier, cutting off the link between the Precambrian source  
560 rocks in the Altyn Tagh Range and the Eboliang section area. Furthermore, the  
561 post-Oligocene samples (EBLN, EB1, ED1 and EE1) were collected in the southern  
562 part of the Eboliang fold structure that formed during or after the early Miocene (Figs.  
563 2 and 11 A; e.g. Shang, 2001). Similarly to the material produced in the Altyn Tagh  
564 Range, the one sourced from the Qilian Shan was thus blocked east of the elevated  
565 growing structure and was not able to reach the deposition area to the south (Figs. 2, 9  
566 and 11A). These results imply that the post-Oligocene clastic material deposited in the  
567 northwestern Qaidam basin was mainly derived from restricted local sources and/or  
568 recycling of the deformed pre- Oligocene strata.

#### 569 6.2.2 Huatugou section

570 Along this section the detrital zircons U-Pb ages are again statistically subdivided  
571 into three major populations of Precambrian (spanning from ca. 3.2 Ga to 600 Ma),  
572 early to middle Paleozoic (peaks at 460~400 Ma) and late Paleozoic to Mesozoic  
573 (peaks at ca. 290~210 Ma) (Fig. 8). The Jurassic to Pleistocene basin depocenters  
574 were consistently situated farther southeast of the Huatugou section, which rules out  
575 any material contribution from the Qilian Shan to the Huatugou section (Fig. 9A;  
576 Meng and Fang, 2008; Yin et al., 2008b; Mao et al., 2014).

577 Late Paleozoic - early Mesozoic granitic intrusions are widespread in the Altyn  
578 Tagh and Eastern Kunlun ranges, however, most of the early Mesozoic intrusions

579 (younger than ca. 260 Ma) are confined to the Eastern Kunlun Range just south of our  
580 sample sites (Fig. 9A). This distinctive pluton distribution, together with the early  
581 Neoproterozoic zircons (1100~850 Ma) issued from the remarkably large intrusion in  
582 the Altyn Tagh Range (Fig. 9A; Wang et al., 2013; Cheng et al., 2015a) can be used as  
583 provenance signatures to identify the source of detrital zircons within our nine  
584 sandstone samples.

585       The poorly sorted, angular grains in the Jurassic samples suggest deposition from  
586 a proximal source (see Figs. 5A and 5B in Cheng et al., 2015a). The zircon ages  
587 spectrum of the Jurassic sample (CSL3, Fig. 8A) is characterized by an exceptional  
588 bimodal distribution (Permian-Triassic and Paleozoic groups). The zircons with ages  
589 younger than 260 Ma account for 15.5 % of the total number of analysis, suggesting  
590 that the Eastern Kunlun Range was a significant source of material for the Jurassic  
591 strata in the Huatugou section. This result is consistent with the general north- to  
592 west- directed paleoflows (Fig. 8A). The few Precambrian zircons (no early  
593 Neoproterozoic zircons) as well as the few south-directed paleocurrents might  
594 indicate limited contribution from the Altyn Tagh Range to the north, which suggests  
595 a limited topographic relief within that range, locally exposing basement rocks  
596 (Delville et al., 2001; Sobel et al., 2001; Ritts and Biffi, 2000).

597       In the Paleocene-early Eocene sample (S23) and the middle Eocene sample  
598 (HTG-E), the age spectrums are still largely bimodal, with about 15% of < 260 Ma  
599 zircons, suggesting that the Eastern Kunlun Range was still a significant source for  
600 these samples. This assumption is consistent with the N-NE-directed paleoflows

601 observed in the Paleocene to middle Eocene series (Fig. 8B and 8C; Meng and Fang,  
602 2008; Fu et al., 2013; Li et al., 2015). On the other hand, the increasing proportion of  
603 Precambrian zircons (over 3% of early Neoproterozoic zircons in both samples)  
604 indicates that the Altyn Tagh Range was gradually becoming a significant source of  
605 clastic material for the Paleocene to middle Eocene strata in the Huatugou section.

606 The late Eocene to Oligocene sample (QX1-2) displays a significant change in the  
607 detrital zircon age distribution pattern (Fig. 8C, 8D and 8E): the major Mesozoic age  
608 peak observed in the previous samples becomes nearly negligible with the proportion  
609 of < 260 Ma zircons decreasing dramatically (from 13.6% in sample S23 and 18.4%  
610 in sample HTG-E to 3.1% in sample QX1-2). In addition, the paleocurrent directions  
611 changed abruptly from generally north-directed in the Paleocene to middle Eocene  
612 strata to south-directed in the late Eocene strata (Fig. 8C and 8D). This implies a  
613 major shift in the source region from the Eastern Kunlun Range to the Altyn Tagh  
614 Range during the middle to late Eocene time. The proportion of early Neoproterozoic  
615 zircons gradually increased (e.g. from 3.1% in sample HTG-E to 5.1% in sample  
616 QX1-2) further attesting that basement rocks in the Altyn Tagh Range served as a  
617 significant source for the sediments in the Huatugou section.

618 Recent sedimentology and paleomagnetic studies demonstrated that the relatively  
619 rigid Qaidam basin, together with the western segment of the Eastern Kunlun Range,  
620 have been transported northeastward along the ATF during the Cenozoic (Wang et al.,  
621 2006a; Yu et al., 2014; Cheng et al., 2015a, 2015b). This displacement occurred  
622 without obvious basin-scale vertical axis rotation with respect to the Eurasia Plate

623 since the early Eocene (Dupont-Nivet et al., 2002; Yu et al., 2014). We suggest that  
624 this sharp change in the detrital zircon age distribution pattern was directly related to  
625 the onset of large-scale left-lateral strike-slip displacement along the ATF. Except for  
626 the still slightly increasing proportion of Precambrian ages, the detrital zircon U-Pb  
627 age distribution registered in the Oligocene sample (QX1-1) is similar to that in the  
628 late Eocene sample (QX1-2), suggesting a relatively stable drainage pattern from the  
629 late Eocene to the Oligocene (Fig. 8D and 8E).

630 The age spectrum of the early Miocene sample (HTG-N) is again characterized  
631 by a major Paleozoic age peak and a minor Mesozoic age sub-peak (Fig. 8F).  
632 However, the amount of Precambrian zircons decreased significantly (early  
633 Neoproterozoic ages only represent 1.1% of the total analysis). A similar decrease in  
634 the proportion of Precambrian zircons was also registered in the early Miocene  
635 sample of the Eboliang section (sample EBLN in Fig. 7E), indicating a regional  
636 change in the source area and/or drainage pattern throughout the Altyn Tagh Range.  
637 As already mentioned in the provenance analysis of samples from the Eboliang  
638 section, we suggest that the regional early Miocene deformation within the Altyn Tagh  
639 Range cut off the link between the Precambrian source rocks in the Altyn Tagh and  
640 Qilian Shan ranges and the depositional area in the Huatugou and Eboliang sections.  
641 The early Miocene clastic material in these two sections was mainly derived from  
642 more restricted local source regions and recycling of the deformed Paleocene to  
643 Oligocene strata.

644 Detrital zircon age distributions in the middle Miocene to Pleistocene samples

645 (CSL4, SZG1 and CSL5) are similar, characterized by a major middle Paleozoic age  
646 peak, a minor but consistent Mesozoic age peak as well as few Precambrian zircons  
647 (Fig. 8G, 8H and 8I). Based on seismic profile interpretation, the fold structures  
648 developing perpendicular to the Altyn Tagh fault trend (e.g. the Yingxiongling  
649 structure, Fig. 2) initiated during or after the Oligocene (Yin et al., 2007; Yin et al.,  
650 2008a; Wu et al., 2014). After the Oligocene onset of deformation, the Huatugou  
651 section, located in the northernmost part of the prominent Yingxiongling uplift  
652 structure, was gradually isolated from the main Qaidam basin. A complex, local  
653 drainage pattern developed while recycling of the deformed Paleocene to Oligocene  
654 strata served as a major material source (Fig. 8).

### 655 *6.3 Tectonics implications*

#### 656 6.3.1 Source to sink relation between the Qaidam basin and the Altyn Tagh Range

657 Provenance analysis results obtained from the two studied sections along the ATF  
658 reveal that the source to sink relation between the Qaidam basin and the Altyn Tagh  
659 Range underwent a three stages evolution:

660 During the Paleocene and early Eocene, the Eboliang and Huatugou sections  
661 were respectively located near the present day position of Anxi and Tula (Figs. 2A and  
662 12A). The basement rocks in the Altyn Tagh Range (including the early  
663 Neoproterozoic intrusion north of the Anxi area) served as the major source area for  
664 the Eboliang section while a part of the material deposited in the Huatugou section  
665 derived from the Eastern Kunlun Range.

666 By early to middle Eocene, left-lateral strike-slip movement along the ATF

667 initiated, resulting in gradually northeastward migration of the Qaidam basin  
668 (including the Eboliang and Huatugou sections). This migration ultimately  
669 disconnected the Eboliang section from the early Neoproterozoic source north of the  
670 Anxi area (Fig. 12B), as attested by the decreasing proportion of early Neoproterozoic  
671 zircons (from 19.4% in Paleocene to early Eocene sample E123, to 5.3% in  
672 middle-late Eocene sample EBLE and 3.6% in the Oligocene sample E22). Similarly,  
673 the Huatugou section gradually moved away from the Tula area towards Anxi (Fig.  
674 12B). This led to a decreasing proportion of < 260 Ma zircons (from ca. 15% in the  
675 Paleocene to middle Eocene samples S23 and HTG-E to ca. 3% in the late Eocene  
676 sample QX1-2; Fig. 8B, 8C and 8D) and to an abrupt change in paleocurrent  
677 directions (Fig. 8C and 8D). In parallel, the gradual increase in early Neoproterozoic  
678 zircons (from ca. 3% in middle Eocene sample HTG-E to 6.5% in Oligocene sample  
679 QX1-1; Fig. 8C, 8D and 8E) suggests that the Huatugou section might be close to the  
680 early Neoproterozoic intrusives north of the Anxi area during the middle Eocene to  
681 Oligocene.

682       On seismic profiles BB' and CC' (trending perpendicular to the Altyn Tagh Range;  
683 Figs. 2, 11A and 11B), several basement-involved thrust faults offset the Mesozoic  
684 strata and die out in the Eocene and Oligocene strata. In addition, the Eocene to  
685 Oligocene strata slightly thicken towards the depocenter exhibiting a growth-strata  
686 structure (Fig. 11B). The oldest unit affected by growth strata is the middle Eocene  
687 lower Xiaganchaigou Fm., suggesting that the deformation along the ATF initiated  
688 around that time. Paleocurrents measurements and provenance analysis of

689 conglomerates in the Xorkol basin (Fig. 2) and western Qaidam basin indicate that  
690 uplift along the central segment of the ATF occurred prior to the Oligocene (Yue et al.,  
691 2001; Ritts et al., 2004; Wu et al., 2012a, 2012b), probably during the early to middle  
692 Eocene.

693 Since the early Miocene, the Eboliang and Huatugou sections continuously  
694 migrated northeastwards along the left-lateral strike-slip ATF. However, the scarcity  
695 of the Precambrian zircons, especially the early Neoproterozoic zircons, in the  
696 post-Oligocene sediments (e.g. sample EBLN in the Eboliang section and sample  
697 HTG-N in the Huatugou section) indicates a major change in the drainage pattern  
698 leading to disruption of the source to sink relation between the Altyn Tagh Range and  
699 the western Qaidam basin. On seismic profiles BB' and CC' (Fig. 11A and 11B),  
700 generally northward-tapering growth strata within the Miocene to Pliocene deposits  
701 are well-developed, likely associated with the left-lateral faulting along the ATF and  
702 deformation within the Altyn Tagh Range since the early Miocene. The post-  
703 Oligocene deformation and uplift within the Altyn Tagh Range and northwestern  
704 Qaidam basin largely modified the regional drainage pattern. Most of the material  
705 derived from the erosion of the Altyn Tagh Range was directed towards the Tarim  
706 basin to the north (Fig. 12C; Yue et al., 2004b). The post-Oligocene clastic materials  
707 deposited in the western Qaidam basin was derived from local sources including  
708 recycling of the deformed Paleocene to Oligocene strata.

### 709 6.3.2 Implications for the Miocene deformation within the Altyn Tagh Range

710 In this study, the disappearance of an early Neoproterozoic component in the

711 detrital zircon age spectra of the Miocene strata both in the Eboliang and Huatugou  
712 sections as well as the Miocene initiation of growth strata within the northwestern  
713 Qaidam basin are indicative of enhanced tectonic activity within the Altyn Tagh  
714 Range and Qaidam basin since the Miocene. This finding is consistent with the results  
715 of several previous multi-faceted studies including: thermochronology on the  
716 basement rocks within the Altyn Tagh Range (e.g. Chen et al., 2001; Jolivet et al.,  
717 1999, 2001; Sobel et al., 2001; Zhang et al., 2012); paleomagnetism studies on the  
718 Cenozoic strata within the northwestern Qaidam basin (e.g. Zhang et al., 2013b; Lu et  
719 al., 2014; Chang et al., 2015); basin-scale seismic profile interpretation (Meng and  
720 Fang, 2008; Yin et al., 2008a, 2008b; Wang et al., 2010; Cheng et al., 2015a);  
721 provenance analyses along the Altyn Tagh Range (e.g. Yue et al., 2001; Yin et al.,  
722 2002; Wu et al., 2012a, 2012b) and synthesized tectonic analysis (e.g. Burchfiel et  
723 al., 1989; Meyer et al., 1998; Fu et al., 2015). In addition, the Miocene deformation  
724 phase has been widely recognized in the northern and eastern Tibetan plateau,  
725 including the Eastern Kunlun Range, the Altyn Tagh Range, the Longmen Shan and  
726 the Qilian Shan (e.g., Kirby et al., 2002; Clark et al., 2004; Ding et al., 2004; Ritts et  
727 al., 2004; Sun et al., 2005; Duvall et al., 2013; Yuan et al., 2013; Cheng et al., 2014,  
728 2015a, 2016; Lease, 2014; Chang et al., 2015; Jolivet et al., 2015), which may reflect  
729 a critical period in the growth process of the Tibetan plateau.

### 730 6.3.3 Implications for the Cenozoic offset of the ATF

731 The Eboliang and Huatugou sections record the northward migration of the  
732 Qaidam basin and can be used as two piercing points for defining the Cenozoic offset

733 of the ATF. In addition, the early Neoproterozoic intrusion in the Altyn Tagh Range  
734 strikes NEE-SWW along the Altyn Tagh fault, and has an elongation of ca. 80 km.  
735 The Eboliang section is located south of this 80 km wide early Neoproterozoic  
736 intrusion and separated from the intrusion by the ATF. Considering the actual 360 km  
737 gap between the center of this early Neoproterozoic intrusion and the Eboliang section,  
738 an average of  $360 \pm 40$  km offset on the Altyn Tagh fault can be estimated. A similar  
739 ~360 km offset is obtained by correlating the Huatugou section to the Mesozoic  
740 plutons south of the Tula area. We concede that, from analyzing detrital zircon spectra  
741 of Mesozoic to Cenozoic strata, the Eboliang-Anxi piercing point is much more  
742 convincing than the Tula-Huatugou piercing point. However, by correlating the  
743 lithology and sedimentary features of the Cenozoic strata and analyzing the detrital  
744 zircon U-Pb ages from Mesozoic strata in both the Tula and Huatugou sections, we  
745 previously found potential links between both sections (Cheng et al., 2015a). We thus  
746 considered that the Tula section used to be a part of the Qaidam basin and was left  
747 behind due to the northeastward migration of the Qaidam basin. Two faults which  
748 have been indentified by previous research (Figs. 1, 2 and 12; e.g. Cowgill, et al.,  
749 2003) are acting as boundaries between the detached Qaidam basin and the relic Tula  
750 sub-basin (Cheng et al., 2015a). Since the early Eocene, faulting on the ATF induced  
751 these NE-SW–trending branch faults, now covered by Quaternary deposits.  
752 Northwards migration of the rigid Qaidam basin left the Tula section and parts of the  
753 Kunlun basement behind (Cheng et al., 2015a). Moreover, considering the strong  
754 mechanical behaviour of the rigid Qaidam basin, the Huatugou section should be

755 approximately located near the present-day position of the Tula section if we restore  
756 the horizontal offset along the AFT based on the convincing Eboliang-Anxi piercing  
757 point. Consequently, we suggest a  $360 \pm 40$  km offset along the ATF, which  
758 contradicts the extraordinary  $\sim 1200$  km offset estimation (CSBS, 1992), but is in  
759 excellent agreement with independent, albeit indirect piercing points suggesting 300  
760 to 400 km of displacement along the Altyn Tagh Range: (1)  $400 \pm 60$  km offset based  
761 on Jurassic lacustrine shorelines along the northern and southern sides of the Altyn  
762 Tagh fault (Ritts and Biffi, 2000), (2)  $\sim 375$  km offset of the Cambrian magmatic arc in  
763 the Qilian Shan and the Altyn Tagh Range (Gehrels et al., 2003a), (3)  $\sim 375 \pm 25$  km  
764 offset of pre-Oligocene strata between the Qaidam and Xorkol basins (Yue et al.,  
765 2001), (4)  $\sim 360 \pm 40$  km offset estimation based on source to sink relation between  
766 the Xorkol basin and the North Qilian Shan (Yue et al., 2005), (5) 350~400 km offset  
767 based on eclogite, ophiolite and blueschist facies units in the Altyn Tagh Range and  
768 Qilian Shan (Yang et al., 2001; Zhang et al., 2001), (6)  $\sim 350$  km offset based on  
769 similar early to middle Jurassic cooling zones on both side of the Altyn Tagh fault  
770 (Sobel et al., 2001). This large-scale lithospheric offset along the ATF would be totally  
771 accomodated by crustal deformation within the terrane to the east, especially by the  
772 NE-SW shortening and eastward extrusion along the faults within the Qilian Shan (e.g.  
773 Yin et al., 2002, 2008a; Cheng et al., 2015b). The confirmation of the hundreds of  
774 kilometers of displacement along the strike-slip ATF again supports the eastward  
775 extrusion of the Tibetan plateau driven by the India-Asia collision.

776

777 **7. Conclusion**

778 Detrital zircon U-Pb age patterns evolution from two Jurassic to Pleistocene  
779 stratigraphic sections in the northwestern Qaidam basin associated to high-quality  
780 seismic-reflection profiles revealed that:

- 781 1. During the Paleocene to early Eocene, the Eboliang and Huatugou sections  
782 were respectively located near the present-day position of the Anxi and Tula  
783 areas. The basement rocks in the Altyn Tagh Range served as the significant  
784 source for the sediments to the Eboliang section, while the material deposited  
785 in the Huatugou section mostly derived from the Eastern Kunlun Range.
- 786 2. Left-lateral strike-slip movement along the ATF initiated during the  
787 early-middle Eocene, resulting in gradual northeastward migration of the  
788 Qaidam basin.
- 789 3. The post-Oligocene deformation within the Altyn Tagh Range and  
790 northwestern Qaidam basin strongly modified the regional drainage pattern.  
791 By Oligocene times, most of the material issued from the erosion of the Altyn  
792 Tagh Range was directed towards the Tarim basin to the north. The  
793 post-Oligocene clastic materials in the western Qaidam basin was mainly  
794 derived from local sources largely including recycling of the deformed  
795 Paleocene to Oligocene strata.
- 796 4. Using the Eboliang and Huatugou sections as piercing points, we estimate a  
797  $360 \pm 40$  km offset along the ATF.

798

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814

815 **Support Information**

816 Appendix A. U-Pb analysis of detrital zircons from the 11 sandstone samples.

817 Appendix B. Detailed description of the U–Pb geochronology results.

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1334 **Figure Caption**

1335 Fig. 1 (A) SRTM based digital topographic map of the Tibetan plateau. (B) Digital  
1336 elevation model (DEM) and major tectonic elements of the Altyn Tagh Range, the  
1337 Qaidam basin and the surrounding regions. The location of Fig. 2 is identified by the  
1338 solid box. The DEM map was generated from the 90 m SRTM data. Note that the  
1339 yellow solid line refers to the location of seismic profile AA'. (C) Interpreted and (D)  
1340 non-interpreted seismic profile AA'. Note that the succession of Cenozoic  
1341 depo-centers is marked along the long axis of the basin. These depo-centers gradually  
1342 migrated eastward since the Eocene.

1343

1344 Fig. 2 Simplified geological map of the northwestern Qaidam basin and eastern

1345 segment of the Altyn Tagh Range, adapted from the Geologic Map of the Tibetan  
1346 plateau and adjacent areas compiled by the Chengdu Institute of Geology and Mineral  
1347 Resources and Chinese Geological Survey (map scale, 1:1,500,000).

1348

1349 Fig. 3 Generalized stratigraphic column of the studied Mesozoic to Cenozoic series.  
1350 Paleocurrent directions in the Huatugou section were obtained from Meng and Fang,  
1351 (2008), Wu et al. (2012b) and Zhuang, et al. (2011). Paleocurrent directions in the  
1352 Eboliang section were obtained from Zhuang, et al. (2011), Wu et al. (2012b) and  
1353 Heermance et al. (2013). Note that sample CSL3 is cited from Cheng et al. (2015a),  
1354 and samples HTG-E, HTG-N, CSL4, SZG1 and CSL5 are cited from Cheng et al.  
1355 (2016). Red arrows refer to the general paleocurrent directions.

1356

1357 Fig. 4 Typical photomicrographs and field photographs of the various analyzed  
1358 sediments. (A) Drill core sample of early to middle Jurassic ( $J_{1+2}$ ) lithic sandstone  
1359 obtained from drill well in the Eboliang section; (B) Thin section image of lithic  
1360 sandstone from the Paleocene to early Eocene strata ( $E_{1+2}$ ) in the Eboliang section,  
1361 under crossed polarized light. (C) Horizontally stratified sandstone interbedded with  
1362 mudstones of the Xiaganchaigou Formation ( $E_3^1$ ) in the Eboliang section. (D) Thin  
1363 section image of siltstone from the Oligocene strata ( $N_1$ ), under crossed polarized  
1364 light, obtained from drill well in the Eboliang section. (E) Thick-bedded sandstone in  
1365 the early Miocene strata, Xiayoushashan Formation ( $N_2^1$ ), Eboliang section. (F) Thin  
1366 section image of siltstone from the Pliocene strata ( $N_2^3$ ), in the Eboliang section,

1367 under crossed polarized light. (G) Greenish white sandstone intercalated with  
1368 mudstone in the middle Eocene strata ( $E_3^1$ ), Huatugou section. (H) Greenish white  
1369 sandstone intercalated with brownish red mudstone in the late Eocene strata ( $E_3^1$ ),  
1370 Huatugou section. (I) Thin section image of sandstone in the Oligocene strata ( $N_1$ ),  
1371 Huatugou section, under crossed polarized light.

1372

1373 Fig. 5 Representative CL images of zircons from the 11 sandstone samples. The  
1374 yellow circles show the location of the U-Pb analysis. Numbers are U-Pb ages in Ma.

1375

1376 Fig. 6 U-Pb concordia diagrams for zircon grains of the 11 sandstone samples.

1377

1378 Fig. 7 Combined probability density functions (lines) and histogram plots (bars)  
1379 depicting detrital zircon U-Pb ages of samples from the Eboliang section, arranged in  
1380 stratigraphic order. Age distributions are colored according to age groups, and the pie  
1381 diagrams show percentages of grains in those age categories. Paleocurrents rose  
1382 diagrams in black are compiled from Heermance et al. (2013) and rose diagrams in  
1383 gray are compiled from Wu et al. (2012b) and Ritts and Biffi (2000).

1384

1385 Fig. 8 Combined probability density functions (lines) and histogram plots (bars)  
1386 depicting detrital zircon U-Pb ages of samples from the Huatugou section, arranged in  
1387 stratigraphic order. Two distinctive age groups, indicative of separate sources, are  
1388 colored. Paleocurrents rose diagrams are compiled from Meng and Fang, (2008), Wu

1389 et al. (2012b) and Zhuang, et al. (2011).

1390

1391 Fig. 9 (A) Sketched geological map of the Altyn Tagh Range and surrounding areas,  
1392 showing the distribution of zircon U–Pb ages for granitoids. The numbers denote  
1393 ages in Ma. Relative probability plots of zircon U-Pb ages from basement rocks and  
1394 intrusives in: (B) the Altyn Tagh Range, (C) the Qilian Shan, and (D) the Eastern  
1395 Kunlun Range. Age data are mainly cited from: Guo and Li, (1999), Sobel and Arnaud,  
1396 (1999), Yang et al. (2001), Zhang et al. (2001), Yang and Song, (2002), Cowgill et al.  
1397 (2003), Gehrels et al. (2003a, 2003b), Jolivet et al. (2003), Lu and Yuan, (2003),  
1398 Robinson et al. 2003, Roger et al. (2003), Chen et al. (2004), IGSQP, (2004), Yue et al.  
1399 (2004, 2005), Liu et al. (2006), Shi et al. (2006), Song et al. (2006), Wang et al.  
1400 (2006b), Yang et al. (2006), Lu et al. (2008), Roger et al. (2008), Bovet et al. (2009),  
1401 Liu et al. (2009), Wu et al. (2009), Xiao et al. (2009), Roger et al. (2010), Zhang et al.  
1402 (2011), Dai et al. (2013), Li et al. (2013), Wang et al. (2013), Long et al. (2014), Song  
1403 et al (2014), Wang et al.(2014b) , Zhang et al. (2014a), Dong et al. (2014, 2015), Chen  
1404 et al. (2015) and references therein. The blue arrow refers to the northeastward  
1405 migration of the Huatugou and Eboliang sections from their origins. The red dashed  
1406 line and the arrow show the ~80 km elongation of the early Neoproterozoic intrusions  
1407 in the Altyn Tagh range.

1408

1409 Fig. 10 (A) Frequency histograms for restricted early Neoproterozoic ages groups of  
1410 detrital zircons from the Paleocene to early Eocene Lulehe Fm. ( $E_{1+2}$ ) and the Th/U

1411 ratio for those zircon ages. (B) CL images of zircons for all early Neoproterozoic ages  
1412 zircons from the Paleocene to early Eocene Lulehe Fm. The yellow circles show the  
1413 location of the U-Pb analysis. Numbers are U-Pb ages in Ma. Note that the ~911 Ma  
1414 peak age for the Neoproterozoic ages groups coincides with the mean crystallization  
1415 age of ~910 Ma for the basement rocks in the western segment of the Altyn Tagh  
1416 Range (Fig. 9A; Wang et al., 2013). The distinctive Th/U ratio and oscillatory zones  
1417 for those zircons indicate magmatic sources.

1418

1419 Fig. 11 Seismic profiles in the southwestern Qaidam basin. See Fig. 2A for location.  
1420 Note the fold and thrusts in seismic profile BB', indicating the deformation in the  
1421 northwestern Qaidam basin since the early Miocene. Offset of the Paleogene strata in  
1422 seismic profiles CC' and DD' indicates the Eocene to Oligocene deformation in the  
1423 northwestern Qaidam basin which would be associated with deformation along the  
1424 ATF. Growth strata of the post-Oligocene strata in seismic profiles BB' and CC'  
1425 indicate intense tectonic movements along the ATF since the Miocene.

1426

1427 Fig. 12 Cenozoic kinematic model of the Altyn Tagh Fault and source to sink relation  
1428 between the western Qaidam basin and the surrounding regions. (A) during the  
1429 Paleocene to early Eocene, the basement rocks in the Altyn Tagh Range served as the  
1430 major source for the clastic material deposited in the Eboliang section, while  
1431 sediments in the Huatugou section were derived from the Eastern Kunlun Range; (B)  
1432 during the early Eocene to the Oligocene, the Qaidam basin migrated northeastward

1433 due to left-lateral strike-slip faulting along the ATF; (3) since the Miocene, intense  
1434 left-lateral faulting along the ATF continuously offset the Qaidam basin towards the  
1435 northeast and triggered post-Oligocene crustal deformation within the Altyn Tagh  
1436 Range and western Qaidam basin. See text for detailed discussion.

1437

1438 **Table 1** Summary of the major characteristics and corresponding U-Pb age data for  
1439 each sample.