Initial rupture and displacement on the Altyn Tagh fault, northern Tibetan Plateau: Constraints based on residual Mesozoic to Cenozoic strata in the western Qaidam Basin

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ABSTRACT

The Altyn Tagh fault, located in the northern Tibetan Plateau, is a large left-lateral strike-slip fault heavily responsible for the growth and formation of the plateau during Cenozoic time. Despite its significance, the initial timing and kinematic patterns of movement along the Altyn Tagh fault remain highly debated. Here, we present a detailed analysis of the stratigraphy and geochronology of three key lithologic sections (Tula, Anxi, and Caishiling) along the Altyn Tagh fault to better understand this kinematic history. By correlating stratigraphic contacts and lithology with the U-Pb age spectra of Mesozoic samples within the western Qaidam Basin, we find the Altyn Tagh fault has experienced a total of ~360 km of displacement during the Cenozoic. By combining seismic profile data with geologic observations, we divide the activity along this fault into two distinct stages of motion: (1) an initial stage, which occurred between early Eocene (ca. 49 Ma) and mid-Miocene time (ca. 15 Ma) and resulted in ~170 km of offset, and (2) an early stage, which began in the late Miocene Epoch and continues into the present, resulting in ~190 km of offset along the fault. We identify the Tula and Anxi sections as piercing points along the western segment of the Altyn Tagh fault and define these regions as residual parts of the original Qaidam Basin. These estimates suggest that motion along the Altyn Tagh fault has accelerated from an average left-lateral strike-slip rate of ~5.0 mm/yr during initial stage faulting to a rate of ~12.6 mm/yr between the late Miocene Epoch and present day.

INTRODUCTION

As a major strike-slip fault on the Tibetan Plateau, the Altyn Tagh fault plays a significant role in the Cenozoic deformation of northern Tibet (Fig. 1). Understanding the Cenozoic kinematic patterns of the Altyn Tagh fault holds important implications for unraveling the evolution of northern Tibet, deciphering the growth history of the entire Tibetan Plateau, and contributing to oil and gas exploration in the surrounding region (Yue and Liou, 1999; Yin and Harrison, 2000; Tapponnier et al., 2001; Yin et al., 2002; Wang et al., 2014). Recent studies have revealed much about the basic geology of the Altyn Tagh Range and the surrounding region (Wang, 1997; Cowgill et al., 2000, 2003; Yin et al., 2001, 2004; Chen et al., 2002; Chen et al., 2003; Dupont-Nivet et al., 2003, 2004; Ritts et al., 2004; Wu et al., 2012a, 2012b; Cheng et al., 2014; Lu et al., 2014; Zhang et al., 2014); however, the immense size and extent of the Altyn Tagh Range make it difficult to locate ideal piercing points with which to estimate the initial timing of left-slip movement and total displacement along the Altyn Tagh fault. As a result, both the timing and amount of slip along the fault are rigorously debated (e.g., Yin et al., 2002; Cowgill et al., 2003; Gehrels et al., 2003a, 2003b; Ritts et al., 2004; Wu et al., 2012a, 2012b).

Although some studies reference Mesozoic shearing in the Altyn Tagh Range, the growth of the Tibetan Plateau is largely related to Cenozoic faulting along the Altyn Tagh fault rather than any pre-Cenozoic shearing in the Altyn Tagh Range (Tapponnier et al., 1986, 2001; Arnaud et al., 2003; Wang et al., 2005; Li et al., 2006; L. Liu et al., 2007). Various approaches have been used to constrain the initial timing of left-slip movement along the Altyn Tagh fault, and the estimates vary greatly. Initial movement along the Altyn Tagh fault is estimated to have occurred broadly between the Eocene and Miocene Epochs (Chen et al., 2001; Meng et al., 2001; Wan et al., 2001; Yu et al., 2001; Yin et al., 2002; Robinson et al., 2003; Wu et al., 2012a, 2012b), and estimates of the total displacement along the Altyn Tagh fault vary anywhere from ~1200 km to less than 90 km (Tapponnier et al., 1988; CSBS, 1992; Wang, 1997; Yin and Harrison, 2000; Yang et al., 2001; Yin et al., 2002; Cowgill et al., 2003; Gehrels et al., 2003a, 2003b; Ritts et al., 2004). The wide variety of estimates regarding the initial timing and offset of the Altyn Tagh fault highlight the incomplete understanding of this remote region.

In particular, Jurassic strata in both the southeast Tarim and northwest Qaidam Basins across the Altyn Tagh fault have been used as the geologic piercing point to constrain the total displacement along the Altyn Tagh fault (e.g., Ritts and Biffi, 2000; Meng et al., 2001). However, Jurassic strata in western China are widespread and well developed in the foothills of several mountain belts (e.g., the Tian Shan, Altun Shan, Qilian Shan, and western Kunlun Mountains). These Jurassic strata are regionally similar, mainly characterized by a
succession of terrestrial detrital rocks with coal-bearing deposits, locally intercalated with relatively few volcanic rocks (Hendrix et al., 1992; Hendrix, 2000; Li et al., 2004; Yue et al., 2004b; Yang et al., 2013; D.D. Liu et al., 2013). While lithologically similar, these sedimentary features do not provide a distinct linear feature that can be matched across the Altyn Tagh fault; thus, Jurassic strata alone on either side of the Altyn Tagh fault are inadequate and insufficient to document the total offset of the Altyn Tagh fault.

In this paper, we present a detailed analysis of stratigraphy, sediment types, and detrital zircon U-Pb ages, which enables us to establish stratigraphic correlations to source terranes and to constrain the amount of tectonic transport along the Altyn Tagh fault (e.g., Gehrels, 2014). We present a synthesis of the stratigraphic and lithologic data along three sections (Tula, Anxi, and Caishiling sections) of the western segment of the Altyn Tagh fault and the detrital zircon U-Pb geochronology for the Tula and Caishiling sections (Figs. 1 and 2). We use this information to constrain the timing of tectonic activity on the northern Tibetan Plateau, to establish a more accurate estimate for the timing of initial movement along the Altyn Tagh fault, and to provide a more accurate estimate of the total length of offset along the Altyn Tagh fault during Cenozoic time.

**REGIONAL GEOLOGY**

**Altyn Tagh Range**

The Altyn Tagh Range is located at the northern edge of the Tibetan Plateau, separating the Tarim Basin to the northwest from the Qaidam Basin to the southeast (Figs. 1 and 2). The bedrock of the Altyn Tagh Range is dominated by Precambrian igneous and metamorphic rocks and Paleozoic sedimentary rocks, whereas Mesozoic and Cenozoic strata are only sporadically represented (Wang, 1997; Sobel et al., 2001; Yin et al., 2002; Chen et al., 2003). Within the Altyn Tagh Range, the ~1600-km-long ENE-trending Altyn Tagh fault starts in the western Kunlun Range in the southwest and terminates in the Qilian Shan Range in the northeast, linking the Kunlun and Qilian Shan thrust belts (Burchfiel et al., 1989; Wang, 1997; Yue and Liu, 1999; Yin and Harrison, 2000; Yin et al., 2002). The origin of the Altyn Tagh fault (Meyer et al., 1998; Chen et al., 2001; Meng et al., 2001; Wan et al., 2001; Yue et al., 2001; Yin et al., 2002; Ritts et al., 2004; Wu et al., 2012a, 2012b) and the total displacement along the Altyn Tagh fault remain heavily debated (CSBS, 1992; Ritts and Biffi, 2000; Yang et al., 2001; Cowgill et al., 2003; Gehrels et al., 2003a, 2003b). Quaternary slip rates
of ~10 mm/yr on the Altyn Tagh fault have been determined using field data, geodetic observations, and global positioning system (GPS) measurements (Bendick et al., 2000; Shen et al., 2001; Yin et al., 2002; Zhang et al., 2004, 2007; Cowgill et al., 2009; Yin, 2010).

Qaidam Basin

The triangular-shaped Qaidam Basin, which lies on the southeastern side of the Altyn Tagh Range, is the largest petroliferous basin within the northern Tibetan Plateau (Figs. 1 and 2). The western Qaidam Basin is bound by the Altyn Tagh Range to the northwest and the Qimen Tagh Range (western segment of the Eastern Kunlun Range) to the south. The westernmost part of the Qaidam Basin is characterized by a unique NE-trending elongate landform known as the Tula trough (E. Wang et al., 2006) or Tula subbasin (Guo et al., 1998; Figs. 1 and 2). High-quality subsurface data have revealed that the southeastern Qaidam Basin is governed by a series of high-angle NW-trending reverse faults with considerable strike-slip component (Cheng et al., 2014, 2015), resulting in stratigraphic throw on either side of these faults in seismic profile (Fig. 3). The tectonic-sedimentary evolution of the Qaidam Basin remains largely unknown, though several hypotheses have been proposed (Métivier et al., 1998; Mock et al., 1998; Xia et al., 2001; E. Wang et al., 2006; Meng and Fang, 2008; Yin et al., 2007, 2008a, 2008b; C.S. Wang et al., 2011). One hypothesis suggests that the western Qaidam Basin experienced two Cenozoic structural phases: the first between the Paleocene and Eocene Epochs and the second between the middle Miocene and Pleistocene Epochs (Y.D. Wang et al., 2010). Growth strata and a regional angular unconformity between the early Miocene and late Miocene successions in the western Qaidam Basin are identified as depositional responses to regional tectonic events in both the Altyn Tagh Range and the Eastern Kunlun Range during middle Miocene time (Song and Wang, 1993; Yin et al., 2002, 2008b; L. Wang et al., 2010; Y.D. Wang et al., 2010; Wu et al., 2012a).

Geologic mapping and petroleum exploration have revealed that the Qaidam Basin consists mainly of Cenozoic to Mesozoic nonmarine strata unconformably overlying an uncertain basement (Xia et al., 2001; E. Wang et al., 2006; Meng and Fang, 2008; Yin et al., 2007, 2008a, 2008b; C.S. Wang et al., 2011). One hypothesis suggests that the western Qaidam Basin experienced two Cenozoic structural phases: the first between the Paleocene and Eocene Epochs and the second between the middle Miocene and Pleistocene Epochs (Y.D. Wang et al., 2010). Growth strata and a regional angular unconformity between the early Miocene and late Miocene successions in the western Qaidam Basin are identified as depositional responses to regional tectonic events in both the Altyn Tagh Range and the Eastern Kunlun Range during middle Miocene time (Song and Wang, 1993; Yin et al., 2002, 2008b; L. Wang et al., 2010; Y.D. Wang et al., 2010; Wu et al., 2012a).
<table>
<thead>
<tr>
<th>Period</th>
<th>Epoch</th>
<th>Age (Ma)</th>
<th>Formation (Fm.)</th>
<th>Thickness (m)</th>
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<th>Lithological description</th>
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<tr>
<td>Cenozoic</td>
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<td>Neogene</td>
<td></td>
<td>0.01</td>
<td>Dabuxun-Yaqiao</td>
<td>0-171</td>
<td>Q_{1+2}</td>
<td>Dominate by gray and yellow-gray sand gravels.</td>
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<td></td>
<td></td>
<td>1.8</td>
<td>Qigequan</td>
<td>30-2,500</td>
<td>Q_{3}</td>
<td>Dominate by gray, yellow-gray conglomerates and pebble sandstones interbed with few argillaceous sandstones; unconformable with the underlying Shizigou Fm.</td>
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<td></td>
<td></td>
<td>5.3</td>
<td>Shizigou</td>
<td>370-1,800</td>
<td>N_{3}y</td>
<td>Characterized by gray-white conglomerates, pebble sandstones intercalated with sandstones and argillaceous siltstones; separated underly Shangyoushashan Fm. by color changing from brown in Shangyoushashan Fm. to gray white in Shizigou Fm.</td>
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<td></td>
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<td>15.3</td>
<td>Shangyoushashan</td>
<td>350-2,230</td>
<td>N_{3}y</td>
<td>Dominate by gray-brown mudstones, intercalated with dark-gray carbonaceous mudstones; unconformable with the underlying lower Xiayoushashan Fm. and conformable or locally unconformable with overlying Shizigou Fm.</td>
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<td>23.0</td>
<td>Xiayoushashan</td>
<td>300-2,900</td>
<td>N_{3}y</td>
<td>Characterized by gray, brownish-red thick bedded mudstones and siltstones, intercalated with marlstones and limestones; separated with the overlying Shangyoushashan Fm. by a local unconformity.</td>
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<td>Oligocene</td>
<td>33.9</td>
<td>Shangganchaigou</td>
<td>600-1,000</td>
<td>N_{3}sg</td>
<td>Dominated by grayish-green, yellowish-gray mudstones and sandstones intercalated with mudstones; separated with the overlying upper Xiayoushashan Fm. by appearance of green gray sandstones; conformable contact with the underlying Shangganchaigou Fm.</td>
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<td>35.5</td>
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<td></td>
<td>Pliocene</td>
<td>37.8</td>
<td>Upper Xiaganchaigou</td>
<td>160-1,230</td>
<td>E_{1}^{3}xg</td>
<td>Characterized by successions of brownish-red sandstones interbed with mudstones; separated with the overlying upper Xiaganchaigou Fm. by the appearance of gray mudstones; conformable contact with the underlying lower Xiaganchaigou Fm.</td>
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<td></td>
<td>43.8</td>
<td>Lower Xiaganchaigou</td>
<td>160-1,230</td>
<td>E_{1}^{3}xg</td>
<td>Characterized by successions of brownish-red sandstones interbed with mudstones, intercalated with argillaceous siltstones and marlstones; conformable contact with the overlying Xiaganchaigou Fm.</td>
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<td>Eocene</td>
<td>55.8</td>
<td>Lulehe</td>
<td>267-1,400</td>
<td>E_{1}^{3}</td>
<td>Dominated by successions of purple-red conglomerates, pebble sandstones, interbed with sandstones, siltstones and mudstones; separated with the overlying lower Xiaganchaigou Fm. by the disappearing of the conglomerates; unconformable contact with the underlying Quanyagou Fm.</td>
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<td>65.5&gt;53.5</td>
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<td></td>
<td>Paleogene</td>
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<td>Quanyagou</td>
<td>Kq</td>
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<td>Dominate by successions of terrestrial detrital rocks with coal-bearing deposition, dominated by brownish and purple red conglomerates interbed with dark brown mudstones; unconformable overlasying on the basement of surrounding mountains.</td>
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<td>Caishiling</td>
<td>J_{3}c</td>
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<td>Dameigou</td>
<td>J_{3}d</td>
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<td></td>
<td>Mesozoic</td>
<td>201</td>
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Figure 3. Stratigraphy and lithologic unit descriptions of the Qaidam Basin. The Cenozoic stratigraphy of the basin has been defined and dated in detail using magnetostratigraphy, palynology, and paleontology studies within the entire basin (Fang et al., 2007; Gao et al., 2009; Huang et al., 1996; Huo, 1990; Lu and Xiong, 2009; QBGMR, 1991; Qiu, 2002; Z.M. Sun et al., 2005; Xia et al., 2001; Yang et al., 1992; Zhao et al., 2006). See Figure 2 for seismic profile location. Note the growth strata above the Xiayoushashan Formation (N_{3}^{3}y).
and Wang, 1993; Xia et al., 2001; Qiu, 2002; J.M. Sun et al., 2005; E. Wang et al., 2006; Yin et al., 2008b). Based on magnetostratigraphy, palynology, and paleontology, the Mesozoic–Cenozoic strata of the Qaidam Basin have been subdivided into 11 units, and the chronostratigraphy of the Cenozoic units has been well constrained (Huo, 1990; QBGMR, 1991; Yang et al., 1992; Huang et al., 1996; Xia et al., 2001; Qiu, 2002; J.M. Sun et al., 2005; Zhao et al., 2006; Fang et al., 2007; Yin et al., 2007; Gao et al., 2009; Lu and Xiong, 2009; Wu et al., 2011). These units are listed in order from oldest to youngest, followed by the symbol for each unit, and the age range capture of each unit, if available: (1) the Dameigou Formation, \( \text{J}_{1+2} \); (2) Caishiling Formation, \( \text{J}_c \); (3) Quanyagou Formation, \( \text{K}_q \); (4) the Lulehe Formation, \( \text{E}_{1+2} \) older than 53.5–43.8 Ma (Yang et al., 1992; Zhang, 2006; Ke et al., 2013); (5) the lower Xiaganchaigou Formation, \( \text{E}_{1+3} \)g, 43.8–37.8 Ma (Zhang, 2006; Z.C. Sun et al., 2007; Pei et al., 2009); (6) the upper Xiaganchaigou Formation, \( \text{E}_{2+3} \)xg, 37.8–35.5 Ma (Z.M. Sun et al., 2005; Z.C. Sun et al., 2007; Pei et al., 2009); (7) the Shangganchaigou Formation, \( \text{N}_s \)g, 35.5–22.0 Ma (Z.M. Sun et al., 2005; Lu and Xiong, 2009); (8) the lower Youyashan Formation, \( \text{N}_s^{x1+2} \)xy, 22.0–15.3 Ma (Fang et al., 2007; Lu and Xiong, 2009); (9) the upper Youyashan Formation, \( \text{N}_s^{x1+2} \)s, 15.3–8.1 Ma (Fang et al., 2007); (10) the Shizigou Formation, \( \text{N}_s^{c} \), 8.1–2.5 Ma (Fang et al., 2007); and (11) Quaternary deposits, including the Qigequan Formation (Q.q) and the Dabuxun-Yanqiao Formation (Q_{xq}), 2.5–0 Ma (Fang et al., 2007; Yin et al., 2008b). The lithologic features of each unit are summarized in detail Figure 3.

RESIDUAL MESOZOIC–CENOZOIC STRATIGRAPHY ALONG THE ALTYN TAGH FAULT

Mesozoic to Eocene Strata in the Tula Section

The Tula section is bounded by the Altyn Tagh fault to the north and the Kunlun Precambrian and Paleozoic basement to the south (Figs. 2 and 4). A narrow valley runs through this region at the westernmost part of the Qaidam Basin. Precambrian, Ordovician, and Carboniferous rocks comprise the basement rock, which is unconformably overlain by Mesozoic to Cenozoic strata (Guo et al., 1998; HGSI, 2003; Ritts et al., 2004). Mesozoic strata in the Tula section are dominantly terrestrial clastic rocks. Several faults are present on the south side of the Tula Basin (Fig. 2). The left-lateral NE-SW–trending slip Baiganhu fault can be identified by a series of distinctive fault scarps and structural lineaments within the mountains, although the fault later becomes obscured by Quaternary deposits in the Tula Basin (Fig. 2; Cowgill et al., 2003; HGSI, 2003).

Jurassic clastic coal-bearing strata rest unconformably on the Altyn Tagh basement (Fig. 4). Based on lithologic associations, sequence stratigraphy, and paleontology, these strata have been divided into two units: the Dameigou Formation (\( \text{J}_{1+2} \)), located in the lower part of the section, and the Caishiling Formation (\( \text{J}_c \)), located in the upper part of the section (XBGMR, 1993; HGSI, 2003; Robinson et al., 2003; Dupont-Nivet et al., 2004). The lower part of the Dameigou Formation (\( \text{J}_{1+2} \)) is composed of fining-upward gray-brown conglomerate beds interbedded with greenish-gray sandstone and siltstone beds. The upper part of the Dameigou Formation (\( \text{J}_{1+2} \)) is characterized by a set of sandstone beds interbedded with conglomerate, siltstone, and lithic sandstone (Fig. 5A). Grain size increases up section, indicating gradual shallowing and subsidence of the basin. In the Caishiling section, thick-bedded lithic sandstone and conglomerate (Fig. 5B) are developed at the base of the Dameigou Formation (\( \text{J}_{1+2} \)), indicating that denudation of the source area began in Early Jurassic time (Robinson et al., 2003).

The Caishiling Formation (\( \text{J}_c \)) is composed of yellowish massive sandy conglomerate (Fig. 5C) intercalated with quartzolithic sandstone at the base, and it is characterized by purple-red, gray-purple siltstone in the lower part of the section. These rocks transition to variated sandstone and siltstone intercalated with conglomerate in the middle and upper parts of the section (Ritts and Biffi, 2000; Robinson et al., 2003). In the upper part of the Caishiling Formation (\( \text{J}_c \)), cross-bedding is well developed in the sandstone, and imbrication can be found in the conglomerate (Fig. 5D). The uppermost part of the Caishiling Formation (\( \text{J}_c \)) contains thick-bedded oil sands (Fig. 5E) and natural asphalt (Fig. 5F), indicating the Tula unit was once a subsidence area characterized by a topographic low different from the narrow valley that exists at present (Fig. 1). Geochemical fingerprints (e.g., carbon isotopic composition) in the Jurassic oil-bearing sandstone of the Tula Basin are similar to the geochemical fingerprints in the Jurassic oil-bearing sandstone oil in the Qaidam Basin (Guo et al., 1998).

More than 2000 m of Cretaceous strata (Quanyagou Formation) unconformably overlie the Late Jurassic strata of the Caishiling Formation (XBGMR, 1993; Robinson et al., 2003). In the Tula section, Cretaceous plutons (ca. 74 Ma) intrude Cretaceous strata, providing a minimum depositional age (XBGMR, 1993; Robinson et al., 2003). The lower part of the Cretaceous strata is dominated by purple-red conglomerate intercalated with sandstone, siltstone, and mudstone interpreted to represent a lacustrine depositional environment. The upper part of Cretaceous strata consists of purple-red siltstone interbedded with silty mudstone interpreted to represent a lacustrine deltaic depositional environment (Ritts and Biffi, 2000; Robinson et al., 2003). The lacustrine to lacustrine delta deposits in the Tula unit reinforce the idea that the Tula unit was characterized by a topographic low during the Cretaceous, a setting very different from the narrow valley that exists at present (Fig. 1).

In the Tula unit, the well-exposed Paleocene to early Eocene Lulehe Formation overlies the Mesozoic strata along a low-angle unconformity (XBGMR, 1993; HGSI, 2003; Robinson et al., 2003). The Lulehe Formation consists mainly of purple-red conglomerate interbedded with fine-grained sandstone at the base, which becomes coarser up section, along with an increase in the abundance of conglomerate toward the top. The formation contains a high metamorphic lithic fraction and limestone clasts with coral fossils that suggest a proximal provenance and syntectonic deposits (Zuffa, 1980; Mack and Rasmussen, 1984; HGSI, 2003; Robinson et al., 2003). The distinctive purple-red conglomerates found in the Lulehe Formation are regionally similar to those
Figure 4. Geologic map (after Qie-mo J45C003002 geologic map, scale 1:250,000) and geologic cross section of the study area, compiled from HGSI (2003), Robinson et al. (2003), and XBGMR (1993). Red stars denote locations of U-Pb detrital zircon samples. Ages (zircon U-Pb) of plutons are mainly compiled from HGSI (2003). The western half and eastern half of the Eocene strata are based on the division of Dupont-Nivet et al. (2004).
Figure 5. Typical photomicrographs and field photographs. (A) Lithic sandstone in early Jurassic strata (J1+2d) of the Tula section, rich in lithic fragments, under plane polarized light. (B) Lithic sandstone in Early Jurassic strata (J1+2d) of the Caishiling section, rich in various lithic fragments, under crossed polarized light. (C) Conglomerate and (D) cross-bedding in Late Jurassic (J3c) strata of the Tula section. (E) Oil sand and (F) asphalt developed in Late Jurassic (J3c) strata. Abbreviations: Sch—schist, Pl—plagioclase, Kp—potash feldspar, Q—quartz, Bt—biotite.
found in the Qaidam Basin. The Lulehe Formation has been dated via magnetostratigraphy to between 65.53.5 and 43.8 Ma (Yang et al., 1992; Zhang, 2006; Ke et al., 2013). These dates further support a Paleocene to early Eocene age for the Lulehe Formation.

The Jurassic–early Eocene strata in the Tula section are heavily deformed, forming a major north-verging syncline with a steeply dipping south limb and a shallowly dipping north limb (Fig. 4). The Jurassic, Cretaceous, and Paleocene to early Eocene strata in the south limb of the syncline are inverted with a high dip angle (dipping mainly to the south from 180° to 200° at angles of 65°–80°). The contact between the Cretaceous and Paleocene to early Eocene strata is characterized by a low-angle angular unconformity or a local fault boundary (XBGMR, 1993; HGSI, 2003; Robinson et al., 2003).

Cenozoic Strata in the Anxi Section

The Anxi section, ~150 km northeast of the Tula section, is located in the Altyn Tagh fault zone and is bounded by the Altyn Tagh basement to the north and the Kunlun Precambrian and Paleozoic basement to the south (Figs. 2 and 6). Precambrian and early Paleozoic metamorphic rocks with igneous intrusions comprise this basement, which is overlain by Mesozoic and Cenozoic strata (Guo et al., 1998; Ritts and Biffi, 2000; GGSI, 2003). The Cenozoic units in the Anxi section have been identified based on detailed field mapping of previous studies, and depositional ages are estimated by correlating these units with the well-constrained Cenozoic strata of the Qaidam Basin (Fig. 7; Huo, 1990; QBGMR, 1991; Yang et al., 1992; Huang et al., 1996; Xia et al., 2001; Qiu, 2002; GGSI, 2003; J.M. Sun et al., 2005; Zhao et al., 2006; Fang et al., 2007; Yin et al., 2007; Gao et al., 2009; Lu and Xiong, 2009; Wu et al., 2011).

Unlike the poorly preserved Cenozoic strata of the Tula section, the Anxi section contains a well-exposed Cenozoic stratigraphic succession that includes most of the Cenozoic units described already. The Anxi section includes the Paleocene to early Eocene Lulehe Formation, the Eocene to Oligocene Ganchaigou Formation, the Miocene Youshashan Formation, and the Pliocene Shizigou Formation. As visible in cross-sectional profile (Fig. 6), the Lulehe, Ganchaigou, and Youshashan Formations of the Anxi section are in conformable contact with one another and have been deformed synformally after early Miocene time. However, in plan view, these Paleocene to Miocene strata are cut by the left-lateral strike-slip Altyn Tagh fault and are separated from the overlying Pliocene strata of the Shizigou Formation by an apparent angular unconformity (Fig. 6).

The Paleocene to early Eocene strata of the Lulehe Formation crop out in the northern part of the valley and trend in a NE direction. These strata are characterized by brick-red conglomerates and pebble sandstones intercalated with sandstones and siltstones. This portion of the Lulehe Formation is separated from the typically overlying Eocene strata of the Xiaganchaigou Formation by the disappearance of the conglomerate layers (GGSI, 2003). The Eocene to Oligocene strata of the Ganchaigou Formation only crop out in the northern part of the valley. The lack of paleomagnetic data in the Anxi section has thus far prevented a further division of these strata into two units as has been done in the western Qaidam Basin (Fig. 3). The lower part of the Ganchaigou Formation is dominated by gray to grayish-green sandstones intercalated with siltstones, biomicrites, and mudstones. The upper part of the Ganchaigou Formation, however, is characterized by grayish-green calcareous shales and mudstones. The Ganchaigou Formation is overlain by the Miocene Youshashan Formation, which contains brown granule conglomerate at its base (GGSI, 2003). Like the overlying Ganchaigou Formation, the Youshashan Formation crops out in the northern part of the valley. The Youshashan Formation has not been subdivided into two units as has been done in the western Qaidam Basin (Fig. 3; GGSI, 2003). The lower and middle sections of the Youshashan Formation strata consist mainly of brown and maroon granule conglomerate interbedded with coarse sandstone, while the upper part is characterized by purple and brown sandstone and pebble sandstone interbedded with conglomerate, siltstone, and mudstone. These primarily brown strata distinguish the Youshashan Formation from the overlying Pliocene strata of the Shizigou Formation, which is characterized by earthy yellow and gray pebble sandstone at its base (GGSI, 2003). The Pliocene strata are then overlain by Quaternary sand-gravel beds, which lie atop an angular unconformity (Fig. 6). The lithology in the lower part of the Pliocene strata consists of sandstone interbedded with siltstone and mudstone, while the middle and upper parts of the Pliocene strata are characterized by conglomerate and sandstone intercalated with siltstone (GGSI, 2003). These thickly bedded conglomerates are interpreted to represent alluvial fan to fluvial facies (Ritts and Biffi, 2000).

Methods

Field Investigation and Seismic Profile Interpretation

We used three sections (Tula, Anxi, and Caishiling) along the western segment of the Altyn Tagh fault to study stratigraphic features of the Mesozoic–Cenozoic deposits (Fig. 2). We integrate three high-quality seismic profiles of the western Qaidam Basin with our surficial field observations to explain the tectonic history of this region. Two of the seismic profiles (A–A’ and D–D’) trend along strike (northeast) of the Altyn Tagh fault, while one of the profiles (E–E’) trends perpendicular (northwest) to the Altyn Tagh fault (Fig. 2). Seismic data were interpreted using SMT Kingdom software.

Sampling and Analytical Process

Detrital zircon geochronology is rapidly developing into an essential tool for sediment provenance analysis and geodynamic study (e.g., Fedo et al., 2003; Thomas, 2011; Gehrels, 2014). U-Pb dating of detrital zircons from sediments is widely used to reconstruct the provenance of ancient sedimentary
Figure 6. Geologic map (after the Washixia J45C002003 geologic map, scale 1:250,000) and geologic cross section of the study area, compiled from GGSJ (2003) and XBGMR (1993).
Figure 7. Chronostratigraphic correlation of the relic Mesozoic to Cenozoic strata along the Altyn Tagh fault. GPTS—geomagnetic polarity time scale of Cande and Kent (1995). Observed polarity was compiled from Yin et al. (2002), Z.M. Sun et al. (2005), Zhang (2006), Fang et al. (2007), and Lu and Xiong (2009). Paleocurrents are from Ritts and Biffi (2000). Chronostratigraphic correlation is based on field observation and previous studies (XBGMR, 1993; Guo et al., 1998; Ritts and Biffi, 2000; GGSI, 2003; HGSI, 2003; Robinson et al., 2003). ATF—Altyn Tagh fault.
Supplemental File. Description of zircon separation and LA-ICP-MS U-Pb dating of zircon, Figure DR1, and Tables DR1–DR2. Please visit http://dx.doi.org/10.1130/GES01070.S1 or the full text article on www.gsapubs.org to view the Supplemental File.

**RESULTS**

### U-Pb Geochronology of Detrital Zircons

Isotopic ages with errors and related raw data are listed in full in Table DR1 (see footnote 1). The various zircon age groups and corresponding data for each sample are shown in Table 1 and Figure 8. Cathodoluminescence (CL) images of typical zircon grains are presented in Figure DR1 (see footnote 1).

#### Jurassic Samples

The zircons from sample G2 (Dameigou Formation) are ~50–200 μm long and mainly subhedral to subrounded. The grains are generally colorless and exhibit prominent oscillatory zoning. Th/U ratios typically clustered between 0.09 and 1.98. Forty-eight out of 99 dated grains yielded a 206Pb/238U range of 530–404 Ma, with a single peak in the age spectrum at 447 Ma (Figs. 8 and 9A). Only one zircon with a Triassic age (250 Ma) was obtained. The ages of all other zircons range from 2781 to 896 Ma.

In sample CSL3 (Dameigou Formation), zircon grain morphology ranges from euhedral to abraded, with an average size ranging between 50 μm and 250 μm. CL images show that most of these zircon crystals are characterized by relatively distinct oscillatory zoning. Th/U ratios vary between 0.25 and 3.82. The U-Pb ages range from 2480 to 220 Ma (Fig. 9B). The ages can be separated in three main groups with two peak ages at 264 Ma and 433 Ma, and 11 ages between 2480 and 852 Ma.

In sample CSL2 (Caishiling Formation), zircon crystals display euhedral to abraded shapes for an average size ranging between 50 μm and 250 μm. The majority of the crystals display distinct oscillatory zoning in CL images, indicating a magmatic origin, which is confirmed by Th/U ratios varying between 0.12 and 1.55 (with two exception of 0.03 and 0.06). Among the 100 crystals analyzed, all zircon ages with a discordance degree of <10% were used. The U-Pb ages range from ca. 2661 to ca. 246 Ma (Fig. 9C). The age distributions are divided into four groups with two major peaks at ca. 254 Ma and ca. 445 Ma.

#### Late Jurassic

In sample CSL2 (Caishiling Formation), zircon crystals display euhedral to subhedral shapes with an average size ranging between 50 μm and 250 μm. The majority of the crystals display distinct oscillatory zoning in CL images, indicating a magmatic origin, which is confirmed by Th/U ratios varying between 0.12 and 1.55 (with two exception of 0.03 and 0.06). Among the 100 crystals analyzed, all zircon ages with a discordance degree of <10% were used. The U-Pb ages range from ca. 2661 to ca. 246 Ma (Fig. 9C). The age distributions are divided into four groups with two major peaks at ca. 254 Ma and ca. 445 Ma.

#### Early–Middle Jurassic

In sample CSL2 (Caishiling Formation), zircon crystals display euhedral to subhedral shapes with an average size ranging between 50 μm and 250 μm. The majority of the crystals display distinct oscillatory zoning in CL images, indicating a magmatic origin, which is confirmed by Th/U ratios varying between 0.12 and 1.55 (with two exception of 0.03 and 0.06). Among the 100 crystals analyzed, all zircon ages with a discordance degree of <10% were used. The U-Pb ages range from ca. 2661 to ca. 246 Ma (Fig. 9C). The age distributions are divided into four groups with two major peaks at ca. 254 Ma and ca. 445 Ma.

#### Cretaceous

In sample CSL2 (Caishiling Formation), zircon crystals display euhedral to subhedral shapes with an average size ranging between 50 μm and 250 μm. The majority of the crystals display distinct oscillatory zoning in CL images, indicating a magmatic origin, which is confirmed by Th/U ratios varying between 0.12 and 1.55 (with two exception of 0.03 and 0.06). Among the 100 crystals analyzed, all zircon ages with a discordance degree of <10% were used. The U-Pb ages range from ca. 2661 to ca. 246 Ma (Fig. 9C). The age distributions are divided into four groups with two major peaks at ca. 254 Ma and ca. 445 Ma.

#### Early–Middle Jurassic

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#### Early–Middle Jurassic

In sample CSL2 (Caishiling Formation), zircon crystals display euhedral to subhedral shapes with an average size ranging between 50 μm and 250 μm. The majority of the crystals display distinct oscillatory zoning in CL images, indicating a magmatic origin, which is confirmed by Th/U ratios varying between 0.12 and 1.55 (with two exception of 0.03 and 0.06). Among the 100 crystals analyzed, all zircon ages with a discordance degree of <10% were used. The U-Pb ages range from ca. 2661 to ca. 246 Ma (Fig. 9C). The age distributions are divided into four groups with two major peaks at ca. 254 Ma and ca. 445 Ma.

### Table 1. Summary of the Major Characteristics and Corresponding Statistical Data for Each of the Samples

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Formation (Fm.)</th>
<th>Sample number</th>
<th>Lithology</th>
<th>Detrital zircon age range (Ma)</th>
<th>Detrital zircon peaks (Ma)</th>
<th>Number of effective data points</th>
<th>Th/U ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tula unit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cretaceous</td>
<td>Quanyagou Fm. G1</td>
<td>Gray-yellow pebbly sandstone</td>
<td>218–2532</td>
<td>ca. 238</td>
<td>89</td>
<td>0.13–1.51</td>
<td></td>
</tr>
<tr>
<td>Early–Middle Jurassic</td>
<td>Dameigou Fm. G2</td>
<td>Gray-white sandstones</td>
<td>254–2430</td>
<td>ca. 250</td>
<td>99</td>
<td>0.09, 0.10–1.98</td>
<td></td>
</tr>
<tr>
<td>Caishiling unit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cretaceous</td>
<td>Quanyagou Fm. CSL1</td>
<td>Gray-white sandstone</td>
<td>228–2915</td>
<td>ca. 262</td>
<td>94</td>
<td>0.10–2.05</td>
<td></td>
</tr>
<tr>
<td>Late Jurassic</td>
<td>Caishiling Fm. CSL2</td>
<td>Gray-white sandstones</td>
<td>246–2661</td>
<td>ca. 254</td>
<td>100</td>
<td>0.03, 0.06, 0.12–1.55</td>
<td></td>
</tr>
<tr>
<td>Early–Middle Jurassic</td>
<td>Dameigou Fm. CSL3</td>
<td>Gray-yellow sandstones</td>
<td>220–2480</td>
<td>ca. 264</td>
<td>97</td>
<td>0.25–3.82</td>
<td></td>
</tr>
</tbody>
</table>
Figure 8. U-Pb concordia diagrams for zircon grains from the five sandstone samples.
a distribution spanning from 1073 Ma to 701 Ma with a peak at 926 Ma, and finally seven ages clustered around 1416 Ma.

**Cretaceous Samples**

The zircons from sample G1 (Quanyagou Formation) are predominantly colorless, euhedral to subhedral, and with a length of 50–150 μm. Most zircons show oscillatory zoning without inherited cores or overgrowths. All analyses have moderate U content, with variable Th/U from 0.13 to 1.51. In this study, 59 out of 89 dated grains yielded a 206Pb/238U range of 521–218 Ma with two age peaks at 414 Ma and 238 Ma (Fig. 9D). The age of the remaining zircons range from 2532 to 818 Ma with several subpeaks at 2502, 1737, and 904 Ma.

In sample CSL1 (Quanyagou Formation), zircon grains show euhedral to abraded shapes with an average size between 50 μm and 200 μm. Most crystals show distinct oscillatory zoning. Th/U ratios vary from 0.10 to 2.05. One-hundred grains were analyzed, and 94 effective data points were obtained. The U-Pb ages range from 2915 to 228 Ma. The ages can be separated in four main groups with three peaks at 897 Ma, 456 Ma, and 262 Ma (Fig. 9E). In addition, 15 Proterozoic ages are given older than 1000 Ma.

## DISCUSSION

### New Piercing Points

Using lithologic and stratigraphic constraints, we conclude that both the Tula and Anxi sections were once regions of extensive subsidence characterized by topographic lows (Figs. 1 and 2). The dark mudstone, oil sands (Fig. 5E), and asphalt (Fig. 5F) found in the Upper Jurassic strata of the Tula section indicate Tula Basin was once a depression during Late Jurassic time. In addition, matching geochemical fingerprints (e.g., carbon isotopic composition) between the Jurassic oil-bearing sandstone of the Tula Basin and the Jurassic crude oil of Qaidam Basin suggest that these two regions must have been parts of the same prototype basin (Guo et al., 1998). Recent studies confirm that the relatively rigid Qaidam Basin was transported northeastward along the Altyn Tagh fault during the Cenozoic, and it has not undergone obvious basin-scale vertical-axis rotation with respect to the Eurasian plate since early Eocene time (E. Wang et al., 2006; Y. Yu et al., 2014). Considering the large-scale, left-lateral, strike-slip displacement of the Altyn Tagh fault during Cenozoic time, we suggest that the Tula and Anxi sections were once part of the Qaidam Basin but detached from the Qaidam during its northeastward migration driven by faulting on the Altyn Tagh fault. We propose that the Qaidam Basin may have actually been originally located much farther southwest along the Altyn Tagh fault than its present position, likely located where the Tula and Anxi sections currently reside.

Stratigraphic successions are generally deposited during basin infilling processes, while periods of nondeposition or erosion are likely related to regional
tectonic events (e.g., Wheeler, 1964; Allen and Allen, 1990; Boggs, 2006). In the Tula section, Paleocene strata correlate well with strata in the Caishiling section; however, post-Paleocene strata are missing (Figs. 4 and 7). In the Anxi section, Paleocene to early Miocene strata cross-correlate with comparable strata preserved in the Caishiling section, whereas the late Miocene strata are missing (Figs. 6 and 7). In the Qaidam Basin, and particularly in the Caishiling section, the Paleocene to Quaternary strata are well developed (Figs. 2 and 7). If we consider a stepwise northeastward migration of the Qaidam Basin along the Altyn Tagh fault throughout the Cenozoic, the absence of post-Paleocene strata in the Tula section marks the detachment of the Qaidam Basin from this section. Similarly, the absence of late Miocene strata in the Anxi section marks the detachment of the Qaidam Basin from this section (Fig. 7). We therefore propose that the Paleocene strata in the Tula section and the Paleocene to early Miocene strata in the Anxi section represent the two piercing points that can identify the initial position and early stages of Qaidam Basin detachment and movement.

The Tula section contains consistently southward-dipping strata on both sides of the low-angle (<10°) Jurassic–Cretaceous and Cretaceous–early Eocene unconformities (Fig. 4). These Jurassic–early Eocene sequences are heavily deformed, forming a major north-verging syncline with a steeply dipping south limb and a shallowly dipping north limb, indicating that the deformation of these Jurassic–early Eocene sequences occurred during or after early Eocene time (Fig. 4). We therefore suggest that the topographic low in the Tula area became isolated during early Eocene time, and the folding of the Tula syncline was related to motion on the fault to the south, which was kinematically linked to the Altyn Tagh fault during this time period. It is therefore likely that the Tula section was part of the Qaidam Basin during early Eocene time and became isolated when the Qaidam Basin migrated northward. This migration was induced by movement along the Altyn Tagh fault, which is consistent with the initial timing of faulting along the Altyn Tagh fault (ca. 49 Ma) as proposed by Yin et al. (2002). We therefore conclude that the Tula section is an appropriate piercing point with which to constrain the initial stage (ca. 49 Ma) of faulting along the Altyn Tagh fault.

In the Anxi section, the fine-grained deposits in the Oligocene to Miocene strata indicate that the Anxi unit was once a topographic low (HGSI, 2003). The lithofacies of the Pliocene Shizigou Formation of the Anxi section are dominated by a succession of proximal fluvial deposits. In the western Qaidam Basin, the Pliocene Shizigou Formation is characterized by lacustrine facies (Yin et al., 2008b), suggesting that these two regions maintained different depositional systems during Pliocene time. The continuous sequences of Paleocene to early Miocene strata and the angular unconformity between the Youshashan and Shizigou Formations demonstrate that the Anxi section experienced a tectonic event between the early Miocene and Pliocene Epochs, and this event in turn resulted in the deformation of the Paleocene to early Miocene strata (Figs. 6 and 7). Seismic profiles from the western Qaidam Basin reveal that the Pliocene strata conformably overlie the Miocene strata and illustrate a distinctive unconformity between the Shangyoushashan and Xiayoushashan Formations, both of which are Miocene in age. This unconformity becomes most prominent in the southern foothills of the Altyn Tagh Range, further indicating intense left-lateral strike-slip faulting along the Altyn Tagh fault (Figs. 3 and 10; Meng and Fang, 2008; L. Wang et al., 2010; Wu et al., 2012a). Within the western Qaidam Basin, this unconformity is characterized by growth strata that started to develop after the initial deposition of Miocene strata. In profile D–D’ (Fig. 10), the deposits are cut by a branch fault of the Altyn Tagh fault, and the pre-Miocene strata are deformed by an anticline, which was later cut and sealed by Miocene strata. Similarly, in profile E–E’ (Fig. 10), the growth strata are well developed, and the thickness of the Eocene to Miocene pregrowth strata remains constant. The middle Miocene to Quaternary deposits thin northwestward (toward the Altyn Tagh Range). Based on magnetostratigraphy, palynology and paleontology within the basin, the accurate timing of this regional unconformity has been constrained to ca. 15 Ma (Fang et al., 2007; Gao et al., 2009; Lu and Xiong, 2009; L. Wang et al., 2010; Wu et al., 2012a). We thus suggest that the apparent unconformity between the Shangyoushashan and Xiayoushashan Formations indicates middle Miocene (ca. 15 Ma) motion of the Altyn Tagh fault system. Based on this, we propose that the deformed Paleocene to Miocene strata of the Anxi section represent another piercing point with which to constrain the historical position of the western Qaidam Basin during mid-Miocene time. The initial stage of left-lateral strike-slip faulting along the Altyn Tagh fault led to a gradual separation of the western Qaidam Basin from the Anxi section. Tectonic movement precluded new deposition of strata, and the Anxi section became isolated from the Qaidam Basin during late Miocene time. In addition to the Altyn Tagh fault, we suggest the left-lateral strike-slip faulting of the Baiganhu fault to the south of the basin also accommodated the northeastward motion of the Qaidam Basin (Cowieill et al., 2003; HGSI, 2003; Wang et al., 2014). The Pliocene marginal conglomerate facies of the Anxi section formed via proximal accumulation sometime after initial-stage left-lateral strike-slip faulting of the Altyn Tagh fault.

Provenance Analysis of Jurassic to Cretaceous Strata

If the Cenozoic strata in the Tula and Anxi sections represent the initial timing and early stages of motion along the Altyn Tagh fault, and the postulated historical position of the Qaidam Basin is reasonable, the prefaulting deposits (Mesozoic strata) in the Tula section and the western Qaidam Basin (Caishiling section) should be lithologically similar and their provenance comparable.

Paleocurrents in the Jurassic strata of the Tula, Anxi, and Caishiling sections all suggest northward current movement, while Cretaceous strata show southward-moving paleocurrents (Fig. 7; Ritts and Biffi, 2000). In general, there are relatively few paleocurrent data for the Tula, Anxi, and Caishiling sections (e.g., n = 4 in the Tula section); however, the generally consistent orientation of paleocurrents across all three sections reflects a similar topography for these regions (Tula, Anxi, and Caishiling) between Jurassic and Cretaceous time. Relative probability histogram plots of pluton ages in the Altyn Tagh and Eastern Kunlun ranges are shown in Figure 9. Based on the morphological characteristics,
Figure 10. Seismic profiles in the southwestern Qaidam Basin; see Figure 2 for location. (A) Uninterpreted and (B) interpreted seismic profiles in the SW–NE direction; (C) uninterpreted and (D) interpreted seismic profiles in NW–SE direction. Note that the growth strata since the Xiayoushashan Formation (N$_{2}$xy) indicate the intense tectonic movement of the Altyn Tagh fault during middle Miocene time.
internal textures, and Th/U ratios of zircons, magmatic zircons (~80%) appear to dominate the section, while metamorphic zircons (~20%) comprise the remainder (Corfu et al., 2003; Hanchar and Rudnick, 1995; Hoskin and Black, 2000).

In the Altyn Tagh Range, Archean and Proterozoic basement rocks are widely exposed with Archean zircon U-Pb ages ranging from ca. 3.6 Ga (Lu et al., 2008) to ca. 2.6 Ga (Lu and Yuan, 2003) and Proterozoic zircon U-Pb ages ranging from ca. 2.4 Ga to ca. 650 Ma (Gehrels et al., 2003a, 2003b; C. Wang et al., 2006; Zhang et al., 2011; Wang et al., 2013). Paleozoic intrusions within this range show zircon U-Pb ages ranging from ca. 550 Ma to ca. 400 Ma (Fig. 2; Sobel and Arnaud, 1999; Zhang et al., 2001; Cowgill et al., 2003; Gehrels et al., 2003a; Chen et al., 2004; Yue et al., 2004a, 2005; Yang et al., 2006; Wang et al., 2008; Liu et al., 2009). Only a few isolated Permian igneous rocks are distributed along the center of this range, with zircon U-Pb ages ranging between ca. 300 Ma and ca. 270 Ma (Cowgill et al., 2003; Gehrels et al., 2003a, 2003b).

With regard to the Eastern Kunlun Range, the Proterozoic basement rocks are isolated and show zircon U-Pb ages ranging from 1900 to 800 Ma (e.g., HGSI, 2003; Wang et al., 2013). The Paleozoic to late Proterozoic intrusions show a zircon U-Pb age peak around 430 Ma, which is based on early Paleozoic metamorphic rocks that represent the Ordovician–Silurian docking of the Kunlun and Tarim blocks (e.g., Matte et al., 1996; Cowgill et al., 2003; Li et al., 2013). The Kunlun basement age distribution is characterized by the occurrence of late Paleozoic–early Mesozoic ages (ca. 300 to ca. 200 Ma), which correspond to the Permian–Triassic closure of the PaleoTethys Ocean and the docking of the Qiangtang block (Roger et al., 2003, 2008, 2010; Dai et al., 2013; Li et al., 2013). Finally, a few Mesozoic ages (e.g., ca. 74 Ma) have been obtained from the Tula section (Robinson et al., 2003).

In order to better constrain the provenance of the five sandstone samples, the plutons of the Altyn Tagh and Eastern Kunlun ranges are simply divided into two groups: those plutons with an age older than 270 Ma, and those with an age younger than 270 Ma. Older plutons are widespread in both the Altyn Tagh and Eastern Kunlun Ranges, whereas younger plutons are confined to the Eastern Kunlun Range just south of our sample sites (Fig. 2). This distinct pluton distribution can be used as a provenance signature to identify the source of detrital zircon for our Mesozoic samples. In general, detrital zircon age clusters in all five samples are basically similar and characterized by two main groups of Permian–Triassic and Paleozoic ages along with a small number of Precambrian ages. The appearance of the Permian–Triassic zircon ages (<270 Ma) in all five samples strongly suggests an East Kunlun Range provenance. We consider that the slightly different peak ages of sample CSL1, CSL2, CSL3, G1, and G2 result from contributions of plutonic debris with a variety of ages (Fig. 9; Table 1).

In the Caishiling section, the sampling sites of the three Jurassic–Cretaceous samples (CSL1, CSL2, and CSL3) are located at the southern piedmont of the Altyn Tagh Range, where the basement is mainly dominated by Paleozoic and Precambrian plutons with ages older than 270 Ma (Fig. 9). If the Caishiling section has been situated in roughly the same region that it occupies today (Fig. 2), the Altyn Tagh Range must serve as the ultimate provenance for the zircons from the Jurassic–Cretaceous samples. If this is the case, the U-Pb age spectrum of these samples should display a Paleozoic and Precambrian age peak (>270 Ma). In samples CSL1, CSL2, and CSL3, the detrital zircon age spectra are similar and characterized by two main groups of Permian–Triassic and Paleozoic ages along with a small number of Precambrian ages. The widespread distribution of the Paleozoic and Precambrian plutons in both the Altyn Tagh and Eastern Kunlun Ranges prevents the use of zircon age spectra to estimate the source area of these Cretaceous and Jurassic samples. Nevertheless, all three samples contain a host of Late Permian to Triassic zircon ages (<270 Ma), which are found only in the plutons of the Eastern Kunlun Range, particularly those in the south Tula section (Figs. 2 and 9). In addition, the angular grains in the Jurassic samples show poor sphericity and poor sorting, indicating deposition from a proximal source terrain (Figs. 5A and 5B). Based on the proximal source feature and the particular age spectrum (containing a host of Late Permian to Triassic zircons) of these three samples, we suggest the Caishiling section was situated far closer to the Tula section in the past as compared with its current position. Meanwhile, plutons in the Eastern Kunlun Range had already been unroofed during Early Jurassic time, representing a main source to the Dameigou (J1s), Caishiling (J1c), and Quanyagou (Kq) Formations since that time.

In the Tula section, two Jurassic and Cretaceous samples (G1 and G2) were selected from the narrow Tula subbasin. The G1 sample was selected near the Eastern Kunlun Mountains, while the G2 sample was selected near the Altyn Tagh Range (Figs. 2 and 4). The age cluster of sample G1 features two main groups of Permian–Triassic and Paleozoic ages along with minor Precambrian ages, a pattern similar to that found in the Cretaceous sample from the Caishiling section (Figs. 9D and 9E). We thus suggest that the Late Permian to Triassic strata of the Eastern Kunlun Range, and the Paleozoic and Precambrian plutons in both Eastern Kunlun and the Altyn Tagh Ranges are the source rocks for the Cretaceous strata (Figs. 2 and 4). In particular, the age spectrum in the Early Jurassic sample (G2) is characterized by an exceptionally unimodal distribution of detrital zircon (age ranging from 404 to 493 Ma, peak at 447 Ma) with only one Triassic age (250 Ma), whereas all of the other samples (G1, CSL1, CSL2, and CSL3) are characterized by bimodal distributions (Permian–Triassic and Paleozoic groups), suggesting that G2 is a distinct sample. The site location for G2 is extremely close to the Altyn Tagh Range, and the older plutons within the Altyn Tagh Range serve as a major source of debris for sample G2 (Figs. 2 and 4). Older plutons from the Altyn Tagh Range represent the dominant source material, resulting in relatively little contribution from the Eastern Kunlun Range, as evidenced by very few Permian to Triassic zircons in the age distribution of sample G2 (Fig. 9A). However, the one zircon grain with a Triassic age found in sample G2 and the northward paleocurrents do suggest some small contribution may have come from the Permian–Triassic rocks of the Eastern Kunlun Range (Figs. 7 and 9A; Ritts and Biffi, 2000). Therefore, we suggest the most plausible explanation for the anomalous detrital zircon ages found in the G2 sample is a mixture of source material from both the Altyn Tagh and the Eastern Kunlun Ranges. If the plutons from both locations (Paleozoic and Precambrian...
in the Altyn Tagh Range and Permian to Triassic in the Eastern Kunlun Range) were exhumed during Jurassic time, they would represent a mixed source for samples G2 and CSL3 during that time.

By reconciling the detrital zircon ages of the sediments from the Altyn Tagh and Eastern Kunlun Ranges and combining these data with the large-scale left-lateral strike-slip displacements measured along the Altyn Tagh fault, we deduce that the Caishiling section must have been located much closer to the Eastern Kunlun Range between Jurassic and Cretaceous time. The Tula unit, on the other hand, likely has not moved since Jurassic time. The lithologic and stratigraphic contact features of the residual Mesozoic to Cenozoic strata along the Altyn Tagh fault combined with U-Pb dating of the Jurassic and Cretaceous samples of the Tula and Caishiling sections enable us to establish the timing of movement along the Altyn Tagh fault. We resolve the motion along the Altyn Tagh fault into two distinct stages: initial movement occurring at ca. 49 Ma and a subsequent early stage of movement occurring at ca. 15 Ma. Both stages promoted strike-slip motion along the fault. The Tula and Anxi sections can be used as piercing points along the western segment of Altyn Tagh fault, and we identify these regions as residual components of the original Qaidam Basin.

Implications for the Initial Timing and Total Offset of the Altyn Tagh Fault

General Review of Previous Estimates

In the past few decades, several approaches have been used to estimate the overall displacement along the Altyn Tagh fault. By comparing Paleozoic suture zones in the western Kunlun Range with those in the Qilian Shan, CSBS (1992) argued for ~1200 km of offset along the fault. By matching similar geologic features, particularly late Paleozoic magmatic belts in the western and eastern Kunlun Shan, ranges of 300–500 km, 475 ± 70 km, and ~550 km of displacement have all been estimated (Tapponnier et al., 1988; Peltzer and Tapponnier, 1988; Cowgill et al., 2003). Comprehensive correlations of the geologic features with the magmatic histories in the Altyn Tagh Range, Qilian Shan, and Nan Shan enabled Gehrels et al. (2003a) to suggest offsets of ~370 km, 375 km, and ~400 km along the Altyn Tagh fault. By reconstructing the shortening of the Nan Shan thrust belt, Yin and Harrison (2000) inferred 360 ± 50 km of displacement. A comprehensive analysis of the geologic features along the north margin of the Tibetan Plateau has yielded estimates of ~400 km of offset (Molnar and Tapponnier, 1975). Using the measured Pliocene–Quaternary slip rate over the inferred duration of faulting along the Altyn Tagh fault, Burchfiel and Royden (1991) estimated ~200 km of fault displacement. By matching the Tertiary rocks along the northern and the central segments of the Altyn Tagh fault, Wang (1997) ascertained 65–90 km of displacement. Chen et al. (2002) suggested an offset of 500 ± 130 km between 24 Ma and present based on paleomagnetic data from the Qaidam Basin. Notably, 400 ± 60 km has also been suggested based on the reconstruction of a Jurassic facies boundary across the Altyn Tagh fault (Ritts and Biffi, 2000).

On the other hand, magnetostratigraphy and sedimentological analysis have led some to suggest that the Altyn Tagh fault has been active since ca. 49 Ma rather than simply 24 Ma (Yin et al., 2002). Thermochronological data from the Altyn Tagh Range in conjunction with sedimentological evidence suggest that left-lateral strike-slip faulting occurred from late Eocene to early Oligocene time (Chen et al., 2001; Meng et al., 2001; Yue et al., 2001; Ritts et al., 2004). Yet we still suggest that the Altyn Tagh fault use plutonic belts or suture zones as the offset markers, but these large tectonic features have poor spatial definition because of high uncertainties in their shape and the extent of their geologic margins (Yin and Harrison, 2000; Yin et al., 2002). The intense deformation and shortening of the eastern and western Kunlun Ranges throughout geologic history as well as the deformation along the Qilian Shan have served to profoundly complicate any measurement of the actual displacement of the Altyn Tagh fault.

Reassessing Cenozoic Kinematic Patterns on the Altyn Tagh Fault Using New Piercing Points

The Qaidam and Tarim Basins are both relatively rigid blocks when compared with the Altyn Tagh Range, which gives them relatively higher crustal strength (E. Wang et al., 2006; Zhou et al., 2006). Paleomagnetic studies have revealed a 13.3° ± 8.8° difference in paleomagnetic declination between the two halves of the arcuate structure outlined in the uplifted region of the Tula section (Fig. 4; see also fig. 3 in Dupont-Nivet et al., 2004) and suggest northward transport along the Altyn Tagh fault of this section, the western segment of the Eastern Kunlun Range (Qimen Tagh Range), and the Qaidam Basin (Dupont-Nivet et al., 2004; Yu et al., 2014). The absence of a large vertical axis of rotation in the area adjacent to the Altyn Tagh fault indicates that the left-lateral shear strain between the Tarim Basin and the northern Tibetan Plateau is concentrated on the relative weak Altyn Tagh fault (Dupont-Nivet et al., 2002, 2003, 2004; J.M. Sun et al., 2005). The relative movement of the Qaidam and Tarim Basins is therefore representative of the actual displacement along the AltynTagh fault. The distinctive sediment features that manifest along the Altyn Tagh fault and identify this displacement history can be used to locate appropriate piercing points, which can further be used to restrict the timing of this displacement (Yin and Harrison, 2000; Chen et al., 2003; Cowgill et al., 2003; E. Wang et al., 2006; Yin et al., 2002, 2008b). In this paper, the residual Mesozoic to Cenozoic strata within the western Qaidam Basin are documented as the piercing points that identify the Cenozoic kinematic pattern of the Altyn Tagh
fault. In order to account for the fact that the Qaidam Basin and the relic Tula units are situated south of the currently active Altyn Tagh fault trace, two faults or major unconformities are required to act as boundaries between the detached Qaidam Basin and relic Tula subbasin (Fig. 11).

Between the Jurassic and early Eocene, the westernmost part of the originally rigid Qaidam Basin was located where the Tula section is situated today (Fig. 11A). Strike-slip movement along the Altyn Tagh fault began shortly after the early Eocene. Faulting on the Altyn Tagh fault induced the NE-SW-trending branch fault (F1) in this region, now covered by Quaternary alluvium, deforming the Jurassic to early Eocene strata in the Tula section as it did so (Figs. 2 and 4). The initial strike-slip movement of the Altyn Tagh fault also transported the original Qaidam Basin northeastwards and gradually separated the Qaidam Basin from the Tula section. The depression in the Tula section then uplifted and was gradually isolated, leading to a pause in deposition during the late Paleogene to Neogene. This left-lateral faulting also lead to compression in the northern Qaidam Basin, which began in the Paleocene to early Eocene as revealed by seismc profile data (Yin et al., 2008a; Fig. 11A). Systematic analysis of the Cenozoic stratigraphic sections along the Altyn Tagh fault suggests that strike-slip movement along the western and central Altyn Tagh fault was initiated at ca. 49 Ma (Yin et al., 2002), roughly consistent with the speculated sediment termination age of the Tula section. This onset age for large strike-slip faulting in the northern Tibetan Plateau is also synchronous with the collision of India and Asia as revealed by newly acquired paleomagnetic evidence in southern Tibet (Dupont-Nivet et al., 2010; Huang et al., 2013; Lippert et al., 2014). This indicates that the deformation in northern Tibet may have begun as India and Eurasia began colliding. It is possible that the dominant cause of the large-scale strike-slip faults in the Asian interior (especially the Altyn Tagh fault) was the India-Asia collision itself, the effects of which may still be felt on the northern Tibetan Plateau today.

Between early Eocene and mid-Miocene time, movement of the Altyn Tagh fault transported the westernmost part of the original Qaidam Basin northeastward to the position where the Anxi unit is at present. During the mid-Miocene, an intense left-lateral strike-slip motion occurred along the Altyn Tagh fault, and the originally rigid Qaidam separated from the Anxi unit and migrated northeastward continuously (Fig. 11B). This fault motion tilted the late Paleocene to early Miocene strata of the Anxi section and created a regional unconformity between the Shangyouhashan and Xiayoushashan Formations. This unconformity matches the widespread unconformity within the western Qaidam Basin (Figs. 3 and 7; L. Wang et al., 2010; Y. D. Wang et al., 2010; Wu et al., 2012a, 2012b). The growth strata above this unconformity reveal a rapid tectonic event occurred just after the mid-Miocene Epoch (ca. 15 Ma). Based on the widespread potassic volcanism in northern Tibet, Yue and Liou (1999) also inferred intense fault movement along the Altyn Tagh fault ca. 13–16 Ma. This mid-Miocene faulting is recorded by the fission track present in both the Altyn Tagh Range and the northern Qaidam Basin (Jolivet et al., 2001; Wan et al., 2001). Overall, the tectonic events of the mid-Miocene are widespread and well developed in the Tibetan Plateau (e.g., Yue and Liou, 1999; Kirby et al., 2002; Clark et al., 2004; Ding et al., 2004; J.M. Sun et al., 2005; Wang et al., 2012), which may reflect a critical period in the process of Tibetan Plateau growth. Following this, as seen in the Anxi section, the depression in the Anxi section became folded, uplifted, and isolated, gradually leading to a pause in deposition during the late Miocene (Figs. 6 and 7).

Since the late Miocene Epoch, continuous left-lateral strike-slip faulting along the Altyn Tagh fault has gradually transported the Qaidam Basin to its present position.
present position (Fig. 11C). Finally, recent left-lateral strike-slip faulting occurred along the entire Altyn Tagh fault, reshaping the original faulting style. The Tula and Anxi units can be selected as piercing points to constrain the Cenozoic kinematic patterns of the Altyn Tagh fault. Based on these offset markers, we estimate ~170 km of offset occurred between the middle Eocene and middle Miocene Epochs, and ~190 km of offset occurred between the late Miocene Epoch and the present, resulting in a total offset of ~360 km along the Altyn Tagh fault during the Cenozoic (Fig. 11). This estimate suggests an average sinistral slip rate of ~5.0 mm/yr between the middle Eocene and the middle Miocene and an increase to ~12.6 mm/yr between the Miocene and the present. Our estimates for the overall displacement (~360 km) and average sinistral slip rate since the mid-Miocene are consistent with previous studies (Peltzer and Tapponnier, 1988; Rits and Biffi, 2000; Yin and Harrison, 2000; Shen et al., 2001; Yin et al., 2002; Cowgill et al., 2003, 2009; Zhang et al., 2004, 2007). The accelerated strike-slip motion along the Altyn Tagh fault between the middle Miocene and present day implies that the increased regional deformation of the northern Tibetan Plateau may be related to the penetrative and far-reaching effects of the Asia-India collision.

CONCLUSIONS

As the major strike-slip fault on the northern Tibetan Plateau, the Altyn Tagh fault holds important implications for unraveling the Cenozoic growth history of the entire Tibetan Plateau.

By correlating the lithology and sedimentary features of the Cenozoic strata along the Altyn Tagh fault, and analyzing the detrital zircon U-Pb ages from Mesozoic strata in three sections along the fault, we find that these strata record the northward migration of the Qaidam Basin and can be identified as the piercing points for defining the Cenozoic offset of the Altyn Tagh fault. Specifically, the Tula section records the early Eocene position of the western Qaidam Basin (e.g., Caishiling section), while the Anxi section documents its middle Miocene position. Based on this, we estimate ~170 km of offset occurred between the early Eocene (ca. 49 Ma) to middle Miocene (ca. 15 Ma), and ~190 km of offset occurred between the late Miocene and the present day, yielding ~360 km of total offset along the Altyn Tagh fault during the Cenozoic period. This estimate implies that motion along the Altyn Tagh fault has accelerated in recent time from an average sinistral slip rate of ~5.0 mm/yr between the early Eocene (ca. 49 Ma) to middle Miocene (ca. 15 Ma) to an accelerated rate of ~12.6 mm/yr from the middle Miocene to the present day.

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