Cenozoic tilting history of the south slope of the Altyn Tagh as revealed by seismic profiling: Implications for the kinematics of the Altyn Tagh fault bounding the northern margin of the Tibetan Plateau

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ABSTRACT

The Altyn Tagh fault (ATF) plays a significant role in the northward growth of the Tibetan Plateau, but its Cenozoic kinematics and related structural response in adjacent basins remain debated. In this study, we identified a transition zone between the ATF and the Qaidam Basin interior and termed it the Altyn Slope, based on a dense network of two- and three-dimensional seismic reflection profiles and isopach maps. Tilted by a series of E-W–trending transpressional faults that constitute the positive flower structure of the ATF, the present Altyn Slope is characterized by a southeast-dipping slope with its undulating southeastern boundary with peaks coincidentally located at the major anticlinal belts in the basin. We propose a method for restoring the Cenozoic tilting history of the Altyn Slope during different time periods by identifying growth-strata geometry from the recent isopach maps. The results show that the Altyn Slope began to form in the late Eocene (ca. 40 Ma) and continued to expand until the mid-Miocene (ca. 15 Ma) albeit with a temporally developing shape. However, the Altyn Slope shrank toward the ATF and underwent significant NE-SW–directed folding since the mid-Miocene (ca. 15 Ma), resulting in formation of undulations of its southeastern boundary. We infer that the left-slip motion on the ATF is divided into two distinct stages: during the first stage, ca. 40–15 Ma, the ATF was activated with slow slip rate, and most transpressional stress was converted to vertical strain, raising the Altyn Slope instead of producing strike-slip motion. During the second stage, since ca. 15 Ma, faster sinistral strike-slip motion on the ATF took place, releasing the stress beneath the Altyn Slope and inducing intense NE-SW–directed shortening within the Northern Tibetan Plateau.

INTRODUCTION

As the northern boundary of the Tibetan Plateau, the ~1600-km-long left-slip Altyn Tagh fault (ATF) links all the major thrust belts and basins in and around the northern plateau (Yin et al., 2002). Knowledge of the ATF therefore is important for understanding the growth of the Tibetan Plateau during the Cenozoic era (Tapponnier et al., 2001; Yin et al., 2002; Cowgill et al., 2003; Meng et al., 2012), as well as understanding the development of adjacent basins (Chen et al., 2004; Ritts et al., 2004; Yue et al., 2001; Wu et al., 2012a, 2012b; Xiao et al., 2013). Since its identification on remote sensing images four decades ago (Molnar and Tapponnier, 1975), an increasing number of studies have been carried out on this large-scale fault system, detailing its geometry (Cowgill et al., 2000; Wittlinger et al., 1998), kinematics (Bendick et al., 2000; Mériaux et al., 2005; Cowgill et al., 2008; Elliott et al., 2015), and evolution (Yue and Liou, 1999; Yin et al., 2002; Cowgill et al., 2003; Liu et al., 2007; Wu et al., 2012b). Some studies also examined possible source-to-sink relationships between the Altyn Tagh and the sediments exposed along specific sections (e.g., Chen et al., 2004; Wu et al., 2012b; Li et al., 2014; J.M. Sun et al., 2005; Cheng et al., 2015). But few studies concentrated on the structural responses to the activity of the ATF in the adjacent basins, which is also of crucial importance for acquiring a detailed knowledge of the specific evolution of the ATF.

The Qaidam Basin is the largest sedimentary basin within the Tibetan Plateau and is bounded by the ATF to the northwest (Fig. 1A). Thick and nearly continuous Cenozoic sediments (Wu et al., 2014) have been well preserved within the basin, containing the most integrated information recording the Cenozoic history of the ATF. Much work has been done to establish a tectonic-sedimentary link between the ATF and the Qaidam Basin (e.g., Bally et al., 1986; Chen et al., 2002; Zhuang et al., 2011; Wu et al., 2012b; Wang et al., 2006; Wang et al., 2010). Bally et al. (1986) proposed that the ATF and the structures along the western edge of the Qaidam Basin were active since the middle Eocene. Wang et al. (2006) inferred that most of the sediments within the depocenters of the Qaidam Basin were sourced from the Pamir folded belt in western Tibet and transported by a lengthy longitudinal river that developed along with the left-lateral motion of the ATF since the Oligocene, and that disappeared at ca. 2–4 Ma. Yin et al. (2002) suggested that the Qaidam Basin was offset from the Tarim Basin by the left strike-slip
of the ATF and developed internal drainage since the Oligocene or possibly late Eocene due to the relative motion of the Altyn Tagh, i.e., the sliding door mechanism. These studies, however, lack a systematic understanding of the structural coupling between the ATF and the Qaidam Basin, possibly because they are mainly based on field investigations, although most areas of the western Qaidam Basin are now covered by late Quaternary sediments (Fig. 1B). Fortunately, natural gas exploration during the past decade has yielded a growing number of two-dimensional (2-D) and three-dimensional (3-D) seismic surveys conducted in the northwestern Qaidam Basin adjacent to the ATF, providing a good opportunity to unravel its structural features and to detail its structural coupling with the ATF. In this study, we identified a structural transition zone between the ATF and the Qaidam Basin interior, which we termed the “Altyn Slope” because its formation and evolution were closely related to the ATF. The tilting history of the Altyn Slope was reconstructed through the analysis of the 3-D patterns of growth strata, based mainly on newly obtained high-resolution seismic reflection data, borehole logs, and isopach maps, which place new constraints on the Cenozoic movement of the ATF.

**GEOLOGICAL SETTING**

The Qaidam basin, with an area of ~120,000 km² and an average elevation of >3000 m, is a rhomb-shaped intermontane basin bounded by the Altyn Tagh to the northwest, the Qilian Shan to the northeast, and the East Kunlun Shan to the south (Yin and Harrison, 2000) (Fig. 1A). It developed on Proterozoic–Paleozoic basement and accumulated thick Mesozoic and Cenozoic terrestrial sediments with an obvious regional unconformity between the Paleogene and the lower Cretaceous (Fig. 1B; GMBQP, 1991). The present-day Qaidam Basin is generally accepted to have formed in the Cenozoic in response to the ongoing
collision between India and Asia (Tapponnier et al., 2001; Yin and Harrison, 2000; Yin et al., 2008a, 2008b; Wang et al., 2006) and is characterized by a large NW-trending syn-depositional Tertiary synclinorium with the depocenters that persist along the central axis but that have migrated eastward throughout the Cenozoic (Bally et al., 1986; Wang et al., 2006; Yin et al., 2008a). Thus, the Cenozoic Qaidam Basin developed as a synclinal depression (Meng and Fang, 2008) rather than a foreland basin (Zhu et al., 2006). Yin et al. (2002) suggested that the Qaidam Basin began to receive sediments from both the north and the south as the corresponding thrust belts were initiated during or immediately after the onset of the Indo-Asian collision (ca. 50–55 Ma). This timing is consistent with the results of balanced cross-section restoration indicating that the Qaidam Basin has undergone continuous shortening since the Paleocene or early Eocene (Zhou et al., 2006; Yin et al., 2008a). Recent study focusing on the activities of the fault system in the southwestern part of the Qaidam Basin based on up-to-date 3-D seismic data suggests that the Qaidam Basin started to experience compressional deformation as early as the Paleocene (Wu et al., 2014). Deformation in the northwestern Qaidam Basin is considered to have occurred since at least the early Oligocene in response to the activation of the ATF; according to growth strata and abruptly altered sedimentary facies (Meng and Fang, 2008; Yue and Liou, 1999; Yue et al., 2005; Wu et al., 2012a, 2012b). Intense NE-SW-directed intrabasinal folding and faulting, which formed the present structural framework within the basin, decreasing eastward (Yin et al., 2007; Zhang et al., 2013), mainly commenced as late as Pliocene (Meng and Fang, 2008; Zhou et al., 2006; Xiao et al., 2013).

Cenozoic deposits within the Qaidam Basin consist generally of nonmarine clastic rocks with a maximum thickness of >15 km (Wang et al., 2006), and can be assigned to the following eight formations from oldest to youngest (Fig. 2): Lulehe Formation (LLH, 53.5–43.8 Ma), Lower Xiaganchaigou Formation (LXG, 43.8–40 Ma), Upper Xiaganchaigou Formation (UXG, 40–35.5 Ma), Shanggan-Lulehe Formation (LLH, 53.5–43.8 Ma), Lower Xiaganchaigou Formation (LXG, 43.8–40 Ma), Upper Xiaganchaigou Formation (UXG, 40–35.5 Ma), Shanggan-Lulehe Formation (LLH, 53.5–43.8 Ma), Lower Xiaganchaigou Formation (LXG, 40–35.5 Ma), Upper Xiaganchaigou Formation (UXG, 40–35.5 Ma), Shanggan-Lulehe Formation (LLH, 53.5–43.8 Ma), Lower Xiaganchaigou Formation (LXG, 40–35.5 Ma), and Qigequan Formation (QGQ, 2.5–0.8 Ma). Ages of these formations have been well constrained by magnetostratigraphy, fossil records, and apatite fission-track ages (Fig. 2; Gao et al., 2009; Z.M. Sun et al., 2005; Lu and Xiong, 2009; Fang et al., 2007). Cenozoic successions in the northwestern Qaidam Basin were predominantly deposited in alluvial, fluvial, and lacustrine environments with significant spatial and temporal facies variations (Meng and Fang, 2008; Wu et al., 2012a), and are composed primarily of conglomerate and sandstone intercalated with siltstone and mudstone, as well local marlstone and gypsum (Fig. 2).

Provenance analysis from paleo-current directions, clast composition, and heavy mineral composition indicates that the Cenozoic sediments in the northwestern Qaidam Basin were derived from the Altyn Tagh to the north (Rieser et al., 2005, 2006; Wu et al., 2012a; Zhuang et al., 2011) and consequently record plentiful information on the Cenozoic evolution of the ATF. Cenozoic sedimentary strata were deformed by faulting and folding generating syn-deformational successions (growth strata) and unconformities between the individual beds on the Altyn Slope that are examined in this paper. We use these features to infer the geological evolution of the ATF and its relationship to the Qaidam Basin.

### Definition and Geometry of the Current Altyn Slope

The Altyn Slope is defined as the transition zone between the ATF and the Qaidam Basin Interior. It extends in the ENE direction from Mang’ai to Lenghu, approximately parallel to the ATF (Fig. 3), and is characterized by the following two features (Fig. 4): (1) its pre-Jurassic basement dips generally toward the southeast; and (2) the thicknesses of the Cenozoic sequences decrease toward the northwest. The present geometry of the Altyn Slope is accurately outlined from the dense network of 2-D and 3-D seismic reflection sections calibrated by drilling data (Fig. 3) because most areas of the Altyn Slope are now covered by Quaternary sediments (Fig. 1B). Tens of NW-, NNW-, and NE-striking seismic reflection sections (in time domain) oriented orthogonally across the Altyn Slope and the Qaidam Basin interior have been interpreted based on borehole logging and surface geology (gray dotted lines in Fig. 3). We identified the hinge points between the basement of the Altyn Slope and the basin interior in each section and projected these points onto the surface (Fig. 4). The present southeastern boundary of the Altyn Slope is depicted by the best-fit line of these projected hinge points, which may represent the maximum extent into the northwestern Qaidam Basin of influence by the ATF. The hinge line undulates, with peaks and valleys, and the peaks are coincidentally located at the antclinal belts within the basin (Fig. 3).

Through interpretation of these subsurface data, we detailed the Cenozoic fault system within the identified Altyn Slope and adjacent Qaidam Basin interior (Fig. 3). In addition to the dominant NW- to NNW-trending faults (e.g., labeled Chainan, Pingdong, and Edong faults in Fig. 3) constituting the overarching structural framework of the Qaidam Basin, previously well documented (Zhou et al., 2006; Yin et al., 2008a, 2008b; Wu et al., 2014), we identify a set of E-W-trending faults that are en echelon distributed and slightly oblique to the main trace of the ATF. To better demonstrate the geometry and deformation history of the Altyn Slope and their coupling with the ATF and the Qaidam Basin interior, we constructed three geologic sections based on surface geology, topography, and seismic and borehole data (Fig. 4). These sections all show that the Altyn Slope is tilted by those E-W-trending, north-dipping basement-involved reverse faults that probably link with the ATF at depth to form typical positive flower structures, e.g., the Niubei, Yuebei, and Caishiling faults. These observations allow us to conclude that the E-W-trending faults are flanking structures of the ATF; manifesting the tilting of the Altyn Slope that is dominated by the left-slip motion of the ATF.

Northwestward-thinning growth-strata sequences, from the Upper Xiaganchaigou formation to the Qigequan formation, are widely preserved along the Altyn Slope (Fig. 4), manifesting late Eocene–early Oligocene initiation of those E-W-trending faults that attach to the Altyn Tagh fault system.
Figure 2. Magnetostratigraphy and lithology of the western Qaidam Basin, China. Black and white stripes indicate normal and reversed polarities, respectively. Numbers denote boundary ages (in Ma) between lithological formations and top and bottom ages. The geomagnetic polarity columns are referred to: A—Gao et al. (2009); B—Z.M. Sun et al. (2005); C—Lu and Xiong (2009); D—Fang et al. (2007). In the geologic time scale: E—early; M—middle; L—late. In the formation names: U.—Upper; L.—Lower. AFT—apatite fission-track.
Intense faulting took place at the end of the deposition of the Xiayoushashan Formation (ca. 14.9 Ma), as demonstrated by the obvious unconformity between the Shangyoushashan and Shizigou Formations and underlying strata, as previously shown by Wang et al. (2010). A typical structure that developed during this period is the notable pop-up bounded by the Niubei fault and its back-thrust; this structure is strongly eroded and unconformably covered by the Shangyoushashan Formation (Fig. 4A). Activity of these E-W–striking faults has diminished since then, only slightly bending the late Cenozoic layers. In contrast, the NW- to NNW-trending reverse faults within the basin were active and accompanied by significant folding in their hanging walls since ca 14.9 Ma (Zhou et al., 2006; Xiao et al., 2013), as revealed by the younger growth sequences (GS-2 in Fig. 4A) ages spanning the mid-Miocene to Pliocene (Shangyoushashan to Qigequan Formations).

### TEMPORAL DEVELOPMENT OF THE ALTYN SLOPE

The present geometry of the Altyn Slope is to be a composite outcome after long-term evolution. To further constrain how the Altyn Slope evolved over time, we applied an approach to delineate its shape during different time periods whereby we identified the extent of syntectonic sequences from precise isopach maps of the corresponding Cenozoic stratigraphic units.

### Methodology

Deposited over the top or against the flanks of growing structures, growth strata are often used to decipher kinematic histories of fault-related folds (Suppe et al., 1997). Much work has been conducted to decipher the relationship between fault-induced tilting of strata and the deposition of syntectonic sediments (e.g., Suppe et al., 1992; Storti and Poblet, 1997; Ford et al., 1997; Zapata and Allmendinger, 1996). Salvini and Storti (2002) provided a method of forward numerical modeling to determine 3-D patterns of growth strata geometries associated with fault-related folds, particularly concerning the thickness variations that clearly reflect the shape of anticline surfaces. Inspired by this work, we developed a way to semiquantitatively restore the tilting history of the Altyn Slope by extracting the extent of the syntectonic sequences affected by the uplift of the Altyn Slope from newly obtained isopach maps of the Cenozoic stratigraphic units.

We assumed that in a compressional depression such as the Qaidam Basin, strata thickness should remain constant or decrease linearly and gently from the basin interior to the margin, given a sedimentation process without tectonic perturbation (Fig. 5A). Once this process is influenced by tectonic activities (e.g., uplift in the hanging walls of reverse faults along the margin), thickness variation no longer maintains this trend but develops steeper gradients toward the margin (Suppe et al., 1992; Salvini and Storti, 2002).
Figure 4 (on this and following page). Geologic sections orthogonal across the Altyn Slope (See Fig. 3 for locations and fault abbreviations, and Fig. 2 for formation abbreviations), and relevant interpreted two-way travel time (TWTT) seismic profiles. The hinge point in each seismic profile is basically identified as the slopebreak of the basement. GS—Growth strata; Mz—Mesozoic; Pz—Paleozoic.
Thus, corresponding hinge points occur in the plot of thickness (T) versus distance (D) (Fig. 5B), which can be obtained from isopach maps. This assumption is verified by forward kinematic modeling of limb-rotation folding process (Storti and Poblet, 1997), which demonstrates clear hinge points on the T-D plot regardless of whether or not the uplift rate is larger than the syntectonic sedimentary rate (Fig. 5C). As the hinge point locations are usually consistent with the growth axial surface marking the transition between folded and unfolded strata (Fig. 5), the area between the Qaidam basin margin (the ATF) and the hinge points is then regarded as the extent of the Altyn Slope at each depositional period. This method is logically simple and reasonable, as attested by forward kinematic modeling (Suppe et al., 1997; Salvini and Storti, 2002), although it lacks accurate quantification because of the variable threshold value of thickness gradient change, influenced by hinge migration, competition between basement uplift and sedimentation, and erosion rate (Storti and Poblet, 1997).

To precisely identify the extent of the Altyn Slope in each period, we first interpolated scattered thickness data into the isopach data for gridding based on the Delaunay triangulation method (Field, 1991), and then measured the thickness variations with a series of NW-trending cross-section rulers (approximately orthogonal to the ATF) to detect the hinge points, and then projected them onto the corresponding gridded isopach maps manually (Fig. 6). Note that the erosion lines are also presented on each isopach map, and none of the NW-trending cross-section rulers exceeds the erosion lines northward, in order to avoid the impact of denudation on the determination of hinge points. A best-fit line is drawn to link these hinge points, depicting the southeastern boundary of the Altyn Slope during each period (Figs. 6C–6G).
Natural sedimentation

Syntectonic sedimentation

Forward models

The current Altyn Slope boundary must be constituted by envelope curves of all these boundaries.

Following this method, we delineated the extents and geometries of the Altyn Slope of seven periods: 53.5–43.8 Ma (Lulehe Formation), 43.8–40 Ma (Lower Xiaganchaigou Formation), 40–35.5 Ma (Upper Xiaganchaigou Formation), 35.5–22 Ma (Shangganchaigou Formation), 22–14.9 Ma (Xiayoushashan Formation), 14.9–8.2 Ma (Shangyoushashan Formation), and 8.2–2.5 Ma (Shizigou Formation). That of the Qigequana Formation (2.5–0.8 Ma) was not analyzed because this formation suffered intense erosion and could not be accurately restored. The isopach maps are modified from Yin et al. (2008b) and further rectified with newly obtained seismic reflection data and borehole data provided by Qinghai Oilfield Company, China National Petroleum Corporation.

We also present four typical cross-sections at different locations showing the T-D plots of individual periods in detail (Fig. 7; see Fig. 6A for locations). In order to highlight the effect of late Cenozoic NE-SW–directed shortening within the basin on the Altyn Slope, we placed three of them (Figs. 6A, 6B, and 6D) on the major anticline belts within the northwestern Qaidam Basin. The values of thickness on these T-D curves are normalized to range between 0 and 1 for comparison.

This work is preliminary and resolution is limited by the density of boreholes and resolution of seismic reflection profiles. However, it can provide an overall view of how the Altyn Slope evolved over time, which can in turn be used as a proxy to study the movement of the ATF.

Results

During the deposition of the Lulehe and Lower Xiaganchaigou formations, the western Qaidam Basin was divided into two NW-striking sub-basins (Figs. 6A and 6B). The northeastern part was mainly occupied by the larger Tilting depression (Y) and a much smaller Niubei depression (N) close to the ATF, while the southwestern part contained several minor depocenters named the Mang’ai (M), OldMang’ai (O), and Jinhongshan (J) depressions. The Mang’ai and Jinhongshan depressions lay against the Altyn Tagh, as inferred by Meng and Fang (2008), and perhaps connect to the Tarim Basin northwestward. The Niubei depression, with a maximum remnant thickness of 600 m, correlates with the thickness in the basin interior. Hinge points were detected locally near the E’boliang and Lenghu areas on the T-D curves of the Lulehe formation (Fig. 6A) but were difficult to resolve on the T-D curves of the subsequent Lower Xiaganchaigou formation (Fig. 6B).

Isopach maps of the Upper Xiaganchaigou formation to the Xiayoushashan formation exhibit similar characteristics to that of the Lower Xiaganchaigou formation, except for the gradual disappearance of the depressions mentioned above in the slope area. Hinge points are evident on all of the T-D curves derived from these maps (Figs. 6C–6E and 7). The southeastern boundaries of the Altyn Slope, as depicted by the best-fit lines of hinge points, have similar undulatory geometry, but with much smaller amplitude. The extent of the Altyn Slope during these periods was smaller than the modern range.
Figure 6 (on this and following two pages). Gridded isopach maps of the Cenozoic stratigraphic units. (A) Lulehe formation (LLH). (B) Lower Xiaganchaigou formation (LXG). (C) Upper Xiaganchaigou formation (UXG). ATF—Altyn Tagh fault. Insets show the typical thickness-distance plot extracted from the corresponding isopach maps, with hinge points highlighted by small rectangles and thickness increasing to the right. The upper ends of the numbered T-D curves in the insets correspond to the northwestern ends of the numbered lines shown in the corresponding panel. Note that these isopach maps are not corrected for compaction. Red solid lines indicate the maximum erosional extents. Blue dots are hinge points. Blue solid lines represent boundaries of the Altyn Slope in different depositional stages, while the black solid line is the current boundary. Y—Yiliping depression; M—Mang’ai depression; O—Old Mang’ai depression; J—Jinhongshan depression; N—Niubei depression.
Figure 6 (continued). (D) Shangganchaigou formation (SG). (E) Xiayoushashan formation (XY). (F) Shangyoushashan formation (SY).
Figure 6 (continued). (G) Shizigou formation (SZG).

Figure 7. Comparison diagram of the thickness-distance (T-D) plots and corresponding hinge points of each period (see Fig. 6A for locations). The vertical and horizontal axes indicate the normalized thickness ($T_N$) and distances away from the basin margin (ATF), respectively. $T_N$ is obtained following the equation $T_N = (T-T_{\text{Min}})/(T_{\text{Max}}-T_{\text{Min}})$, where $T$, $T_{\text{Max}}$, and $T_{\text{Min}}$ represent the true, the maximum, and the minimum strata thicknesses in a certain period, respectively. Eroded portions are marked as dotted lines. The shaded blue and gray areas are used to highlight the tendencies of the T-D curves during the stages of the Upper Xiaganchaigou–Xiayoushashan formations and the Shangyoushashan–Shizigou formations, respectively. 1—Lulehe Formation (LLH); 2—Lower Xiaganchaigou Formation (LXG); 3—Upper Xiaganchaigou Formation (UXG); 4—Shangganchaigou Formation (SG); 5—Xiayoushashan Formation (XY); 6—Shangyoushashan Formation (SY); 7—Shizigou Formation (SZG). It is evident that the hinge points are located relatively farther away (by >10 km) from the Altyn Tagh fault on the major anticline belts after ca. 15 Ma compared to the previous stage (panels A, B, and D).
However, the boundaries obtained from isopach maps of the Shangyou-shashan and Shizigou formations become much more undulatory, with amplitudes as large as that of present day (Figs. 6F and 6G). The hinge points are located >10 km farther away from the ATF on the major anticline belts within the northwestern Qaidam Basin than those during previous stages (Figs. 7A, 7B, and 7D), but show subtle disparity elsewhere (Fig. 7C).

## DISCUSSION

### Geometrical Evolution of the Altyn Slope

Our study on the current geometry of the Altyn Slope shows that it is a NE-trending, SE-dipping slope corrugated with ridges on the surface correlating with fold axes trending perpendicular to the general strike of the slope. Its southeastern boundary is undulatory, with the peaks coincidentally located at the major anticline belts within the basin (Fig. 3). As revealed by the subsurface data, the Altyn Slope was primarily tilted by motion on a series of E-W-trending, north-dipping transpressional faults that constitute the positive flower structure of the ATF (Fig. 4), indicating that the formation of the Altyn Slope is closely related to the activity of the ATF.

Given these analyses of our isopach maps, the Altyn Slope did not form during the deposition of the Lulehe and Lower Xiaganchaigou formations (ca. 53.5–40 Ma), because (1) several depocenters (e.g., the Mang’ai depression) persisted in the western margin of the Qaidam Basin, where the strata thickened toward the ATF, reflecting a low relief (Figs. 4B, 4C, 6A, and 6B); and (2) the hinge points can only be detected locally near the E’boliang and Lenghu areas on the T-D plots of the Lulehe formation (Fig. 6A), but are absent on those of the subsequent Lower Xiaganchaigou formation (Fig. 6B), which we interpreted as the result of paleo-topography forming in the late Mesozoic when the Altyn Tagh uplifted and suffered erosion (Jolivet et al., 2001). As the hinge points are widely detected on T-D plots of the growth strata spanning the Upper Xiaganchaigou and Shizigou formations (ca. 40–2.5 Ma; Figs. 6C–6G), we infer that the Altyn Slope began to form at ca. 40 Ma. This agrees well with the occurrence of the NW-thinning growth strata in the slope area (GS-1 in Fig. 4), and with previous studies of sedimentary features adjacent to the ATF and thermochronologic dating in the Altyn Tagh showing that the ATF initiated its activity in the late Eocene–early Oligocene (Bally et al., 1986; Yue et al., 2001; Wang, 1997; Meng et al., 2001; Yin et al., 2002; Chen et al., 2004, 2006; Wu et al., 2012b; Cheng et al., 2015).

To quantitatively unravel the geometrical evolution of the Altyn Slope since its initiation at ca. 40 Ma, we plotted width of the Altyn Slope during different periods versus the location along the ATF (Fig. 8), and the area of the Altyn Slope versus time (black solid line in Fig. 9). It is obvious that: (1) during ca. 40–15 Ma, the Altyn Slope continued to enlarge southeastward with increasing areas (Figs. 8A–8C and 9), and that the slope shapes apparently differed from that of the current surface (Figs. 8A–8C); and (2) since ca. 15 Ma, the area and shape of the Altyn Slope have been nearly constant (black solid line in Fig. 9), and the Slope geometry is characterized by an undulatory boundary with peaks located on the major anticlinal belts within the basin (Figs. 8D and 8E).

The above analysis shows that the southeastern boundary of the Altyn Slope was significantly transformed into the undulatory shape of the current geometry at ca. 15 Ma (Figs. 6F, 6G, and 8) and that the area of the Altyn Slope increased gradually until ca. 15 Ma, but has remained nearly constant since then (Table 1 and Fig. 9). Two possible interpretations could account for these phenomena: first deposition, uplift, and erosion on the Altyn Slope reached a steady state in the early Miocene (22–15 Ma), continuing to present. However, this is incompatible with the fact that despite a similar area, the shapes of the Altyn Slope varied during the deposition periods of the Xiayoushashan, Shangyoushashan, and Shizigou formations (Figs. 6 and 8). The alternative and acceptable explanation is that the area of the Altyn Slope was enlarged by late Cenozoic NE-directed shortening within the Qaidam Basin, as indicated: (1) by the increasing undulation of the southeastern boundary of the Altyn Slope since ca. 15 Ma, with its valleys shrinking toward the ATF and peaks expanding into the basin interior; (2) the peaks coincide well with major anticlinal belts inside the basin (Fig. 8); and (3) previous studies proposed that these anticlines mainly formed since ca. 15 Ma with southeastward-decreasing intensity of deformation (Yin et al., 2007; Xiao et al., 2013), leading to southeastward tilt of the anticlines (Fig. 4A). If the areas generated by this later NE-directed contraction were removed, the southeastern boundary of the Altyn Slope would systematically shrink toward the ATF (Figs. 8D and 8E), and the slope area shows a sharp decrease since ca. 15 Ma (the red dotted line in Fig. 9), indicating that tilting of the Altyn Slope caused by the E-W-trending faults has weakened since then.

### Implications for the Cenozoic Kinematic Pattern on the Altyn Tagh Fault

Our result shows that the Altyn Slope experienced a dramatic structural change at ca. 15 Ma. Because the above analysis demonstrates that the formation of the Altyn Slope is closely related to the ATF, it suggests a kinematic change of the ATF at that time. We therefore propose a simple model to explain this change and its structural coupling with the Altyn Slope as well as deformation inside the Qaidam Basin in the Cenozoic era (Fig. 10).

The ATF was not active prior to ca. 40 Ma (Fig. 10A). The southwestern Qaidam Basin was connected to the Tarim Basin (Meng and Fang, 2008), where a large sedimentary depocenter persisted to receive sediments through westward-flowing drainages in the Qaidam Basin (Yin et al., 2002), while the northern part developed as a paleo-high inherited from the late Mesozoic palaeotopography (Jolivet et al., 2001; Wu et al., 2015).

During ca. 40–15 Ma (Fig. 10B), the ATF was activated, but with a relatively slower slip rate than at present (Cheng et al., 2015). It behaved more like a basal shear zone and was characterized by a series of en echelon distributed E-W-trending transpressional faults (Wu et al., 2012a, 2012b), forming typical positive flower structures convergent downward toward the current ATF.
Figure 8. Superimposed diagram of the geometries of the Altyn Slope during different periods in the Cenozoic; each subsequent slope geometry is shown superimposed on the previous one(s) (see Fig. 2 for formation abbreviations). The horizontal axis of each panel is the location along the Altyn Tagh fault from Lenghu to Mang’ai (Fig. 6), while the vertical axis shows the width of the Altyn Slope of the corresponding location extracted from Fig. 6. It is clear that the Altyn Slope continued to enlarge after 40 Ma, with its shape differing from that of the current slope. However, it abruptly began to be corrugated with folding-generated ridges (the anticlinal belts) and has gradually formed the current geometry since ca. 15 Ma. Note that the red dotted lines in Panels d and e indicate the width of the Altyn Slope after eliminating the influence of NE-directed folding since ca. 15 Ma. See text for detail.

Figure 9. Plots of the normalized areas of the Altyn Slope over time. (See Fig. 2 for formation abbreviations.) The red dotted line is a trendline fitting the areas eliminating the effect of NE-directed folding since ca. 15 Ma, while the black solid line represents the measured area-variation trend of the Altyn Slope extracted from Fig. 6 (corresponding data are shown in Table 1). The plot shows a significant increasing trend in slope area prior to ca. 15 Ma but a decreasing one since then, suggesting a kinematic change of the Altyn Tagh fault at that time.

Table 1. Summary of Area (S) and Mean Width (w) of the Altyn Slope at Each Period

<table>
<thead>
<tr>
<th>Formation</th>
<th>UXG</th>
<th>SG</th>
<th>XY</th>
<th>SY</th>
<th>SZG</th>
<th>Present</th>
</tr>
</thead>
<tbody>
<tr>
<td>S (km²)</td>
<td>10750.7</td>
<td>11246.6</td>
<td>13005.6</td>
<td>12861.9</td>
<td>12927.8</td>
<td>14253.9</td>
</tr>
<tr>
<td>w (km)</td>
<td>39.8</td>
<td>41.6</td>
<td>48.1</td>
<td>47.6</td>
<td>47.8</td>
<td>52.7</td>
</tr>
<tr>
<td>Ns</td>
<td>0</td>
<td>0.14</td>
<td>0.64</td>
<td>0.6</td>
<td>0.62</td>
<td>1</td>
</tr>
<tr>
<td>S*(km²)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>12133.4</td>
<td>11540.6</td>
<td>–</td>
</tr>
<tr>
<td>Ns*</td>
<td>–</td>
<td>–</td>
<td>0.39</td>
<td>0.23</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Note: Ns—normalized slope area following the calculation of Ns=(S−S_{UXG})/S_{UXG}. S*—area of the Altyn Slope excluding the portions generated by late Cenozoic shortening of the basin. Ns*—normalized slope area derived from S*. See Figure 2 for formation abbreviations.
As the slip rate of the ATF was fairly slow at the time (Cheng et al., 2015), stresses concentrated on the ATF system were perhaps accommodated by vertical shear rather than strike-slip motion, which tilted the basement of the northwestern margin of the Qaidam Basin, leading to the formation of the Altyn Slope between the ATF and the Qaidam Basin interior. This process persisted throughout this period, and the extent of the Altyn Slope continued to increase because of sustaining stress build-up from the ongoing indentation of the Indian plate into the Eurasian (Dayem et al., 2009). At this time, except for the slight southeastward migration of the depocenters within the Qaidam Basin (Fig. 10B), only weak deformation was detected (Zhou et al., 2006; Wu et al., 2014), even in other areas within the northern Tibetan Plateau (Ritts et al., 2008; Lin et al., 2011).

Faster slip on the ATF developed since ca. 15 Ma (Cheng et al., 2015), possibly due to formation of a through-going fault system allowing pure strike-slip motion that localized the strain on the ATF (Le Guerroué and Cobbold, 2006; Fig. 10C). A regional unconformity was therefore formed and recorded in the northwestern margin of the Qaidam Basin because of this change in kinematics of the ATF (Fig. 4; Wang et al., 2010; Wu et al., 2012a). This process released the strain accumulated beneath the Altyn Slope, causing its southeastern boundary to shrink toward the ATF (Fig. 8) and its area to decrease (red dotted line in Fig. 9). To absorb the fast slip on the ATF, intense NE-directed crustal shortening occurred within the northern Tibetan Plateau (Yue and Liou, 1999; Turner et al., 1993; Ding et al., 2004; Fang et al., 2007; Royden et al., 2008; Bovet et al., 2009; Lease et al., 2011; Wang et al., 2012), and many NW-trending faults and folds formed within the Qaidam basin at the time (Zhou et al., 2006; Wu et al., 2014; Xiao et al., 2013; Fig. 4 in this paper), folding the Altyn Slope to shape its current geometry (Fig. 10C). In response to this kinematic change on the ATF, sedimentary facies in the western Qaidam Basin changed from fluvial-lacustrine facies prior to ca. 15 Ma to alluvial fan and fan delta facies since then, with acceleration of sedimentary rates, as revealed by new well-logging data and field investigations (Wu et al., 2012a, 2012b; Chang et al., 2015).

**CONCLUSIONS**

As a transition zone between the Altyn Tagh and the Qaidam Basin, the Altyn Slope preserved critical geological evidence for the strike-slip history of the ATF. The current geometry of the Altyn Slope was identified by a dense network of NW- to NWN-directed seismic profiles and is characterized by a southeast-dipping slope tilted by a set of E-W-trending, north-dipping reverse faults forming typical flower structures of the ATF. The Altyn Slope has an undulatory southeastern boundary with peaks coincidentally located at the major anticlinal belts in the Qaidam Basin. An outline of the temporal evolution of the Altyn Slope geometry was obtained by analyzing the syntectonic sequences from isopach maps of adjacent stratigraphic units, and seismic reflection profiles. The result shows that the Altyn Slope began to form at ca. 40 Ma, continued to expand southeastward over time with a relatively straight boundary.
prior to ca. 15 Ma, but started to shrink toward the ATF with decreasing area since ca. 15 Ma. This implies a kinematic change of the ATF at ca. 15 Ma, and two distinct stages of the left-slip motion on the ATF are therefore inferred for the Cenozoic era. During the first stage of ca. 40–15 Ma, the ATF was activated as a basal shear zone with fairly slow left-slip rate, and large transpressional stresses were converted to vertical strain, raising the Altyn Slope, instead of producing strike-slip motion. However, during the second stage, since ca. 15 Ma, faster left-lateral strike-slip motion on the ATF took place due to the formation of a through-going fault system, releasing the stress beneath the Altyn Slope and inducing intense NE-SW-directed shortening within the Northern Tibetan Plateau that folded the Altyn Slope.

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REFERENCES CITED


Zhao et al. | Cenozoic tilting history of the Altyn Tagh fault