Neogene Paleomagnetic Study of the Western Baicheng Depression: Implications for the Intensiﬁed Deformation of Tian Shan Since the Latest Miocene


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Abstract The fold-and-thrust belts in the southern forelands of Tian Shan were tectonically deformed as a result of intracontinental deformation in response to the India-Asia collision; therefore, they are essential for understanding tectonic evolution and basinward propagation of the Tian Shan Range. Although the reactivation of Tian Shan has long been studied, when and how this deformation was initiated and propagated are still controversial. In this study, we present new paleomagnetic results, anisotropy of magnetic susceptibility, tectonic rotations, and interpretations of subsurface seismic images on the Kalayuergun Structural Belt, western Baicheng Depression. Our new results suggest that the deformation of the Kalayuergun Structural Belt initiated at ~5.3 Ma and became young southeasterly, indicating that the deformation reached to the study area in the latest Miocene and propagated basinward progressively since then. The clockwise rotations, about half amounts of which must have been occurred at around ~5.3 Ma, can be linked to the activity of the Kalayuergun dextral strike-slip fault on the western end of the anticline. Combined with previous results around Tian Shan, we suggest that the long range has been subjected to an episode of intensiﬁed tectonic deformation since the latest Miocene, which was caused by the accelerated northward motion of the Tarim Block and Pamir in response to the India-Asia collision.

1. Introduction

The Tian Shan Range, stretching over 2,500 km from west to east, with the highest peak above 7,000 m, is located on the southern margin of the Central Asian Orogenic Belt (Windley et al., 2007; Xiao et al., 2013). It contains two late Paleozoic sutures representing two collisional events, which resulted in the uplift of the ancestral Tian Shan (Allen et al., 1991; Windley et al., 1990). During the Mesozoic, it experienced a relatively quiescent period and was denuded into peneplain (Allen et al., 1994; Shu et al., 2004; Zhang & Wu, 1985). The present high relief of Tian Shan can be attributed to the reactivation caused by the Cenozoic India-Asia collision (Molnar & Tapponnier, 1975; Patriat & Aochace, 1984).

The Tian Shan Range is ﬂanked by sedimentary foreland basins (i.e., the Kashgar and Kuqa-Baicheng Depressions to the south and the southern Junggar Basin to the north; Figure 1a). The Cenozoic deformation of the foreland is closely linked to the crustal shortening and mountain-building processes of Tian Shan, which resulted in the subsidence of the margins of the Junggar and Tarim Basins. The up to ~10-km-thick Meso-Cenozoic sediments derived from the surrounding orogens have been subjected to tectonic folding and thrusting and are well exposed by river incisions in the foreland basins. These sediments provide great potential for studying the crustal shortening and tectonic evolution history of Tian Shan in the Cenozoic.

Although numerous studies have been carried out to understand the Cenozoic tectonic evolution of Tian Shan, including low-temperature thermochronology (Bande et al., 2015, 2017; Glorie et al., 2011; Hendrix et al., 1994; Sobel, Oskin, et al., 2006; Yu et al., 2014), magnetostratigraphy (Charreau et al., 2005, 2006, 2009; Heermance et al., 2007, 2008; Huang et al., 2006, 2010; Lu et al., 2010, 2015; Sun & Zhang, 2009; Sun et al., 2004, 2009; Thompson et al., 2015; Zhang et al., 2015, 2016), crustal shortening estimation (Burchﬁel et al., 1999; Charreau et al., 2008, 2018; Hubert-Ferrari et al., 2007;
Saint-Carlier et al., 2016; Tian et al., 2016; Zhang et al., 2014), and geodynamics (Reigber et al., 2001; Yang et al., 2008; Zubovich et al., 2010), the uplift time and propagation of Tian Shan still remain controversial, which may be caused by different methods used to estimate the onset of mountain building and/or by the diachronous tectonic deformation along the long range.

In forelands, syntectonic deposits are important evidence of growth folding and active faulting, as they provide key information about the tectonic deformation and history of active orogenic belts (e.g., Burbank et al., 1996; Suppe et al., 1991). In recent years, significant progresses have been made in understanding the mechanism and implications of syntectonic sediments in many forelands around the world (e.g., Ahmadi et al., 2013; Ford et al., 1997; Martin-Rojas et al., 2015; Riba, 1976; Shaw & Suppe, 1994; Suppe et al., 1997).

In this study, in order to understand the timing and propagation of the late Cenozoic deformation, we focus on the magnetostratigraphy of syntectonic deposits on the deformation frontal edge in the southern Tian Shan foreland, where the chronology of the Cenozoic sediments is still unclear. Our new paleomagnetic results from the Neogene sediments, together with the interpretations of subsurface seismic data, suggest that the deformation in the Kalayuergun Structural Belt initiated at ~5.3 Ma and began to propagate basinward since then. These results provide potentials for understanding the tectonic history of the Tian Shan Range in the late Cenozoic and the propagation of deformation in the southern Tian Shan foreland in response to the far-field effect caused by the India-Asia collision.

2. Geological Setting and Stratigraphy

The Baicheng-Kuqa Depression, which is located on the northern margin of the Tarim Basin, is a typical rejuvenated foreland basin in the southern Tian Shan (Figure 1b). Several rows of fold-and-thrust belts stretching roughly parallel to the orogenic belt represent geological evidence for the north-south tectonic compression induced by the intracontinental deformation caused by the India-Asia collision.

Within the depression, five tectonic units can be identified: the Northern Monocline Belt, the Kelasu-Yiqikelike Structural Belt, the Baicheng-Yangxia Sag, the Quilitage Structural Belt, and the Frontal Uplift Belt (including the Kalayuergun and Yaken Structural belts; Figure 1b). The Kalayuergun Structural Belt was previously believed to represent the deformation frontal edge of the foreland (Tang et al., 2010). The western part of the Kuqa-Baicheng Depression is bordered by the prominent Kalayuergun dextral
strike-slip fault, which plays a key role in accommodating the crustal shortening in this area (Li et al., 2013; Tang et al., 2010).

The Kalayuergun Structural Belt is characterized by en echelon folds consisting of the northern, middle, and southern Kalayuergun anticlines (Figure 2). The relief of the three folds decreases gradually from NW to SE, which can be easily recognized in the Digital Elevation Model (DEM) images (Figure 2). This trend indicates that the magnitude of deformation decreases to the SE progressively (Fu et al., 2004). The NWW-SEE stretching northern Kalayuergun anticline was faulted by the Kalayuergun dextral strike-slip fault in its western end (Figures 1 and 2), whereas the middle and southern Kalayuergun anticlines are roughly elongated in the E-W direction and form a Z shape in map view (Figure 2).

Magnetostratigraphic analysis in this study has been focused on the northern limb of the northern Kalayuergun anticline, where late Cenozoic strata are well exposed. The studied section (from 41.404°N, 80.905°E to 41.411°N, 80.916°E) can be divided into two parts based on lithology and color. The lower part (Kangcun formation) is dominated by reddish-brown lacustrine mudstones interbedded with lacustrine-fluvial sandstones/siltstones and occasionally with conglomerates, whereas the upper part (Kuqa formation) consists of light yellowish sandstones interbedded with conglomerates with increasing thickness and grain size. The uppermost part of the section is covered by modern eolian sands (Figures 3 and 4). No major unconformities were identified in the studied Cenozoic strata, suggesting that the sedimentary sequence is relatively continuous and is suitable for magnetostratigraphic study.

According to our field investigations and measurements on stratigraphic geometry, syntectonic deposits occur near the boundary between the Kangcun and Kuqa formations on both limbs of the northern Kalayuergun anticline. On the northern limb, the bedding attitudes range from 46° to 58°, with no obvious decreasing trend in the lower part of the section (Kangcun formation), whereas progressive decreases in bedding dips can be observed in the upper part (Kuqa formation), and it is just ~10° in the uppermost part of the section (Figures 3 and 4). The systemic decreases in bedding attitudes suggest a wedge-shaped geometry of the Kuqa formation on the northern limb of the northern Kalayuergun anticline, which is related to continuous growth folding. Although the subsurface seismic imaging is not so clear in the core of the anticline, the deduced fold geometry based on surface structural measurements and subsurface seismic imaging data (Li et al., 2013) also suggests the existence of growth strata (Figure 5).

![Figure 2. The 90-m-resolution DEM map of the western part of the Baicheng Depression. The Kalayuergun Structural Belt is characterized by en echelon folds containing the northern, middle, and southern Kalayuergun anticlines. Note that the northern Kalayuergun anticline is faulted by the Kalayuergun dextral strike-slip fault in the western end. The red star represents the studied section on the northern limb of the northern Kalayuergun anticline. A-A', B-B', and C-C' represent the three seismic profiles across the northern, middle, and southern Kalayuergun anticlines, respectively. The seismic profile across the studied section was shown in Figure 5.](image)
3. Sampling and Methods

The paleomagnetic samples were collected using a portable gasoline-powered drill and were oriented in situ using a magnetic compass and inclinometer excluding the block samples. The coarse-grained sediments and the strata covered by weathered debris, which are not suitable for the paleomagnetic study, were avoided. A total of 328 oriented specimens and 48 block samples were obtained along the well-exposed sedimentary section. All the oriented specimens were cut into standard paleomagnetic samples (2.2 cm in length and 2.5 cm in diameter) in the lab, whereas the block samples were cut into cubes with 2.5 cm in length; they were then subjected to stepwise thermal demagnetization in 17–18 steps using an ASC TD-48 thermal demagnetizer. The measurements of remanent magnetization were carried out using 2G-755 and 2G-760 superconducting magnetometers in the Institute of Geology and Geophysics, Chinese Academy of Sciences.

Figure 3. Cross section of the studied section showing the changes of lithology and growth strata. The sampled section can be divided into two parts: the lower part (Kangcun formation) is dominated by reddish siltstones and mudstones, occasionally interbedded with conglomerates, and the upper part (Kuqa formation) is characterized by yellow sandstones interbedded with conglomerates. The uppermost part of the section is buried by modern eolian sands. Note that the bedding attitudes decrease progressively toward the top of the section.

Figure 4. Photographs of growth strata on the northern limb of the northern Kalayuergun anticline. (a) Photo of the growth strata, taken from a distance. Yellow box indicates the area showed in Figure 4b. (b) The amplified photo showing the base of the growth strata. The yellow dashed lines indicate the attitudes of the growth strata. Note that the dips of the growth strata decrease toward the top of the section progressively.
demagnetization results were evaluated on Zijderveld diagrams (Zijderveld, 1967), and the magnetic directions were calculated using principal component analysis (Kirschvink, 1980). In this study, the methods for calculating tectonic rotations proposed by Butler (1992) are used. Prior to thermal demagnetization, the anisotropy of magnetic susceptibility (AMS) of all the samples was measured using a KLY-4s Kappabridge with an applied field of 300 A/m.

4. Results

4.1. Magnetic Minerals

Curie point analyses were carried out using an AGICO KLY-3s Kappabridge susceptibility meter coupled with a CS-3 furnace. All spectra were determined by heating from room temperature to ~700 °C and then cooling to room temperature in argon gas atmosphere. Hysteresis loops were measured using a MicroMag 3900 Vibrating Sample Magnetometer. The applied magnetic field was cycled between ±1.5 T. The results of rock magnetism are shown in Figure 6. All the samples show irreversible behaviors during the thermomagnetic analysis. There are two dominant decreases, with a major one at ~585 °C and a minor one at ~680 °C.

Figure 5. The interpretation of the subsurface seismic data across the northern Kalayuergun anticline (see the location in Figure 2). The lines drawing the seismic profile of the anticline were modified after Li et al. (2013) based on the our field measurements. (a) The raw seismic profile; (b) the interpretation of the seismic profile.
which corresponds to the unblocking temperature of magnetite and hematite, respectively. Moreover, the wasp-waisted hysteresis loops (Figure 6) suggest that a ferrimagnetism dominated either by both soft and hard coercivity magnetic minerals or by a single ferromagnet with a broad grain size distribution (Roberts et al., 1995). The above two lines of evidence therefore indicate that both magnetite and hematite are generally present as remanence carriers.

4.2. Demagnetization

As shown in Figure 7, two or three components can be isolated for most of the samples: one occurs at low temperatures (generally < 350 °C), whereas the middle component can be acquired between 400 °C and 585 °C. After removing one or two components, a high-temperature component can be isolated (usually between 610 °C and 680 °C), which decays toward the origin on the orthogonal diagrams (Figure 7). However, the directions of the middle components acquired at 400 °C–585 °C are similar to those of the high-temperature component; therefore, we suggest that both magnetite and hematite recorded the same magnetic directions. In this study, all the high-temperature components were determined between 610 °C and 680 °C using four consecutive points at least. Samples with the maximum angular deviation larger than 15° were rejected for further analysis. In addition, outliers and transitional directions lying over 45° from the mean were systematically discarded (Deenen et al., 2011, 2014). Among the 354 demagnetized samples, 175
oriented and 26 unoriented samples can be isolated stable ChRM directions (supporting information Table S1).

4.3. Reliability Analysis

The normal and reversed ChRMs of the oriented samples were used to calculate the Fisher mean directions, respectively, for the subsequent reversals test. The method proposed by McFadden and McElhinny (1990) was used. The Fisher mean direction of the normal polarities ($D_N = 17.6°$, $I_N = 44.8°$, $\alpha_{95} = 4.2°$, $\kappa = 19.2$, $N = 64$) is nearly antipode with that of the reversed polarities ($D_R = 195.9°$, $I_R = -47.0°$, $\alpha_{95} = 3.0°$, $\kappa = 21.0$, $N = 111$; Figure 8). The angle between the Fisher mean directions of the normal and reversed polarities is $2.5°$, which is smaller than the critical angle ($\gamma_c$) of $5.03°$ providing a B classification reversals test. Moreover, the mean values of the normal and reversed polarities are relatively far away from both the geocentric axial dipole and present geomagnetic field directions (Figure 8), excluding a possible recent magnetic overprint. Therefore, the ChRM directions were acquired at or close to the time of rock formation and can be regarded as primary in origin.

4.4. Magnetostratigraphy

The inclinations of the 175 oriented and 26 block samples were used to define the magnetic polarity zones (Figure 9). Excluding the polarity zones suggested by just one or two samples, a total of 10 normal (N1–N10) and 11 reversed (R1–R11) polarity zones are clearly identified in this section. Then the constructed magnetozone sequence was correlated to the geomagnetic polarity timescale (GPTS 2012; Gradstein et al., 2012) using the following criteria: (1) the characteristics of the magnetozone sequence, (2) previous fossil spore-pollen assemblages reported by previous publications (Yin et al., 1998, and references therein; Editing Committee of the Stratigraphy of China, 1999), and (3) other magnetostratigraphic results obtained from the late Cenozoic sediments in adjacent areas (Charreau et al., 2006; Huang et al., 2006, 2010; Sun et al., 2009; Zhang et al., 2015, 2016).

As shown in Figure 9, the lower part of the sequence (0–370 m) is characterized by one thick reversed and normal polarity zones (R5 and N9) punctuated by mixed polarity and short events (N5–R11). In the lowest part (0–100 m) of the section, there are two relatively thick reversed polarity zones (R10 and R11) interbedded with one thin normal polarity zone (N10). This pattern of magnetozones appears to correlate well with...
chronostratigraphy includes the recognition of the reversed polarity sequence dominated by a mixed polarity characterized by magnetozones with varying length (R1-N4). This distinctive polarity sequence can be correlated well with the chron C2Ar to C3n.4n. Some magnetozones cannot be identified (e.g., C3Br.2n and C4Ar.1n), which are likely because of their relatively short duration and/or the low sampling density due to the coarse-grained sediments.

Based on the presence of ostracoda fossils, previous biostratigraphic studies attributed the ages of the Kangcun and Kuqa formations in the Baicheng-Kuqa Depression to the late Miocene and Pliocene, respectively (Editing Committee of the Stratigraphy of China, 1999; Yin et al., 1998). This result is consistent with our magnetostratigraphic division (Figure 9). The magnetozone sequence of the studied section can be correlated with the geomagnetic timescale (GPTS 2012; Gradstein et al., 2012) well. The age of the studied section ranges from ~9.3 to ~4.0 Ma, and the basal age of Kuqa formation is ~5.3 Ma, which is also the basal age of the growth strata (Figure 9).

The sedimentation rate was calculated using the magnetostratigraphic age versus thickness (Figure 10). The results show an abrupt increase in sedimentation rate at ~5.3 Ma, which is synchronous with growth strata. The sedimentation rate remained constant at ~93 m/Myr from ~9.3 to ~5.3 Ma, whereas it increased to ~130 m/Myr since ~5.3 Ma. Additionally, the grain size and thickness of conglomerates also increased after that time (Figure 9). The sedimentation rates in this study are much lower than those of other parts in the eastern part of the depression; for example, it is ~200 m/Myr (~430 m/Myr), ~130 m/Myr (~230 m/Myr), and ~325 m/Myr (~403 m/Myr) in the Kangcun (Kuqa) formation of the Yaha section, Kuqa section, and Kuchetawu section, respectively (Charreau et al., 2006; Huang et al., 2006; Sun et al., 2009). It might be because that the Kalyuergun Structural Belt is located on the southern margin of the foreland, being relatively far away from the orogen. In addition, the sedimentation rates can be underestimated as the sampled strata just contain the lowest part of the Kuqa formation. However, the sedimentation rate in the Kangcun formation is much higher than that of the Kelasu section (~47 m/Myr; Zhang et al., 2015, 2016), which can be attributed to the shorter distance of the studied section to the Cenozoic depocenter of the depression. Generally, the variations of sedimentation rates in different parts of the depression are roughly comparable to the coeval sedimentary thickness (Wang et al., 2011).

4.5. AMS

Equal-area stereographic projections of the maximum and minimum axes ($K_1$ and $K_3$) of the AMS ellipsoids before and after tilt correction are shown in Figure 11. In order to track the potential changes of AMS, the results were divided into two parts: 0 to ~370 m (pregrowth strata) and ~370 to ~531 m (growth strata).
projections suggest that \( K_1 \) in the tilt correction coordinates are well clustered in NWW-SEE with low dips, which are roughly parallel to the fold axis of the northern Kalayuergun anticline. The minimum axes \( (K_3) \) are clustered around the center after tilt correction with high inclinations, indicating that they are nearly normal to the bedding in both parts. On the \( P_j-T \) diagrams, most of the samples are distributed in the top area with \( 0 < T \leq 1 \) indicating that the magnetic ellipsoids are dominated by oblate shapes.

The parameters of AMS were determined based on their principle axes as defined by Jelinek (1981). The plots of AMS parameters (the bulk magnetic susceptibility \( K_m \), corrected anisotropy degree \( P_j \), and shape parameter \( T \)) versus depth are shown in Figure 12. \( K_m \) ranges from \( 104 \times 10^{-6} \) SI to \( 567 \times 10^{-6} \) SI, with an average value of \( 308 \times 10^{-6} \) SI. It is relatively low in the pregrowth strata (0–370 m) but then shows an increasing trend to the top. Moreover, the other two parameters \( (P_j \) and \( T \)) also show similar trends (Figure 12). It is worth noting that the changes in AMS parameters \( (K_m, P_j, \text{and } T) \) are synchronous with the upsection coarsening trends of sediments, as well as the abrupt increases in the sedimentation rate and growth strata.

Figure 9. Lithology and magnetostratigraphic results of the northern Kalayuergun anticline in this study, with inclination plotted as a function of the thickness. The polarity sequence can be correlated with the GPTS 2012 (Gradstein et al., 2012) well as described in the text. The red stars indicate the sampling positions of gravel composition analysis.
4.6. Tectonic Rotation

The stratigraphically grouped 13 interval-mean directions were calculated using two approaches. The first approach simply calculates the Fisher mean of the ChRM directions within each interval (Group A in Table 1). However, Deenen et al. (2011, 2014) suggested that Fisher statistics should not be applied to average paleomagnetic directions but to virtual geomagnetic pole (VGP) distributions instead. Therefore, in order to better constrain the tectonic rotations, the second approach is to calculate the Fisher mean of VGPs within each interval (Group B in Table 1). The calculated $A_{95}$ for each of our Group B VGP is within the envelope $(A_{95\text{min}}, A_{95\text{max}})$ proposed by Deenen et al. (2011, 2014). Then the interval-mean directions of ChRM and VGP were used to calculate the tectonic rotations by comparing them with apparent pole wander path of the stable Eurasian plate at ~10 Ma (Torsvik et al., 2012; Table 1).

The results suggest that the magnitude of tectonic rotations calculated from these two different methods is indistinguishable for each interval (Table 1) indicating that both methods can be used to constrain the tectonic rotations. Therefore, the late Miocene Kangcun formation (0–370 m, corresponding to ~9.3–5.3 Ma in age) has been subjected to $16.2^\circ \pm 4.9^\circ$ clockwise rotations, whereas limited clockwise rotations ($6.5^\circ \pm 6.1^\circ$) have been found in the Pliocene Kuqa formation (370–531 m, corresponding to ~5.3 to ~4.0 Ma in age), taking the confidence intervals into consideration. We can conclude that about half amounts of these clockwise rotations likely occurred at around ~5.3 Ma (Figure 13), and since then, the tectonic rotations have been weakened. However, due to the indistinguishable confidence levels of the interval-mean directions, it is difficult to deduce whether the clockwise rotations occurred

Figure 10. Sedimentation rates calculated by magnetostratigraphic ages versus stratigraphic thickness from the studied section. One obvious increase in sedimentation rate can be identified at ~5.3 Ma, consistent with the basal age of growth strata and the coarsening trend toward the top of the section.

Figure 11. Results of the anisotropy of magnetic susceptibility (AMS). They are divided into two parts (pregrowth strata and growth strata).
progressively or not. It is worth noting that the obvious clockwise rotations of the northern Kalayuergun anticline are roughly synchronous with the beginning of growth strata.

5. Discussions

5.1. The Deformation Timing of the Kalayuergun Structural Belt

The field observations and magnetostratigraphy of syntectonic deposits on the northern limb of the northern Kalayuergun anticline allow us to constrain the basal age of growth strata at ~5.3 Ma (Figure 9), indicating that the growth of the northern Kalayuergun anticline initiated at ~5.3 Ma, which is close to the initial age of growth strata in the Kuchetawu (~6.5 Ma; Sun et al., 2009), Kelasu (~5.3 Ma; Zhang et al., 2016) and Yaken (~5.5 Ma; Hubert-Ferrari et al., 2007) sections in the southern Tian Shan forelands and the age of ~6 Ma in the forelands of the northern Tian Shan (Lu et al., 2010; Sun et al., 2009). These results suggest that a prominent crustal shortening episode initiated since the latest Miocene in the forelands of the Tian Shan Range.

The interpretations of the subsurface seismic images of the northern, middle, and southern Kalayuergun anticlines (Figure 14) reveal that the initiation of growth became younger from NW to SE progressively. Although growth strata can be recognized on the seismic profile of the middle Kalayuergun anticline (Figure 14b), our field observations and measurements suggest that the Pliocene strata exposed both on the northern and southern limbs of the anticline have relatively constant dips. Therefore, we conclude that the growth of...
Table 1
Summary of the Interval-Mean Directions of ChRM, VGPs, and Rotation Results From the Studied Section

<table>
<thead>
<tr>
<th>Age</th>
<th>Site ID</th>
<th>Thickness range (m)</th>
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<th>Group B</th>
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Note: Site ID, site identification; N/R, number of the normal/reversed polarity directions used to calculate the Fisher mean directions; Group A and Group B, the two approaches used in this study, Fisher mean ChRMs and Fisher mean VGPs; D_{k}, I_{k}, and K represent the declination, inclination, estimate of precision parameter of Fisher mean, and radius of 95% confidence circle about the mean direction, respectively; Long, Lat, K, and A_{95} represent the longitude, latitude, corresponding confidence envelope, and precision parameter calculated by Fisher mean VGPs; A_{95min} and A_{95max} upper and lower limits of the calculated A_{95} confidence limit (Deenen et al., 2011, 2014); R ± ΔR, calculated rotation and associated confidence limit.

5.2. Variations in AMS Parameters

The AMS of sedimentary rocks is an important indicator of rock fabrics and has been used to study their depositional regimes and deformation history (Tarling & Hrouda, 1993). Some previous studies demonstrated that AMS can provide insight into deformation in different tectonic settings such as fold-and-thrust belts in foreland basins (Borradaile & Tarling, 1981; Borradaile & Henry, 1997; Parés & van der Pluijm, 2002; Soto et al., 2003, 2009, 2014; Robion et al., 2007; Pueyo Anchuela et al., 2010). In recent years, the AMS has also been used to infer the deformation in the forelands of Tian Shan (e.g., Charreau et al., 2005, 2006, 2009; Huang et al., 2006, 2010; Tang et al., 2012, 2015).

In the AMS study of weakly deformed sedimentary rocks, the first point that should be clarified is whether the reconstructed AMS has a sedimentary (primary) or tectonic origin (Sagnotti & Speranza, 1993). The orientations of the principal susceptibility axes and the shape of magnetic susceptibility ellipsoid are usually used to evaluate the AMS origin. Previous studies in different tectonic settings, particularly in foreland FTBs, have identified the evolution of AMS as the strain increases based on the distribution of the three principal susceptibility axes (e.g., Mattei et al., 1997; Parés et al., 1999; Saint-Bezar et al., 2002). Moreover, the angle between magnetic foliation and the bedding was also used to check the magnetic fabric of a weakly deformed sedimentary rock depositional or tectonic origin (Robion et al., 2007; Sagnotti & Speranza, 1993). Additionally, Parés (2004) defined a general P_{T}-T path to show the development of AMS ellipsoids as the strain increases in weakly deformed sedimentary rocks.

Based on the distributions of K_{1} and K_{3} (Figure 11), the P_{T}-T projections in both parts, and the angles between magnetic foliation and bedding (Figure 12), the magnetic fabrics suggested an incipient deformation fabric. Additionally, the subhorizontal magnetic lineation, which is roughly parallel to the fold axis of the anticline...
and stable distributions of the principal susceptibility axes within the bedding planes in both parts, indicates that the whole section has equally subjected to simple folding in the postsedimentary stage. The interpretation of the seismic profile across the northern Karayuergun anticline indicates that it is a relatively simple detachment fold (Figure 5). Therefore, we suggest that AMS is sedimentary origin overprinted by tectonic strain, but it is still in the earliest stage of deformation.

As shown in Figure 12a, $K_m$ remains generally constant from the base to a thickness of ~370 m (from ~9.3 to ~5.3 Ma in age), whereas it shows an increasing trend toward the top of the section. Similar trends can also be observed for $P_j$ and $T$ (Figures 12b and 12c). $P_j$, which describes the degree of orientation of magnetic minerals, is thought to be sensitive to the changes of lithology or strain, whereas the shape parameter $T$ is considered as an indicator of grain shape dominated by strain (Charreau et al., 2009, and references therein). If $P_j$ and $T$ are dominated by tectonic strain, both of them should show increasing trends as a function of thickness because older strata have experienced stronger tectonic shortening in forelands compared with the younger strata (e.g., Parés et al., 1999). However, neither is observed. The general synchronous variation trends of the bulk magnetic susceptibility $K_m$ and that of the corrected anisotropy degree $P_j$ and the shape parameter $T$ (please see Figure 12) suggest a dominant sedimentary control on the AMS. Therefore, we suggest that $P_j$ and $T$ should be related to sedimentary factors. Although the magnetic susceptibility ellipsoids are dominated by oblate, the prolate ellipsoids in both parts should be caused by later tectonic strain, probably related to the folding.

![Figure 13. The tectonic rotation results of the northern Kalayuergun anticline revealed by the 13 interval-mean directions using two methods (Group A are the results of Fisher mean of ChRMs, and Group B are the results of Fisher mean of VGPs). The results suggest that both methods can be used to evaluate the tectonic rotations in this area. The red and blue dashed lines indicate the mean values of rotations obtained from these two different methods, respectively. The reference plate is the APWP of the stable Eurasia at 10 Ma (Torsvik et al., 2012).](image)
In order to better explain the variations of the AMS parameters, six conglomerate samples (in stratigraphic levels of 275, 325, 364, 386, 450, and 513 m, respectively) were collected from the studied section (Figure 9). The results of gravel composition analysis are shown in Figure 15. The types of pebbles from the three samples collected from the pregrowth strata are similar, as they are dominated by sandstones, granites, and conglomerates. Generally, the gravels are subrounded to rounded with diameters mostly ranging from 1 to 10 cm. However, in the growth strata, the gravels mainly comprise igneous rocks (e.g., granite, rhyolite, and diorite), sandstones, conglomerates, and metamorphic rocks (slate and gneiss). Although the subangular-subrounded gravels are mostly >10 cm in diameter, with a maximum diameter of ~30 cm, they are poorly sorted. The increase in the percentage of igneous and metamorphic rocks suggests a greatly increased denudation depth and/or an expansion in the scope of denudation, which may be related to the uplift of the adjacent mountains. Moreover, the coarsening trend observed
toward the top of the studied section implies high-energy hydrodynamic conditions or close sediment provenance.

In this study, the variations in AMS parameters ($K_m$, $P_j$, and $T$) coincide well with the changes of lithology and the occurrence of growth strata. Therefore, we use the following mechanism to account for these abrupt changes. Before ~5.3 Ma, the Tian Shan Range just remains a relatively low relief after a long period of denudation from the Mesozoic to the early Cenozoic. The corresponding detrital sediments in the foreland were mainly derived from the erosion of sedimentary cover with low contents of magnetic minerals. Thus, the magnetic susceptibility of these sediments is relatively low. However, the Tian Shan Range began to be subjected to intensive uplift after ~5.3 Ma in response to the accelerating underthrusting of the northern Tarim Block beneath Tian Shan. This can be further supported by the cooling event in the late Miocene suggested by apatite fission track analysis results (Bande et al., 2017; Glorie et al., 2011; Macaulay et al., 2013) and the deceleration in the strike slip of the Kashgar-Yecheng Transfer System in the latest Miocene-Pliocene (Sobel et al., 2011). The uplift of mountains can accelerate the denudation of bedrocks, including igneous rocks that provide new additions of ferromagnetic minerals (e.g., from I-type granites), being responsible for the abrupt increase in $K_m$ and $P_j$.

5.3. Late Cenozoic Tectonic Rotation of the Northern Kalayuergun Anticline

Although several paleomagnetic studies have been carried out on the rotation of the northern Tarim Basin in recent years (e.g., Charreau et al., 2009; Chen et al., 1992; Huang et al., 2006), its mechanism is still uncertain. Previous paleomagnetic studies have suggested that the Tarim Basin exhibited clockwise rotation (e.g., Chen et al., 1991; Gilder et al., 1996), which was believed to be the continuation of the clockwise rotation after the late Paleozoic (e.g., Avouac et al., 1993; Fang et al., 2001; Reigber et al., 2001). However, the results may be different in the forelands that have been affected by intensive deformation in response to the ongoing India-Asia collision. For example, based on the data from the Kuqa Depression, Chen et al. (1992) suggested that the northern Tarim Basin has been subjected to local counterclockwise rotation; Huang et al. (2006) suggested that the Kuqa Depression was subjected to progressive counterclockwise rotation relative to the stable Eurasia about ~10°, which resulted from interactions with adjoining crustal blocks; Charreau et al. (2009) synthesized several paleomagnetic results and indicated that all the localities on both flanks of Tian Shan exhibited counterclockwise rotations. They suggested that the entire Tian Shan Range rotated...
counterclockwise with respect to the stable Eurasia because the Tian Shan Range was subjected to not only compression but also some transpression, which was partitioned into a strike-slip component in the forelands.

The results of tectonic rotations in this study show that the late Miocene sediments have been subjected to \(-16.2^\circ \pm 4.9^\circ\) clockwise rotation, half amounts of which were roughly synchronous with the occurrence of growth strata (Figure 9). We interpret the clockwise rotation to represent regional tectonic activity. In the study area, the Kalayuergun dextral strike-slip fault delimits the boundary between the Baicheng Depression and the vast area to the west (Figures 1 and 2). The interpretation of the subsurface seismic profile across the northern Kalayuergun anticline and the Kalayuergun dextral strike-slip fault (Figure 14a) shows that the Cenozoic sediments on its eastern side have been deformed intensively, whereas they are roughly horizontal on the western side, indicating that they have not been subjected to obvious deformation. In addition, the fault just breaks through the overlying Cenozoic strata, whereas the Paleozoic-Mesozoic basement is still continuous and nearly horizontal. Therefore, the Kalayuergun dextral strike-slip fault is just a thin-skinned structure that formed in order to accommodate the discrepancies in crustal shortening caused by the N-S contraction stress on both sides of it. The shearing force caused by the activity of the Kalayuergun dextral strike-slip fault resulted in the clockwise rotations of the northern Kalayuergun anticline. The NWW-SEE trending fold axis of the anticline can also indicate the movement nature of the strike-slip fault.

However, the limited tectonic rotations in the Pliocene sediments should be attributed to the weakened activity of the Kalayuergun dextral strike-slip fault. According to our field observations and subsurface seismic images, the duration of the Kalayuergun dextral strike-slip fault must be short as it did not extend farther north and the sediments since Pliocene have not been faulted obviously. Additionally, earthquake records in the study area (Tang et al., 2017) showed that there were few earthquakes on both sides of the Kalayuergun dextral strike-slip fault during the past several decades. Therefore, we suggest that the activity of the Kalayuergun dextral strike-slip fault initiated at \(\sim 5.3\) Ma and has been weakened soon.

### 5.4. The Intensified Deformation of the Tian Shan Range and its Southward Propagation in the Late Cenozoic

Most thermochronological data suggested that the uplift of Tian Shan initiated in the late Oligocene-early Miocene and significantly intensified in the last \(\sim 10\) Ma (Glorie et al., 2011; Hendrix et al., 1994; Macaulay et al., 2013; Sobel & Dumitru, 1997; Sobel, Chen, et al., 2006; Sobel, Oskin, et al., 2006; Yang et al., 2003). In a recent apatite fission track study of the SW Tian Shan (Bande et al., 2017), researchers proposed an onset of exhumation at \(\sim 25\) Ma, which was followed by a final strong late Miocene rapid cooling event. The chronology of syntectonic sediments constrained the initiation of deformation to \(\sim 7-5\) Ma (Lu et al., 2010; Sun et al., 2009; Sun & Zhang, 2009; Zhang et al., 2016). The extrapolation of shortening rates suggested that the initial growth of Tian Shan occurred at \(\sim 10\) Ma, which may be related to the tectonic uplift of Tibet (Abdrakhmatov et al., 1996). However, the late Oligocene-early Miocene sediments in both the southern and northern forelands of Tian Shan are dominated by fine-grained lacustrine mudstones from a distal source. Glorie et al. (2011) suggested that the episode of uplift initiating at \(\sim 25\) Ma likely represents local activation or the deformation has not propagated steadily into the forelands until the late Miocene.

Based on the magnetostratigraphy of syntectonic deposits on the northern limb of the northern Kalayuergun anticline, we suggest that the anticline growth initiated at \(\sim 5.3\) Ma. The interpreted latest Miocene intracontinental deformation in the western Baicheng Depression is roughly synchronous with tectonic events observed around the Tian Shan Range and the Tarim Basin, such as the tectonic uplift of the Kunlun Mountains (Sun et al., 2008; Zheng et al., 2000), the northward propagation of the northeast Pamir thrust system (Thompson et al., 2015), the eventual collision between the Pamir Plateau and the SW Tian Shan (Fu et al., 2010; Sun et al., 2015, 2017), and the deformation in other parts of Tian Shan forelands (Huang et al., 2006, 2010; Hubert-Ferrari et al., 2007; Lu et al., 2010, 2015; Saint-Carlier et al., 2016; Sun et al., 2009; Sun & Zhang, 2009; Wang et al., 2008; Zhang et al., 2016). The above mentioned geological facts suggest that the deformation initiating in the latest Miocene was a regionally distributed tectonic event. Considering the several episodes of deformation observed in different parts of Tian Shan, the tectonic event since \(\sim 5.3\) Ma should be an important part during the basinward propagation of deformation. It is worth emphasizing that this episode of deformation must be an intensified one, as nearly synchronous deformation evidenced by syntectonic deposits have been observed on the first and second rows of fold-and-thrust belts in the Baicheng
Depression (Sun et al., 2009; Zhang et al., 2016) and in the northern Tian Shan forelands (Lu et al., 2010, 2015; Sun & Zhang, 2009).

The younger basal ages of the growth strata on the middle and southern Kalayuergun anticlines suggest the later basinward propagation of deformation. Additionally, this deformation must have continued to present which can be evidenced by the records of growth strata (Sun et al., 2009; Sun & Zhang, 2009; Zhang et al., 2016), the migration of Quaternary folding (Fu et al., 2003), and the current crustal shortening rates across the long range revealed by GPS observations (Abdrakhmatov et al., 1996; Wang et al., 2001; Yang et al., 2008).

5.5. The Mechanism of the Intensiﬁed Deformation Since the Latest Miocene

The northward indentation of India into Eurasia is believed to be the driving force for the late Cenozoic rejuvenation of the Tian Shan Range (Buslov et al., 2007; De Grave et al., 2007; Yin et al., 1998). The tectonic stress caused by the collision propagated farther north in the lithosphere via the transmission of the rigid Tarim Block into the weaker crust of Tian Shan, where it invoked tectonic deformation (Avouac et al., 1993). Therefore, the Tarim Block plays a key role in affecting the tectonic uplift of Tian Shan and the intracontinental deformation in the forelands. The observed deformation since the latest Miocene around the long Tian Shan Range indicates the accelerated underthrusting of the Tarim Block underneath the Tian Shan Range. Based on the extensive tectonic events initiating in the latest Miocene on the southern margin of the Tarim Basin, we suggest that the tectonic stress resulted by the India-Asia collision reached here and propagated northward rapidly. As a relatively rigid block, the Tarim Basin accommodated the tectonic stress mainly via its accelerated northward movement, rather than internal deformation. The deceleration of the Kashgar-Yecheng Transfer System in the late Miocene-Pliocene reﬂects a substantial increase in the northward motion of Tarim, rather than a significant decrease in the northward velocity of the Pamir Plateau (Sobel et al., 2011). However, the deformation was signiﬁcantly affected by the indentation of the Pamir Plateau in the SW Tian Shan, especially its ﬁnal collision with SW Tian Shan in the late Miocene (Fu et al., 2010; Sun et al., 2015, 2017). Therefore, we suggest that the northward movement of the Pamir Plateau and the Tarim Block dominated the intensiﬁed deformation of Tian Shan since the latest Miocene.

It is worth emphasizing that the western part of the Tian Shan forelands has been subjected to stronger intracontinental stress than the eastern part, as evidenced by the westward increases in range width and topography. In other words, the SW Tian Shan near Kashgar received full force of the Pamir Plateau due to the lack of the bulwark of the Tarim Block (Allen et al., 1994; Tian et al., 2016). GPS observations revealed that the current shortening rate across the western Tian Shan is ~20 mm/yr, whereas it is only 4.7 ± 1.5 mm/yr between the longitudes 81°E and 85°E, and it decreases to < 1 mm/yr between 86°E and 87°E (Reigber et al., 2001; Wang et al., 2001; Yang et al., 2008). These values are consistent with the eastward decreasing shortening rates estimated by balanced cross sections and geological investigations (Burchfiel et al., 1999; Scharer et al., 2004; Tian et al., 2016). Additionally, geophysical data also indicate that the underthrusting depth of the northern Tarim Block beneath the Tian Shan Range decreases from west to east (Gao et al., 2013; Zhao et al., 2003). However, the deformation of the eastern part did not obviously lag behind that of the western part, indicating that the relatively rigid Tarim Block has behaved as a secondary indenter transmitting collisional stresses to the Tian Shan Range rapidly (Molnar & Tapponnier, 1975; Neil & Houseman, 1997; Yang & Liu, 2002). Both sides of Tian Shan undertook N-S contraction synchronously as it is a relatively solid terrane when the tectonic stress propagated to the northern margin of the Tarim Basin. This can account for the roughly simultaneously intracontinental deformation along the Tian Shan Range.

6. Conclusions

1. Based on detailed magnetostratigraphy of the syntectonic deposits and interpretations of subsurface seismic reﬂection images of the Kalayuergun Structural Belt, we suggest that the deformation initiated at ~5.3 Ma and propagated basinward progressively since then.

2. The paleomagnetic results suggest that the late Miocene and early Pliocene sediments have been subjected to 16.2° ± 4.9° and limited clockwise rotations, respectively. About half amounts of these clockwise rotations occurred at around ~5.3Ma, which is roughly synchronous with deformation timing of the northern Kalayuergun anticline. These clockwise rotations were closely related to the activity of the Kalayuergun dextral strike-slip fault, which accommodates the discrepancy in crustal shortening on both sides of it.
3. The entire Tian Shan Range has been subjected to an episode of intensified deformation since the latest Miocene, which was dominated by the increase in northward motion of the Pamir Plateau and the Tarim Block.

References


