Magnetostratigraphy of syntectonic growth strata and implications for the late Cenozoic deformation in the Baicheng Depression, Southern Tian Shan

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ABSTRACT

The collision between India and Eurasia in the Cenozoic has caused a series of intracontinental deformation in the foreland basins of Tian Shan, but there are debates about the timing of tectonic deformation and the relationship between tectonic uplift and sediment accumulation in the foreland basins. Based on the magnetostratigraphy of growth strata in the Baicheng Depression, Southern Tian Shan, we suggest that an episode of crustal shortening in the late Cenozoic evidenced by syntectonic growth strata in the Kelasu-Yiqikelike structural belt (KYSB) initiated at 5.3 Ma, since then the sedimentation rate accelerated abruptly and coarse molasse deposits accumulated. Combined with the results of growth strata on both flanks of Tian Shan and the fact that the Xiyu Formation on the southern limb of the Kasangtuokai Anticline was involved into the growth strata, we conclude that the period from 7–5 Ma to the early Pleistocene was one of the important episodes of intracontinental deformation in the foreland basins of Tian Shan, as a response to the Cenozoic collision between India and Eurasia.

1. Introduction

The Tian Shan Range, stretching east–west for at least 2500 km (Fig. 1a), is a late-Paleozoic orogen (Burman, 1975; Windley et al., 1990; Allen et al., 1991, 1993; Xiao and Kusky, 2009) but was denuded into peneplain in the Mesozoic (e.g., Zhang and Wu, 1985; Shu et al., 2004; Du and Wang, 2007; Gao et al., 2014), the present high relief of Tian Shan is attributed to the tectonic reactivation as a response to the intracontinental deformation of the Cenozoic India–Eurasia collision (Molnar and Tapponnier, 1975; Patriat and Achache, 1984; Avouac et al., 1993).

The collision between India and Eurasia has caused intense deformations within Asia (Avouac et al., 1993). The crustal movement measured from GPS observations indicated that the convergence is still ongoing (Abdrakhmatov et al., 1996; Wang et al., 2001). In Tian Shan and its adjacent areas, 80–90% of the total convergence was absorbed by the N–S shortening along the southern and northern edges (Yang et al., 2008). As one of the most famous intracontinental belts in the world, the Tian Shan Range, lying in the north of the Tarim Basin, provides significant potentials for studying intracontinental deformation and mountain building.

To the north and south, Tian Shan is flanked by sedimentary foreland basins. In the Southern Tian Shan, the Baicheng and Kuqa depressions are examples of Cenozoic forelands (Fig. 1). The fold-and-thrust belts at Baicheng and Kuqa, roughly parallel to the Southern Tian Shan, indicating that the Cenozoic intracontinental deformation and crustal shortening is caused by N–S contraction (Tapponnier and Molnar, 1979; Avouac et al., 1993; Burchfiel et al., 1999; Sun et al., 2004, 2009).

However, due to the absence of palaeontological fossils and volcanic rocks appropriate for accurately dating, the age of the Cenozoic deposits within the foreland basins are still controversial. Although some magnetostratigraphic studies have been carried out in recent years (e.g., Teng et al., 1997; Charreau et al., 2005, 2006, 2009a; Huang et al., 2006, 2010; Zheng and Meng, 2006; Sun et al., 2004, 2009; Zhang et al., 2014), the ages of Cenozoic deposits, especially the Paleogene deposits, have not been well constrained. Moreover, the exact timing of tectonic uplift of Tian Shan is still in debate. There have been several different opinions about the timing of the major tectonic deformation and uplift ranging from Eocene (Du and Wang, 2007; Du et al., 2007) to Oligocene...
TUB are the abbreviation for the northern monocline belt, Kelasu-Yiqikelike structural belt, Baicheng-Yangxia sags, Qiulitag structural belt and Tabei uplift belt, respectively.

China Block, INC: Indochina. (b) Topographic map showing tectonic framework of the Baicheng Depression and the location of the Kelasu section. NMB, KYSB, BYS QSB and TUB are the abbreviations for the northern monocline belt, Kelasu-Yiqikelike structural belt, Baicheng-Yangxia sags, Qiulitag structural belt and Tabei uplift belt, respectively. (1) Jing et al. (2011); (2) Sun et al. (2009); (3) Huang et al. (2006); (4) Huang et al. (2010); (5) Charreau et al. (2006); (6) Zhang et al. (2014).

Fig. 1. (a) Simplified structural map of Asia showing the location of the Baicheng Depression. KAZ: Kazakhstan, IND: India, SIB: Siberia, NCB: North China Block, SCB: South China Block, INC: Indochina. (b) Topographic map showing tectonic framework of the Baicheng Depression and the location of the Kelasu section. NMB, KYSB, BYS QSB and TUB are the abbreviations for the northern monocline belt, Kelasu-Yiqikelike structural belt, Baicheng-Yangxia sags, Qiulitag structural belt and Tabei uplift belt, respectively. (1) Jing et al. (2011); (2) Sun et al. (2009); (3) Huang et al. (2006); (4) Huang et al. (2010); (5) Charreau et al. (2006); (6) Zhang et al. (2014).

2. Geological setting and stratigraphy

The Baicheng Depression, located in the piedmont of the Southern Tian Shan, is the north edge of the Tarim Basin (Fig. 1b). As a consequence of Cenozoic N–S compressive stress, five structural belts can be divided in the Baicheng and Kuqa depressions (Fig. 1b). From north to south, they are: the northern monocline belt (NMB), Kelasu-Yiqikelike structural belt (KYSB), Baicheng-Yangxia sags (BYS), Qiulitag structural belt (QSB) and Tabei/Frontal uplift belt (TUB) (Lu et al., 1999; Zhang et al., 2013; Yu et al., 2014). The strata exposed in the Baicheng and Kuqa depressions, in the foothills of the Southern Tian Shan, show classic sedimentary and structural features of foreland basins (Lu et al., 1994; He and Chen, 2004). The Mesozoic to Cenozoic strata were deformed in the Baicheng and Kuqa depressions, forming three roughly parallel rows of fold-and-thrust belts (Fig. 1b), which are visible in the satellite images. The first row contains two anticlines (the Kumugeliemu Anticline to the north and the Kasangtuokai Anticline to the south) and one syncline between them, cut by the south-flowing Kelasu River (Figs. 1 and 2). The Kumugeliemu and Kasangtuokai anticlines are composed of Cretaceous to Miocene deposits in other structural belts and their links with the Cenozoic deformation are still not clear.

The aims of this paper are to address: (1) the chronology of the syntectonic growth strata in the Baicheng foreland basin of the Southern Tian Shan; (2) constrain the timing of the late Cenozoic deformation evidenced by growth strata at Baicheng; and (3) understand the relationship between sedimentation and mountain building.

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It is overlain unconformably by the Wusu Group, which is characterized by nearly horizontal gravels. In the study area, the Xiyu Formation is absent and the Neogene strata are overlain by the Wusu Group unconformably.

Our new magnetostratigraphic study focused on the northern limb of the Kasangtuokai Anticline along cross sections of CC and DD (Fig. 2), which belongs to the first row of the fold-and-thrust belts, in the Baicheng Depression. The sampling section was from the lowest part of the Kangcun Formation to the upper part of the Kuqa Formation (Figs. 2 and 3). In order to correlate well with the previous magnetostratigraphic study (Zhang et al., 2015) which was terminated in the middle part of the Kangcun Formation due to large floods of the local Kelasu River in the summer of 2010, there was an overlap about 200 m in thickness between the new sampling route (CC) and the previous one (BB) (Fig. 2).

According to our field observations, syntectonic growth strata occur in the upper part of the studied section (Figs. 3 and 4) and on the southern limb of the Kumugeliemu Anticline (Fig. 5). The growth strata are characterized by the occurrence of a series of growth unconformity (or syntectonic progressive unconformity) (Riba, 1976; Ford et al., 1997), the dips decrease from 35° to 7° toward the top and the thickness gradually increase toward the core of the syncline (Figs. 4 and 5). Although the migration of curved hinge can also result in shallowing bedding dips, we interpret the upper part of the studied section as growth strata because the dips decrease gradually (Figs. 3–5) which cannot be caused by curved hinge. And our field observations suggest that the hinges of Kasangtuokai and Kumugeliemu anticlines are short and straight. Curved hinge indeed exists in the second row of thrust-and-fold belt (QSB, see Fig. 1b), rather than the study area. Therefore, we suggest that the gradual decrease in bedding dips was caused by syntectonic growth strata, rather than curved hinge migration. The basal lines of growth strata on the two anticlines are near the boundary between the Kangcun and Kuqa formations, which indicate that deformation of the two anticlines were roughly synchronous.

3. Materials and methods

Paleomagnetic sampling intervals for the new specimens are less than 2 m, except the beds which are dominated by coarse-

![Fig. 2. Landsat image map of the study area showing the Kumugeliemu and Kasangtuokai anticlines along the Kelasu River (download from Google Earth). The white dashed lines are the boundary lines among different formations. KMGLM Fm. SWY Fm. and K1 are the abbreviations for the Kumugeliemu, Susweyi formations and Lower Cretaceous strata, respectively. AA and BB are the two overlapped sections studied by Zhang et al. (2015); CC and DD show the sampling route in this study. The white dot indicates the dip measuring point of strata which is used to calculate the thickness of the gap. The GPS locations of the starting and end points have also been shown.](image1)

![Fig. 3. Cross-section of the sedimentary succession showing the lithologic changes in the study area. The green dashed lines indicate the changes of the dips along the sampled section. TF: thrust fault.](image2)
grained sandstones or conglomerates. There are 276 oriented core-samples collected from the upper part of the section, and all the samples were oriented with a magnetic compass. The cores were cut into standard paleomagnetic samples (2.2 cm in length and 2.5 cm in diameter) in room, and then they were subjected to step-wise thermal demagnetization in 17–18 steps. Remanent magneti-
zation was measured using 2G-755 and 2G-760 superconducting magnetometers in the Paleomagnetism and Geochronology Laboratory (PGL), the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). The demagnetization results were evaluated on Zijderveld diagrams (Zijderveld, 1967) and magnetic components were determined by the principal component analysis (Kirschvink, 1980). Four consecutive points at least were used to calculate the directions of high-temperature components.

4. Results

4.1. Magnetic mineralogy

Curie point analyses were carried out using an AGICO KLY-3S KappaBridge coupled with a CS-3 furnace. Two decreases in heating curves were apparent (Fig. 6a–f): a dominant one at around 580 °C indicating the existence of magnetite, and a minor one at around 700 °C corresponding to hematite. However, because the magnetic susceptibility of magnetite is much higher than that of hematite, the magnetic minerals in the sediments are dominated by hematite, with magnetite present as a subordinate magnetic mineral.

Acquisition of isothermal remanent magnetization curves show rapid increase from 0 to ~200 mT and above 70% of the maximum magnetization were acquired by ~300 mT for most samples (Fig. 6h and j). The results suggest the presence of magnetic mineral with low coercivity (such as magnetite). However, they are still not saturated when the applied field is up to ~1500 mT, indicating a magnetic mineral with relatively high coercivity (such as hematite).

4.2. Demagnetization

As shown in Fig. 7, most of the samples have two components: one at low temperature (generally <350 °C) which is maybe the viscous remanent magnetism caused by the modern magnetic field. Above this temperature, the characteristic remanent magnetism (ChRM) of either normal or reversed polarity was identified which decays toward the origin. Much of the original natural remanent magnetism (NRM) intensity of the most samples remained until 580 °C and was unblocked completely at ~670 °C which can be explained by the dominant hematite of the sediments. There is no significant difference in the remanent directions between 300–585 °C and 585–670 °C, which indicates that both magnetic carriers (magnetite and hematite) recorded the same/similar paleomagnetic field during or soon after deposition (Zhu et al., 2005).

Among the 276 samples subjected to stepwise thermal demagnetization, 274 have stable high-temperature components with the maximum angular deviation (MAD) smaller than 15° (Appendix A1).

Fig. 6. Temperature dependence of magnetic susceptibility (χ–T curves) (a–f) and acquisition of isothermal remanent magnetization (h–j) for representative samples from the Kelasu section.
4.3. Reversal and fold tests

The tilt-corrected ChRMs were used to calculate the mean directions and then to carry out the reversal test. The Fisher mean direction of the normal polarities \( (D = 3.5^\circ, I = 43.8^\circ, \alpha_{95} = 4.8, N = 76) \) is nearly the antipode of the mean direction of the reversed polarities \( (D = 175.3^\circ, I = -46.3^\circ, \alpha_{95} = 3.0, \kappa = 16.1, N = 198) \) with B classification (see Fig. 8) (the angle between the mean directions of the normal and reversed polarities is 6.3°, which is smaller than 10°) (McFadden and McElhinny, 1990).

Eigen fold test (Tauxe and Watson, 1994) was also performed based on 19 site-mean ChRMs, and the results are shown in Fig. 9. The Eigen values reached the maximum when the beds are 89–126% unfolded, thus indicating a positive fold test. Secondary mineral growth related to fluid migration or other chemical processes often obscure or replace the primary magnetizations completely in sedimentary rocks (Huang et al., 2015). However, the secondary hematite usually has a very fine grain size and is characterized by a very different distribution within the rocks from the primary. It often distributes along cracks, cleavages in rocks or mineral which will result in the discordance of magnetization directions leading to negative fold test.

The results of reversal and fold tests suggest that hematite in the sediments was detrital origin and the ChRMs were acquired at or close to the time of rock formation. Thus, the ChRMs of the 274 samples are suitable for yielding magnetostratigraphy.

4.4. Magnetostratigraphy

The ChRMs after tilt-corrections are used to calculate the virtual geomagnetic pole (VGP) latitudes, together with the declinations and inclinations, yielding a magnetostratigraphic polarity sequence (Fig. 10). There are eleven normal (N1–N11) and reversed (R1–R11) polarity zones identified in the studied section, except the short zones determined by just one sample. We still correlated the magnetostratigraphic sequence to the geomagnetic polarity time scale (GPTS) CK95 (Cande and Kent, 1995) in order to correlate well with the previous results of the lower part of Kelasu section. The correlations used the following criteria: (1) the previous magnetostratigraphic results (Zhang et al., 2015); (2) the fossils

Fig. 7. Stepwise thermal demagnetization diagrams in-situ of representative samples from the Kelasu section. Solid and open circles represent vectors projected on horizontal and vertical planes, respectively.
of bivalves and ostracoda reported by previous studies (GMRMXUAR, 1993; Editing Committee of the Stratigraphy of China, 1999); (3) the characteristics of the polarity sequence.

The assemblages of ostracoda found in the Kangcun and Kuqa formations indicated that they should be assigned to late Miocene and Pliocene in age, respectively (GMRMXUAR, 1993; Editing Committee of the Stratigraphy of China, 1999). As shown in Fig. 10, the lower part of the section (<100 m in height) is dominated by reversed polarity punctuated by four relatively short normal polarity zones which can be correlated with the dominant reversed chron zones by several relatively short normal polarities (C5n.1n–C4r.1r) of the GPTS CK95 (Fig. 10). The distinct magnetozones between 100 m and 200 m have five normal polarity zones (N5–N9) which can correlate well with chrons C4n.2n to C3An.1n. The normal polarity zone N4 can be correlated with C3n.4n in CK95. The longest reversed polarity zone (R2) can correlate with C2Ar (from 4.18 Ma to 3.58 Ma). The normal polarity zone N2 should not be correlated with C3n.2n as there is a long reversed polarity zone R2 which should be correlated to C2Ar, rather than C3n.1r. Extrapolation of the accumulation rate above the youngest geomagnetic boundary yields a terminal age of ~3.2 Ma. Thus, the age of the studied section is from ~10 Ma to ~3.2 Ma (Figs. 10 and 11). It is worthy to stress that the terminal age of the studied section is not the top boundary age of Kuqa Formation due to the missing of its uppermost part. Combined with our previous magnetostratigraphic results (Zhang et al., 2015), the age range of the whole section on the northern limb of the Kasangtuokai Anticline is from ~43 Ma to ~3.2 Ma (Fig. 11).

Within active foreland basins, syntectonic growth strata are closely linked with the growth of folds and/or faults (Suppe et al., 1992; Burbank et al., 1996; Hubert-Ferrari et al., 2007; Sun and Zhang, 2009; Sun et al., 2009). Syntectonic growth strata can provide information on tectonic and deposition interactions (Vergés et al., 2002). Growth strata are coeval with deformation, thus, dating the growth strata in foreland basins is key to understand the timing of crustal shortening and then the tectonic history of mountains. In recent years, several studies have been carried out in the foreland basins of Tian Shan to constrain the initial time of deformation (e.g., Hubert-Ferrari et al., 2007; Sun and Zhang, 2009; Sun et al., 2009; Lu et al., 2010).

Growth strata are present on the northern limb of the Kangsangtuokai Anticline (Figs. 3 and 4), as well as on the southern limb of the Kumugeliemu Anticline (Fig. 5). Our field observations indicate that the strata above the eroded strata have constant thickness and relatively high dip angle from 42° to 50° implying pre-growth strata, whereas it decreases to 35° at the bottom of the eroded strata and then gradually decrease to ~7° in the upper part of the studied section (Fig. 3). The thickness of the eroded strata is ~50 m. The base of the growth strata (~240 m in thickness) can be correlated to ~5.3 Ma (Fig. 10), since then, the deposits changed from alternations of conglomerates and siltstones/sandstones to dominant coarse conglomerates with thin siltstone intercalations.

Growth strata were also found on the southern limb of the Kumugeliemu Anticline (Fig. 5) according to our field investigation. Although there were no age constraints, the bottom of the growth strata is also near the boundary between the Kangcun and Kuqa formations. Therefore, we suggest that the basal age of the growth strata on the southern limb of the Kumugeliemu Anticline is also ~5.3 Ma.

5. Discussion

Our magnetostratigraphic results of the growth strata enable us to discuss the timing, characteristics of the tectonic deformation and the relationship between sediment accumulation and tectonic uplift. Combined with previous results, we also discuss the implications of the Cenozoic deformation in the foreland basins of the Southern Tian Shan.

5.1. The tectonic mechanism of growth strata

The KYSB in the study area, consists of two shallow anticlines (the Kumugeliemu Anticline to the north and the Kasangtuokai Anticline to the south), with an open syncline between them.
As a structural belt deformed in response to the Cenozoic contraction of the Southern Tian Shan, the KYSB is bounded by north-dipping thrust faults. A “delaminate contraction and vertical stack” model was proposed by Qi et al. (2009) to interpret the structures of KYSB, in which they suggested that the shallow structures are not only affected by the deep structures, but also by regional decollement layers (gypsum layers in the Kumugeliemu Anticline and Jurassic coal beds). The shallow Cenozoic strata mainly developed detachment folds and then formed break faults. However, the growth strata on the northern limb of the Kasangtuokai Anticline were affected by a reversed fault in the deep and the syncline is shallow. Combined with the scarcity of high-quality seismic profiles in the studied area, it is difficult to recognize the growth strata in deep (Fig. 12). The syntectonic growth...
strata in the Kelasu section can be explained by a conceptual model (Fig. 13a). The basement with high-angle tilting to the north was involved in the hanging wall of thrust fault, whereas a series of small faults constitute imbricated structures. The shallow strata were affected by the deep structures and formed a detachment fold. The growth of the Kasangtuokai Anticline resulted in the increasing thicknesses and syntectonic progressive unconformities toward the fold limb. In addition, the uplift of the Kasangtuokai Anticline resulted in the progressive rotation of fold limbs.

5.2. The relationship between sediment accumulation and tectonic uplift

In a tectonic active foreland basin, sedimentation rates are controlled by many factors, such as climatic changes, the migration of depocenters, possible sedimentary hiatuses and tectonic uplift. It is worthy to stress that cautions must be taken when sedimentation rates are used to infer tectonic uplift only, it is better to combine them with the analysis of syntectonic growth strata.

The mountains and the related foreland basins constitute a coupled mountain-basin system. The sediments flux into the foreland basins are affected by the denudation of the mountains, while uplift of the mountain can accelerate bedrock denudation processes due to high energy release (Sun and Zhang, 2009), which will result in the increase in sedimentation rates.

As shown in Fig. 13b, the sedimentation rate accelerates abruptly at ~5.3 Ma (the initial age of growth strata), marked by a change from an average rate of ~40 m/Ma from ~43 Ma to ~5.3 Ma to a tripled increase of 120 m/Ma after ~5.3 Ma. The increase in sedimentation rate is simultaneously with the beginning of the syntectonic growth strata, implying that it is a response to high denudation rate induced by tectonic uplift of the Southern Tian Shan. Although conglomerates also existed in the lower part of the Kelasu section in this study (just as shown in Figs. 3, 10 and 11), both the gravel sizes and thickness are much less compared with that of the conglomerates accumulated since 5.3 Ma. As previous studies have proven that Tian Shan underwent several pulses of tectonic uplift in Cenozoic (Charreau et al., 2005, 2009a; Huang et al., 2006; Ji et al., 2008), some of the conglomerates may be denuded from the reactivated Tian Shan. In addition, the Kelasu section is closer to the Southern Tian Shan than other sections (Fig. 1b), parts of the gravels in the lower part of the section can be explained by proximal sources due to short-distance transportation compared with other sections.

In recent years, several studies have been carried out in order to decipher the timing of tectonics in Kuqa and Baicheng depressions (Charreau et al., 2006; Huang et al., 2006, 2010; Hubert-Ferrari et al., 2007; Sun and Zhang, 2009; Sun et al., 2009; Jing et al., 2011; Wang et al., 2011; Zhang et al., 2014, 2015). For example, Charreau et al. (2006) found that the sedimentation rate of Yaha section accelerated abruptly at ~11 Ma. Combine with the changes of sedimentation rates in other parts of Tian Shan, they proposed that Tian Shan underwent a rapid uplift and erosion at ~11 Ma; Huang et al. (2006) argued that the increase in sedimentation rate at ~17–16 Ma and ~7 Ma were controlled by the tectonic uplift of the Southern Tian Shan. Jing et al. (2011) also suggested that Tian Shan underwent a rapid uplift event based on the increase in sedimentation rate at ~7 Ma. However, palynological evidence from the Kuchetawu section (Zhang and Sun, 2011) indicated that the climate was relatively warm and humid from 13.3 to 7 Ma, and thus, it is difficult to rule out the influence of climatic changes on the sedimentation rate. Moreover, the age ranges of the Yaha and

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**Fig. 10.** Magnetostratigraphic sequence defined by declinations, inclinations and VGP latitudes plotted versus thickness. Polarity sequence is compared with geomagnetic polarity time scale (GPTS) of Cande and Kent (1995). The results indicate that the basal age of growth strata is ~5.3 Ma.
Kuqa sections are still in debates (Charreau et al., 2006, 2008; Huang et al., 2006, 2008, 2010; Zhang et al., 2014). Based on the changes of sedimentation rates, Ji et al. (2008) suggested that Tian Shan underwent multiple stages of uplift, at $\sim$24–22.5 Ma, $\sim$13–11 Ma and $\sim$7 Ma, respectively. The abrupt increase in sedimentation rate in the studied section is synchronous with the occurrence of growth strata indicating that Tian Shan underwent a rapid uplift and exhumation event since $\sim$5.3 Ma.

5.3. Tectonic implications

To date, there have been debates about the timing of the tectonic uplifts of Tian Shan, ranging from Oligocene (Windley et al., 1990; Yin et al., 1998), to the early Miocene (Hendrix et al., 1994; Sobel et al., 2006), late Miocene (Abdrakhmatov et al., 1996; Bullen et al., 2003; Sun et al., 2004, 2009; Charreau et al., 2005, 2006, 2009a; Huang et al., 2006; Sun and Zhang, 2009) and even Pliocene-early Pleistocene (Burchfiel et al., 1999; Fu et al., 2003). It is necessary to compare our results with other views.

The unconformity between the Kumugeliemu Formation and the underlying lower Cretaceous strata in the Kuqa and Baicheng depressions has previously interpreted as the onset of the Cenozoic thrusting in the Southern Tian Shan (Windley et al., 1990; Allen et al., 1991). Apatite fission-track (AFT) analyses suggested that uplift of Tian Shan began at $\sim$46 Ma in response to the collision between India and Eurasia (Du and Wang, 2007). However, other low-temperature thermochronological studies suggested that uplift initiated at $\sim$25–24 Ma (Hendrix et al., 1994; Sobel and Dumitrau, 1997; Yang et al., 2003). Recently, the cooling records from low-temperature thermochronology of apatite (U–Th)/He in the Kuqa Depression suggested southward propagation of the tectonic uplift in the depression and the Kanyaken Anticline (located in KYSB) uplifted rapidly at $\sim$6 Ma (Yu et al., 2014), which is in accordance with the results of growth strata, indicating the synchronism between deformation of the study area and uplift of
Yu et al. (2014) suggested that the lack of the Kuqa Formation in some wells in the KYSB implies the onset of uplift may be \( \sim 5.9 \) Ma. However, this event was not recorded by AFT data (Hendrix et al., 1994; Sobel and Dumitru, 1997; Yang et al., 2003; Du and Wang, 2007), which may be due to the insufficient magnitude of erosion for AFT dating (Yu et al., 2014).

Given that the total Cenozoic shortening across the Tian Shan Range is 200 ± 50 km (Avouac et al., 1993), the extrapolation of the geodetic shortening rate suggested that the initial Tian Shan growth was at \( \sim 10 \) Ma (Abdrakhmatov et al., 1996), which may be linked to tectonic uplift of the Tibet Plateau (Molnar et al., 1993; Abdrakhmatov et al., 1996). Based on the revised shortening estimates across the Kyrgyz Tian Shan (40–80 km) with shortening rate (Abdrakhmatov et al., 1996, 2001), Bullen et al. (2003) suggested that the deformation of Tian Shan initiated at \( \sim 7–3 \) Ma.

Additionally, the changes in anisotropy of magnetic susceptibility (AMS) have been used to reveal tectonic uplift of Tian Shan in Cenozoic (e.g. Charreau et al., 2005, 2006, 2009; Huang et al., 2006, 2010; Tang et al., 2012, 2015). According to the changes of the AMS parameters, Charreau et al. (2005, 2006, 2009a) suggested that the growth history of the modern Tian Shan underwent two pulses of uplift and exhumation at \( \sim 16 \) Ma and \( \sim 11 \) Ma. The changes of AMS parameters were in accordance with the increase in sedimentation rate. However, the AMS parameters cannot be used to reflect the tectonic uplift of Tian Shan in the study area as there is a positive correlation between the parameters of AMS \((P, T)\) and sediment provenance \((K_m)\) in the study area (Zhang et al., 2015), suggesting that AMS cannot be used to infer tectonic uplift in the study area.

Fig. 12. (a) Cross-section of the Kasangtuokai and Kumugeliemu anticlines (modified after Tian et al., submitted for publication). (b) A seismic reflection profile showing the growth strata and deep structures along the Kelasu River (modified after Wang et al., 2011).

Fig. 13. (a) The conceptual structural model of the Kasangtuokai Anticline. Deep and shallow structures are based on seismic-reflection profiles (Qi et al., 2009; Wang et al., 2011). The occurrence of growth strata is related to the deformation of anticline. (b) The changes of sedimentation rate calculated from magnetostratigraphic age versus thickness. The abrupt increase occurred at \( \sim 5.3 \) Ma, which is in accordance with the initial time of growth strata.
Based on the chronology of syntectonic growth strata in the Kuqa Depression, Sun et al. (2009) suggested that the deformation in the foreland basin initiated at ~6.5 Ma, and the accelerated sedimentation rate was a response to the tectonic uplift of Tian Shan. Used the sedimentation rate in the Kuchetawu section estimated by Sun et al. (1999), Hubert-Ferrari et al. (2007) suggested that the growth of the Qiulitage and Yaken anticlines initiated at ~5.5 Ma. Based on growth strata of seismic profiles, Wang et al. (2011) suggested that the deformation of the northern Kuqa depression began at approximately 25–26 Ma and it propagated to the Qiulitage and Yaken anticlines at ~5.5 Ma. The deforming time of the Qiulitage Anticline is in accordance with the results suggested by Sun et al. (2009), taking the error bars of magnetostratigraphic study into consideration. However, for the Yaken Anticline, it is difficult to explain the difference in the age of growth strata studied by Hubert-Ferrari et al. (2007) and Wang et al. (2011) and the others (e.g., Lu et al., 1999; Liu et al., 2000) as growth strata were found in the Quaternary strata. Although there is no accurate age constraint for the Yaken Anticline, we tend to support the view that the deforming age of this anticline should be younger than ~2.6 Ma because the optically stimulated luminescence (OSL) results from terraces indicated that the deforming of the Yaken Anticline should be earlier than 34 kyr (Poisson, 2002). Combined with the analysis of terraces, growth strata, shortening rate and sedimentation rate, Daëron et al. (2007) suggested that the oldest terrace deposited since ~150 kyr, which was close to the deforming time of the Yaken Anticline.

Wang et al. (2011) suggested that the growth strata is located within the Kangcun Formation and extends up into the Kuqa formation, which is different from our result. It is worthy to note that it is not easy to define the exact boundary between the Kangcun and Kuqa formations. In addition, the magnetostratigraphic age is important to constrain the initial age of growth strata.

It is worthy to stress that the deformation extent of QSB is much stronger than that of KYSB according to the amount of crustal shortening (Tian et al., submitted for publication) and our field observations. The amount of crustal shortening of the Kuchetawu section is 6.4 km, whereas the total amount of the Kumugeliemu and Kasangtuokai anticlines is just 6.1 km. Additionally, strata in the core of the Kuchetawu Anticline are almost steeply dipping and even overturned, while the Kumugeliemu and Kasangtuokai anticlines are open folds with gentle strata in the cores.

The dating results of growth strata in the Northern Tian Shan suggest that the forelands underwent a widespread deformation initiating at ~6 Ma in different parts (Wang et al., 2008; Sun and Zhang, 2009; Lu et al., 2010; Li et al., 2011).

Therefore, the well-preserved growth strata on both sides of Tian Shan have a basal age of ~7–5 Ma, which indicate that both the southern and northern Tian Shan had undergone a synchronous episode of deformation in the late Cenozoic. It has been suggested that the uplift of the Tibetan Plateau was diachronous due to the oblique subduction of the India plate under Eurasia as discussed by Tapponnier et al. (2001), the intracontinental deformation of the Tian Shan orogen should be much latter compared with the 55–50 Ma initial collision between India–Eurasia (e.g., Molnar and Tapponnier, 1975; Patriat and Achache, 1984; Klootwijk et al., 1992) due to the remote distance to the collision zone. Because the Tian Shan orogen is a solid terrane, when the intracontinental deformation propagated to the Tarim block in the late Miocene, both sides of Tian Shan underwent N–S contraction, which can account for the roughly simultaneously deformation in the forelands as evidenced by the syntectonic growth strata (Hubert-Ferrari et al., 2007; Wang et al., 2008; Sun and Zhang, 2009; Sun et al., 2009; Lu et al., 2010; Li et al., 2011).

Based on the magnetostratigraphy of syntectonic growth strata in the southwestern Tian Shan, the growth strata were found in the Xiyu Formation and the deformation occurred in Pleistocene (Scharer et al., 2004). These results indicated that the uplift of Tian Shan was still ongoing in Pleistocene.

By now, there have been many different opinions about the basal age of the Xiyu Formation. Many researchers insisted that the basal age of the Xiyu Formation is diachronous from the mountains to the foreland basins (Teng et al., 1997; Scharer et al., 2004; Charrœau et al., 2005, 2009b; Huang et al., 2006, 2010). The other researchers suggested that its basal age is around 2.6 Ma (e.g., Sun et al., 2004, 2007, 2009; Sun and Zhang, 2009; Zhang et al., 2014; Chen et al., 2015). The debates may be caused by the following reasons: (1) the definition of the Xiyu Formation is different, for example, Charrœau et al. (2009b) suggested that its base can be determined when the content of boulder-size fraction exceeds 95% in the sediments; the others insisted that the Xiyu Formation is completely gray-black pebble to boulder conglomerates (Sun et al., 2004, 2007; Zhang et al., 2014; Chen et al., 2015), following the original definition of Huang et al. (1947); (2) the presence of regional faults which can result in unconformability between the Xiyu Formation and the underlying strata; (3) hiatuses caused by uplift or migration of river channels in forelands; and (4) misleading the other old conglomerate to the Xiyu Formation. It is worthy to stress that the Xiyu Formation is absent in the study area and it is impossible to decide whether its basal age is diachronous or not. However, it was involved into the growth strata on the southern limb of the Kasangtuokai Anticline (Wang et al., 2011), so its terminal age is important for constraining the lasting time of the deformation evidenced by growth strata.

According to the magnetostratigraphic age of the uppermost part of the Xiyu Formation, it lasted into the early Pleistocene at least (Charrœau et al., 2009b; Huang et al., 2010; Zhang et al., 2014). In addition, the K–Ar age of the basalt overlying the Xiyu Formation along Keliya River is 1.19 Ma (Liu et al., 1999). Therefore, we suggest that the late Cenozoic deformation evidenced by growth strata began at ~7–5 Ma and lasted to the early Pleistocene at least.

6. Conclusions

Age control of syntectonic growth strata is important for studying the crustal shortening and tectonic uplift of orogenic belts. Based on the new magnetostratigraphy, we have constraint the timing of tectonic deformation of KYSB, in the Baicheng Depression, Southern Tian Shan. Our results suggested that (1) the age range of the whole section on the northern limb of the Kasangtuokai Anticline is from ~43 Ma to ~3.2 Ma; (2) the foreland basins on both the southern and northern Tian Shan have experienced a roughly synchronous deformation which initiated at ~7–5 Ma and this represents a rapid uplift event of the Southern Tian Shan; and (3) although the reactivation of Tian Shan in the Cenozoic may be initiated early, the syntectonic evidence of growth strata suggest that crustal shortening lasted from ~7–5 Ma to the early Pleistocene at least, being one of the important episodes of intracontinental deformation in the forelands on both sides of Tian Shan, in response to the Cenozoic collision between India and Eurasia.

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Appendix A. Supplementary material

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References


