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Key Points:

- Flexural modeling shows topographic loads generated by Eastern Kunlun Shan and Qilian Shan account for the subsidence of the Qaidam basin
- We infer a low (0.4–1.0 km) Eastern Kunlun Shan and a moderate (0.4–1.5 km) Qilian Shan during the Paleogene
- Neogene surface uplift was more pronounced in the Eastern Kunlun Shan compared with Qilian Shan

Supporting Information:

Supporting Information may be found in the online version of this article.

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Diachronous Growth of the Northern Tibetan Plateau Derived From Flexural Modeling

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Abstract The early Cenozoic topography of the northern Tibetan plateau remains enigmatic because of the paucity of independent paleoelevation constraints. Long-held views of northward propagating deformation imply a low Paleogene elevation, but this prediction is speculative. We apply flexural modeling to reconstructed Paleogene isopach data obtained from the Qaidam basin, which requires a larger topographic load in the Qilian Shan and a smaller load in the Eastern Kunlun Shan. Incorporating knowledge of proto-Paratethys marine incursions in the Paleogene Qaidam basin, we infer a topographically low (0.4–1.0 km) Eastern Kunlun Shan and a higher (0.4–1.5 km) Qilian Shan during the Paleogene. This implied paleo-relief contrasts with previous predictions and suggests more recently, Neogene surface uplift in the Eastern Kunlun Shan has been more significant than in Qilian Shan, highlighting diachronous growth of the northern Tibetan plateau. The low-moderate paleoelevation implies a warmer and more humid climate in Northern Tibet during the Paleogene.

Plain Language Summary The Tibetan plateau is Earth's highest and largest plateau and has a protracted growth history closely related to Cenozoic convergence between India and Asia. Resolving its paleoelevation in the early Cenozoic is instructive to understand its growth history and Asian climate changes. Although paleoaltimetry studies have provided critical constraints for the southern Tibetan plateau during Paleogene, the paleoelevation of the northern Tibet remains enigmatic. The largest basin in the plateau is the Qaidam Basin, surrounded by high elevation thrust belts. We conducted flexural modeling of early Cenozoic strata from the Qaidam basin, which suggests higher topography in the north (0.4–1.5 km) and lower topography (0.4–1.0 km) in the south. This unique topographic relief in the northern Tibetan plateau suggests that very significant surface uplift (3–4 km) occurred along the southern margin of Qaidam basin in the late Cenozoic. These results of early topographic relief in northern Tibet support hypotheses of a Paleogene warmer and more humid climate in North Tibet. This study provides a new approach that provides an independent constraint on the Paleogene paleoelevation of northern Tibet, contributing to our understanding of the growth of the Tibetan plateau and Asian paleoclimate.

1. Introduction

The growth and uplift of the Tibetan plateau (Figures 1a and 1b) has implications for our knowledge of continental tectonics and intracontinental deformation (Cheng et al., 2014; Clark & Royden, 2000; DeCelles et al., 2002; Law & Allen, 2020; Murphy et al., 1997; Rowley, 1996; Tapponnier et al., 2001; Wang et al., 2008; Yin & Harrison, 2000) and the evolution of the East Asian monsoon (An et al., 2001; Clift et al., 2008; Harris, 2006; Licht et al., 2014; Molnar et al., 1993; Porter, 2001). Despite ongoing debate, numerous paleoaltimetry studies based on stable isotope hydrology, clumped isotope thermometry, and physiognomy of plant fossils have provided constraints on the early Cenozoic paleoelevation for the southern Tibetan plateau (Botsyun et al., 2019; Ding et al., 2014; Garzione et al., 2000; Hoke et al., 2014; Quade et al., 2011; Su et al., 2020). However, the early Cenozoic paleoelevation of the northern Tibetan plateau remains unclear,

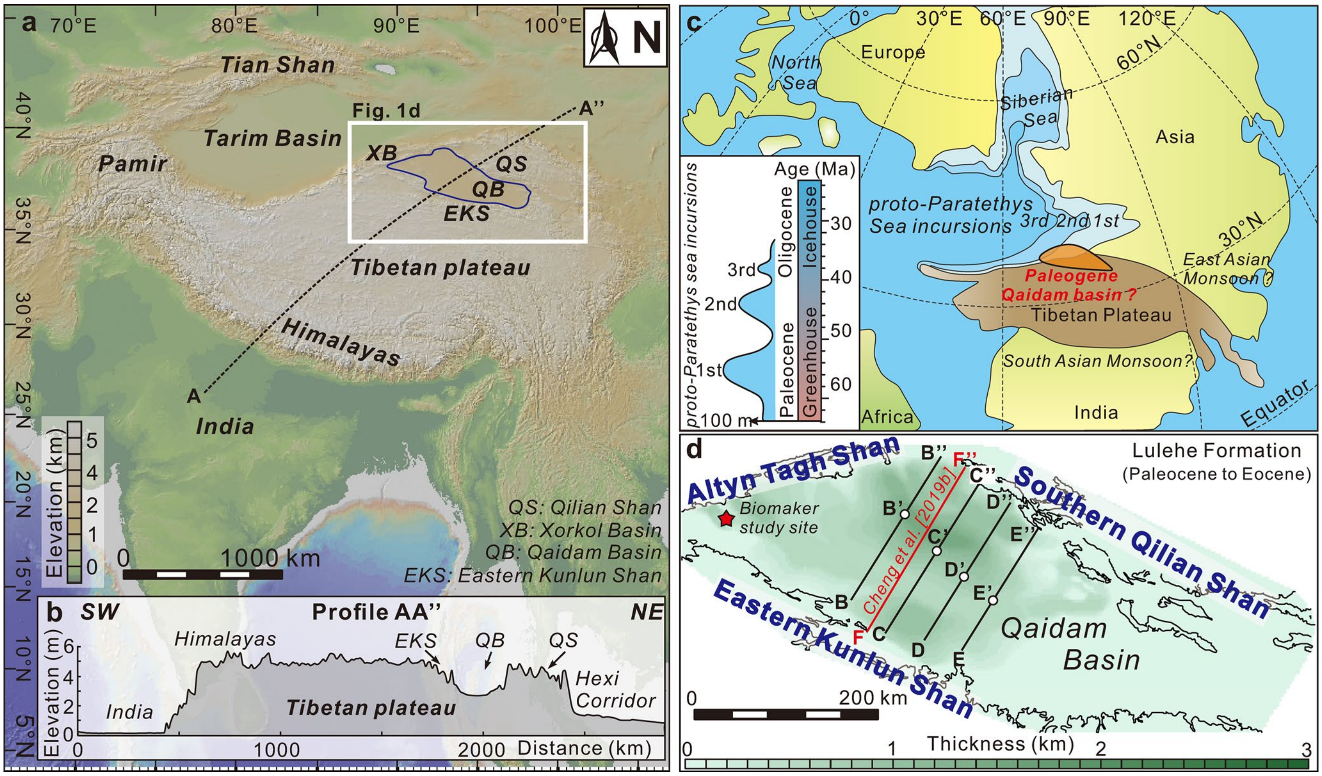

Figure 1. (a) Topographic map of East Asia. (b) Topographic profile AA′ across the Tibetan plateau. (c) Preliminary paleogeographical map showing the incursions of the proto-Paratethys Sea, from Kaya et al. (2019). (d) Isopach map of the Paleogene Lulehe Fm. in the Qaidam basin. Red star is to the site of biomarker record reported by Ma et al. (2019).

partly due to the inapplicability of these paleoaltimetry approaches to northern Tibet (Quade et al., 2011; Rowley & Garzione, 2007; Song et al., 2020). For instance, isotope-based paleoaltimetry methods widely applied in southern Tibet cannot be used in the northern Tibetan plateau due to uncertainty between elevation and the $\delta^{18}O$ values of meteoric waters. Due to the lack of preservation of early Cenozoic strata, physiognomy of plant fossils is also not well applied to the northern Tibetan plateau.

Currently, many studies presume negligible topography in northern Tibet during the Paleogene, mainly based on the models of northward propagating deformation across the plateau since the early Cenozoic (England & Houseman, 1986; Mulch & Chamberlain, 2006; Tapponnier et al., 2001; Wang et al., 2008) and the abundant evidence of Neogene-dominated exhumation in the northern Tibetan plateau (Duvall et al., 2013; Meyer et al., 1998; Yuan et al., 2013). In particular, it is usually assumed that the Eastern Kunlun Shan to the south was higher than the Qilian Shan during the Paleogene (Tapponnier et al., 2001; Wang et al., 2008; W Wang et al., 2017). Some studies have indicated, however, that pre-Cenozoic topography might have existed in Northern Tibet, suggesting that the Paleogene paleoelevation of the northern Tibetan plateau could be partly inherited from pre-existing topographic relief (Cheng, Fu, et al., 2016; Cheng, C. N. Garzione, Jolivet, et al., 2019; Cheng, Jolivet, et al., 2019; Jolivet et al., 2001; Robinson et al., 2003). All these deductions are based on the indirect knowledge of the deformation history of the mountain belts and source to sink analysis. Paleotopography of the Tibetan plateau is also considered as an important factor that controlled the establishment of the Asian monsoon by changing the atmospheric circulation (Clift et al., 2008; Licht et al., 2014; Molnar et al., 1993; Xie et al., 2019), although there is growing appreciation for monsoon intensification driven by atmospheric CO_2 concentrations and other factors (Nie et al., 2018; Ren et al., 2020). Therefore, there is an urgent need for independent paleoelevation proxies for the northern Tibetan plateau.

Recent biomarker studies indicate episodic proto-Paratethys marine incursions within the Qaidam basin, the largest depression in the Tibetan plateau (Figure 1c), since the Paleogene (Kaya et al., 2019; Ma et al., 2019).

If the Qaidam basin was at or near sea level in the early Cenozoic, a better understanding of the topographic relief of the surrounding mountain belts relative to the Qaidam basin would allow estimation of the paleoelevation of the northern Tibetan plateau. Flexural modeling provides insight into how topographic loads/relief have varied to define flexural basin geometry (P DeCelles, 2011; Royden & Karner, 1984; Saylor et al., 2018; Wang et al., 2015; Y Yang and Liu, 2002). To characterize the spatial distribution of paleorelief in the Eastern Kunlun Shan and Qilian Shan, we performed flexural modeling of four NE-trending stratigraphic sections across the Qaidam basin to reveal the lateral distribution of topographic loads/relief along the Eastern Kunlun Shan and Qilian Shan (Figure 1c). By incorporating flexural modeling results with the knowledge of proto-Paratethys marine incursion in Central Asia during the Paleogene, we further discuss the paleoelevation of northern Tibet and explore the deformation patterns of the northern Tibetan plateau.

2. Geological Setting

The topographically high Eastern Kunlun Shan and Qilian Shan and relatively lower Qaidam basin are the most dominant Cenozoic tectono-geomorphological features in the northern Tibetan plateau (Figures 1a and 1b). Field mapping and petroleum exploration indicate that the Qaidam basin contains as think as >14 km of Cenozoic clastic sedimentary fill (Cheng et al., 2018; Xia et al., 2001; Yin, Dang, Wang, et al., 2008; Yin, Dang, Zhang, et al., 2008). Marking the onset of the Cenozoic sedimentation in the Qaidam basin, the Lulehe Formation (Fm.) is generally considered to be Paleocene to early Eocene in age (Chang et al., 2015; Ji et al., 2017; Ke et al., 2013; Wang et al., 2007; Yang et al., 1992; Yin, Dang, Wang, et al., 2008; W Zhang, 2007). However, recent magnetostratigraphy studies of the Lulehe Fm. at one section site in the northern Qaidam basin assigned an Oligocene or early Miocene depositional age (Figure S1)(Nie et al., 2019; W Wang et al., 2017). Given that our flexural modeling experiment is based on the entire basin-wide stratigraphic framework of the Lulehe Fm., we adopt the old age model validated by independent studies across the basin (Ji et al., 2017; Wu et al., 2019; Yin, Dang, Zhang, et al., 2008). Further discussion of the Lulehe Fm. age models is in the Supporting Information Text S1.

3. Approach and Method

The goal of modeling was to test for the optimal height of the Eastern Kunlun Shan and Qilian Shan that provided the best fit to the original shape of the Qaidam basin, quantified as the smallest least squares and highest coefficient of determination. To start with the modern shape of the Qaidam basin, we selected four NE-trending stratigraphic sections across the basin according to the Lulehe Fm. Isopach map obtained from the Qinghai Oilfield Company, PetroChina: Sections BB", CC", DD", and EE" (Figure 1c). We carried out shortening restoration, based on estimates of Wei et al. (2016), and sediment decompaction to obtain the original shape of the basin. Decompaction of the Lulehe Fm. strata followed the approach, porosity values, and porosity-depth coefficient of Sclater and Christie (1980). Detailed description is given in the Supporting Information Text S1 and calculation results is given in Supporting Information Data Set S1.

For an elastic infinite/continuous plate acted upon by an end load, the deflection of the lithosphere is given as (Saylor et al., 2018; Turcotte & Schubert, 2002; Wangen, 2010):

$$\omega(x) = \frac{\rho_c H W g \alpha^3}{8D} e^{-\frac{x}{\alpha}} \left(\cos\frac{x}{\alpha} + \sin\frac{x}{\alpha} \right) \tag{1}$$

where $\omega(x)$ is the deflection at x (horizontal distance relative to the center of the load), ρ_c is the density of topographic load (crust); H and W are the height and width of the load, respectively, g is gravity, α is the flexural parameter, which is a function of flexural rigidity of plate (D), density of fluid asthenosphere (ρ_m) and density of the basin fill (ρ_s) and gravity (g), given as:

$$\alpha = \left[\frac{4D}{(\rho_m - \rho_s) g} \right]^{1/4} \tag{2}$$

D is given as:

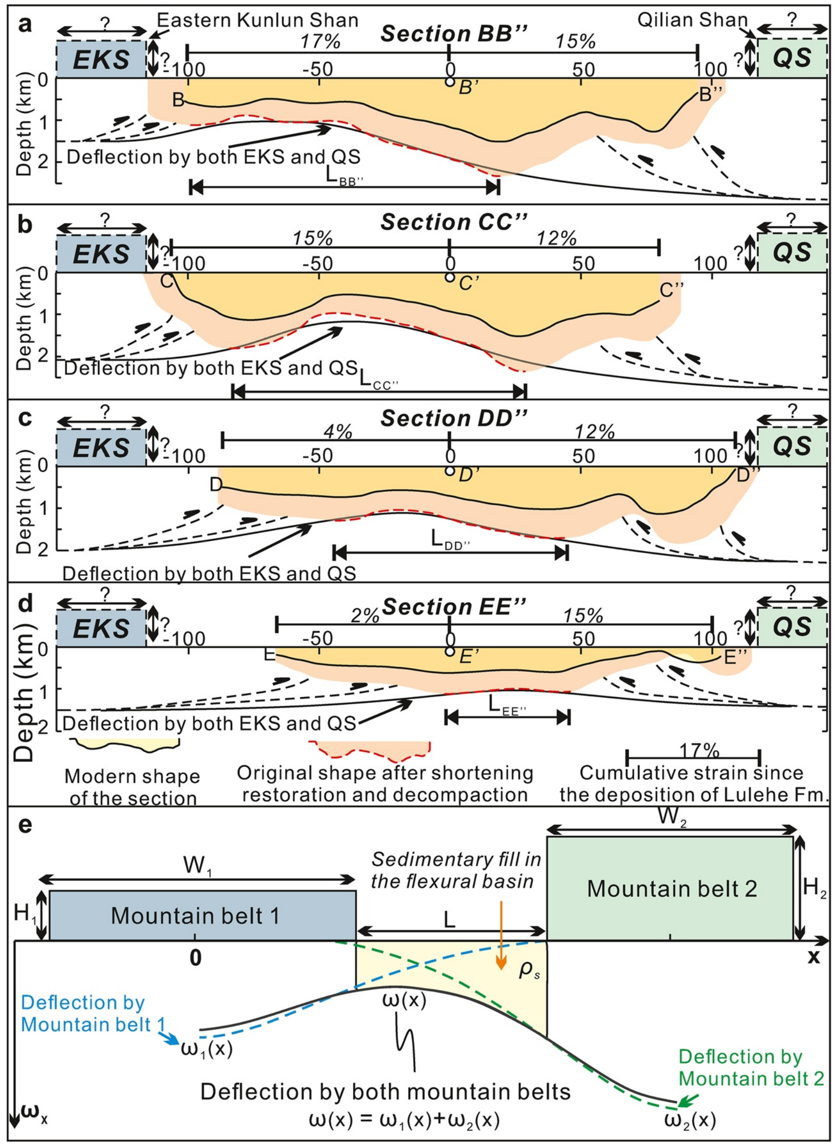

Figure 2. (a–d) Palinspastic section BB′, CC′, DD′, and EE during the deposition of Lulehe Fm. after the shortening restoration and decompaction. Shortening strain is based on estimate of Wei et al. (2016). (e) Two-load beam model, showing the relationship between the topographic loads of the mountains and the deflection of the sedimentary basin. Note the modeled shape of deflection by both Eastern Kunlun Shan and Qilian Shan should match with the palinspastic shape of the associated profile. Equation for $\omega_1(x)$ and $\omega_2(x)$ is given in Supporting Information Text S1.

$$D = E\frac{T_e^3}{12\left(1-\sigma^2\right)} \tag{3}$$

Flexural modeling methods of our two-load beam flexural model and uncertainty analysis are given in Figure 2e and Supporting Information Text S1. Relevant parameters (e.g., effective elastic thickness, gravity, mantel density, crustal density, basin fill density, width of the Qilian Shan and the Eastern Kunlun Shan) are in Table S1.

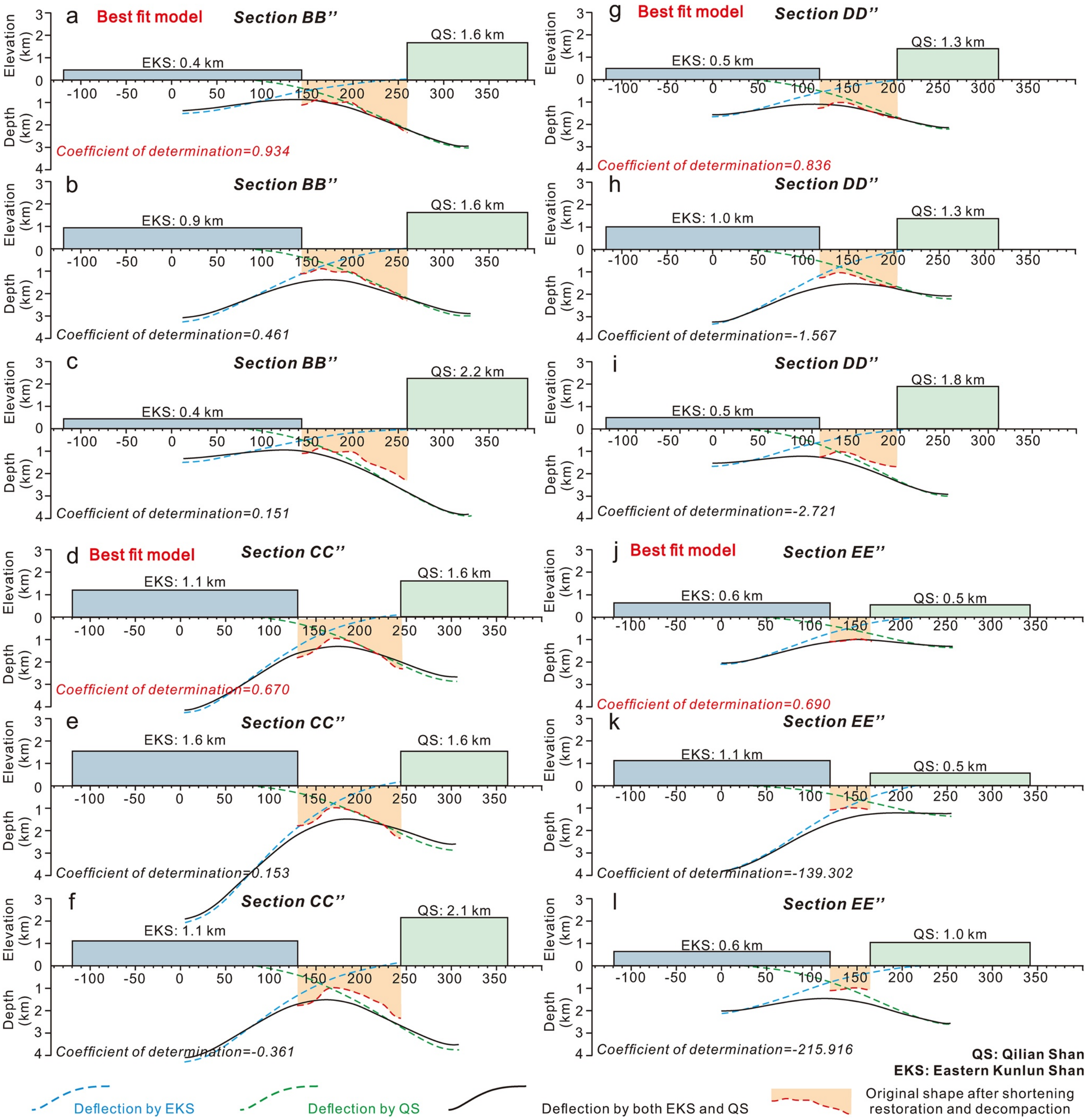

Figure 3. (a), (d), (g), and (j) show the modeled deflections of Qaidam basement best fits the original shape of sections BB′, CC, DD, and EE′, respectively. Changing parameters, for example, increasing the height of Eastern Kunlun Shan (b, **e**, **h**, **k**) and Qilian Shan (**c**, **f**, **i**, **l**) cannot improve the fit (a decrease in R^2 value) between the modeled deflection of the Qaidam basement and the original shape of the Qaidam basin.

4. Flexural Modeling and Paleoelevation Estimates

After shortening restoration and decompaction, the original shapes of the sections during the deposition of the Lulehe Fm. are shown in Figure 2. Best-fit flexural modeling results, including optimal Eastern Kunlun Shan and Qilian Shan heights that recreate the shape of the Qaidam basin, are summarized in Figure 3 and Table S1. We also provide multimedia animations to show the variation of flexural modeling results when changing the effective elastic thickness and the height of the Eastern Kunlun Shan and the Qilian Shan. See

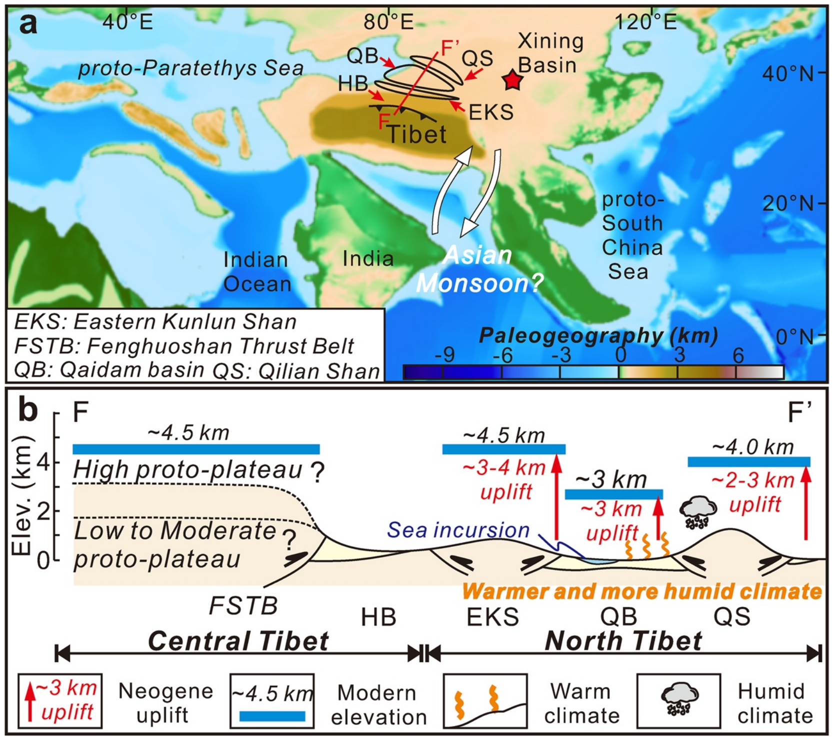

Figure 4. (a) Eocene (~40 Ma) paleogeographic maps of Asia showing the location of the proto-Paratethys Sea and mountain belts in Northern Tibet, modified from Poblete et al. (2021). (b) Schematic paleogeographic cross section of the central and northern Tibet, showing our proposed surface-uplift history for the northern Tibet. FSTB: Fenghuo Shan Thrust belt; EKS: Eastern Kunlun Shan; HB: Hoh Xil basin; QS: Qilian Shan; QB: Qaidam basin.

the Multimedia Animation S1-28 in the Supporting Information for more details. The code that was used to calculate the flexural modeling is given in the Supporting Information Data Set S2.

Marine incursions in the western Qaidam basin imply that it was close to proto-Paratethys sea level during the Paleogene (Kaya et al., 2019; Ma et al., 2019). With the knowledge that the proto-Paratethys sea level may have been slightly higher (≤200 m) than global sea level (Bosboom et al., 2017; Kaya et al., 2019; Meijer et al., 2019), we then estimate that the Eastern Kunlun Shan at the southwest end of Sections B, C, D, and E was 0.5 ± 0.1 km, 1.0 ± 0.1 km, 0.4 ± 0.1 km and 0.5 ± 0.1 km high above the mean sea level (a.m.s.l.), respectively. The Qilian Shan at the northeast end of the four sections was 1.5 ± 0.1 km, 1.5 ± 0.1 km, 1.2 ± 0.1 km, and 0.4 ± 0.1 km high a.m.s.l., respectively (Table S1). The results imply that the Qilian Shan was higher in all profiles, except section E, which displays the thinnest Lulehe Fm deposits (Figure 3d) and thus may have been at the eastern extent of the Paleogene basin.

5. Discussion

5.1. Paleogene Topography of the Northern Tibetan Plateau

These flexural modeling constraints refute the existence of a negligible relief in the northern Tibetan plateau during the Paleogene (Meyer et al., 1998; Tapponnier et al., 2001), but are in agreement with independent, albeit indirect evidence suggesting Paleogene topographic relief in the northern Tibetan plateau (Figure 4a), including: 1) Eocene exhumation recorded by thermochronology (He et al., 2018; Jolivet et al., 2001; Li et al., 2020; F Wang et al., 2017); 2) proximal deposition along the margin of the Qaidam basin and Eastern Kunlun Shan/Qilian Shan provenance of Qaidam basin sediments during the Paleogene (Cheng, Guo, et al., 2015; Cheng, C. N. Garzione, Mitra, et al., 2019; Wang et al., 2020; W Wang et al., 2017; Zhang et al., 2013); and 3) Paleogene thrusts observed in seismic profiles along the Qaidam basin margin (Cheng, C. N. Garzione, Jolivet, et al., 2019; Sun et al., 2020; Wu et al., 2014; Yin et al., 2007; Yin, Dang, Zhang, et al., 2008). In particular, our flexural modeling suggests a low (0.4–1.0 km) Eastern Kunlun Shan and a

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higher (0.4–1.5 km) Qilian Shan, contrasting the inference of a low Qilian Shan relative to a higher Eastern Kunlun Shan advocated by northward-propagating deformation models (England & Houseman, 1986; Tapponnier et al., 2001).

Our flexural modeling results show variable along-strike relief within the Eastern Kunlun Shan and Qilian Shan, with the Eastern Kunlun Shan showing a local topographic high in its center and the Qilian Shan yielding eastward decreasing topography. These variations may reflect lithological heterogeneities within the mountain belts or may result from their structural setting. For example, our results support a kinematic linkage between the early Cenozoic Qilian Shan and Altyn Tagh fault, resulting in higher topography closer to the Altyn Tagh fault in the west (Cheng, Jolivet, et al., 2015; Cheng, Jolivet, et al., 2016; He et al., 2018; Jolivet et al., 2001), whereas the early Cenozoic Eastern Kunlun Shan (Staisch et al., 2020) may have been an isolated thrust system with a local topographic high in its center. Variable along-strike relief in the Eastern Kunlun Shan would have developed a laterally irregular drainage divide between the Qaidam basin to the north and the Hoh Xil basin to the south. The relatively low topographic relief (~0.4 km) in the Eastern Kunlun Shan implies the possibility of drainage connection between the Qaidam and Hoh Xil basins during the Paleogene as hypothesized in the Paleo-Qaidam basin model (Cheng, Fu, et al., 2016; Cheng, C. N. Garzione, Mitra, et al., 2019; McRivette et al., 2019; Yin, Dang, Zhang, et al., 2008). On the other hand, such a potential connection should be completely cut off in those areas with a relative higher relief (~1.0 km). This finding reconciles the early Cenozoic exhumation of the Eastern Kunlun Shan (Cheng, Fu, et al., 2016; Cheng, C. N. Garzione, Mitra, et al., 2019; Wang et al., 2020; Zhang et al., 2013) with the existence of a large depression in the northern Tibet (McRivette et al., 2019; Wu, Zuza, Zhou, et al., 2019; Yin, Dang, Zhang, et al., 2008).

This unique Paleogene topographic feature in the northern Tibetan plateau indicates that the strain concentrated first in the Qilian Shan to the north, partially skipping the Eastern Kunlun Shan (Figure 4b)(Yin, Dang, Zhang, et al., 2008). Paleozoic suture zones acted as preexisting weaknesses to focus Cenozoic in both the Eastern Kunlun Shan and Qilian Shan (Allen et al., 2017; Wu et al., 2016; Zuza et al., 2016; Zuza, Wu, Wang, et al., 2018). Strength heterogeneities between the stronger North China craton and the weaker Tibetan lithosphere may have concentrated initial strain along the Qilian suture zone. After protracted crustal thickening across the Qilian Shan, it became more efficient for deformation to jump south to the Eastern Kunlun Shan. This kinematic history may have been enhanced by lithospheric buckling at a first-order wavelength of ~200 km (Bischoff & Flesch, 2018; Burg et al., 1994). Alternatively, evidence from geological mapping (Chen et al., 2012; Zuza, Wu, Reith, et al., 2018), source to sink analysis (Cheng, C. Garzione, et al., 2019; Cheng, C. N. Garzione, Mitra, et al., 2019), thermochronology (Dai et al., 2013; He et al., 2017; Jolivet et al., 2001; Liu et al., 2007), and seismic profiles (Cheng, C. Garzione, et al., 2019; Cheng, C. N. Garzione, Mitra, et al., 2019; Wu et al., 2014) suggest that the bimodal topography may reflect some pre-Cenozoic topographic inheritance in both mountain belts. However, given the unknown extent and distribution of the potential pre-existing topographic relief in the northern Tibet, it is still difficult to distinguish the contribution of pre-Cenozoic topographic inheritance from the lithospheric buckling. A more comprehensive geological investigation on the Mesozoic evolution of the northern Tibetan plateau is still needed.

Given our inferences of a low Eastern Kunlun Shan and relatively higher Qilian Shan, and considering the modern high elevation in Eastern Kunlun Shan and the Qilian Shan, we estimate ~3–4 km and ~2–3 km surface uplift after the deposition of the Lulehe Fm. in the Eastern Kunlun Shan and the Qilian Shan, respectively (Figure 4b). Cenozoic crustal shortening across the northern Tibetan plateau is sufficient to raise the elevations of the mountain ranges by these postulated magnitudes (Yin, Dang, Zhang, et al., 2008; Zuza et al., 2016). Our estimates imply that during the Neogene, substantial tectonic surface uplift concentrated more in the Eastern Kunlun Shan than in the Qilian Shan. The strength of the lithosphere and gravitational potential energy (GPE) are the two important forces that resist mountain building in the orogenic belts (Molnar & Lyon-Caen, 1988). The lithospheric strengths of the Eastern Kunlun Shan and Qilian Shan should be comparable because they share similar crustal compositions (Cheng et al., 2017; Karplus et al., 2011; Wu, Zuza, Chen, et al., 2019; Yin & Harrison, 2000; Zhao et al., 2013; Zuza, Wu, Reith, et al., 2018), which is further supported by similar elastic thickness (T_e) estimates (Braitenberg et al., 2003).

Accordingly, GPE probably modulated the relative Neogene growth of the Qilian Shan and Eastern Kunlun Shan. As uplift-related GPE is balanced by deviatoric stress across a mountain belt, it becomes less favorable to support continued range growth and uplift, and thus orogenic belts reach a maximum mean elevation related to the applied stress (Molnar & Lyon-Caen, 1988). Erosion of high topography with increased relief, perhaps modulated by local climate, may further drive enhanced deformation of high GPE areas (Cheng, C. N. Garzione, Mitra, et al., 2019). In northern Tibet, the present high elevation Eastern Kunlun Shan is at steady state GPE and topography whereas the Qilian Shan is at non-equilibrium state, evidenced by large maximum shear strain but negligible dilatation along the Kunlun fault and the strong negative dilatation and moderate shear strain along Haiyuan fault in the Qilian Shan derived from the GPS velocity field (M Wang & Shen, 2020). We thus infer that the Eastern Kunlun Shan reached its maximum mean elevation after the Miocene but prior to the present, due to crustal shortening and possible late Cenozoic magmatic inflation (Chen et al., 2018; Molnar et al., 1993; Yin, Dang, Zhang, et al., 2008). Since peak elevation attainment, plate convergence across the Eastern Kunlun Range has been accommodated primarily via lateral shear strain (Duvall et al., 2013; Fu & Awata, 2007; Jolivet et al., 2003; Staisch et al., 2020). Conversely, with no late Cenozoic magmatism in the Qilian Shan, Neogene convergence was partitioned in the Qilian Shan as outward growth (Bovet et al., 2009; Cheng, C. N. Garzione, Mitra, et al., 2019; Zheng et al., 2017) and/or eastward translation and block rotation (Cheng et al., 2021), preventing the Qilian Shan from reaching its maximum mean elevation.

5.2. Paleoclimate Implications

How and when did the Asian monsoon system develop has intrigued geoscientists for decades (An et al., 2001; Boos & Kuang, 2010; Holbourn et al., 2018; Licht et al., 2014; Nie et al., 2018; Porter, 2001; Saylor et al., 2016; Spicer, 2017; Sun & Wang, 2005; Wang et al., 2005). The well-exposed Quaternary losses-paleosol sequences and late Miocene-Pliocene red clay sequences in the Chinese Loess Plateau record the East Asian Monsoon history since the late Miocene (An et al., 1990, 2001; Ding et al., 1999; Heller & Tungsheng, 1984; Kukla, 1987; Sun et al., 1997). The finding of the dust records in the Chinese Loess Plateau and adjacent regions push the East Asian monsoon history back to late Oligocene to early Miocene (Guo et al., 2002, 2008). Recent studies further argue that a monsoon-like arid climate conditions may have initiated as early as the ~40 Ma (Licht et al., 2014, 2016) although some climate simulations challenge the establishment of a monsoon-like climate in East Asian since the Eocene (X Li et al., 2018).

Despite the importance of the atmospheric CO_2 concentration (Ren et al., 2020) and global cooling (Zhang et al., 2018), climate models and geological records show that the Asian paleoclimate is sensitive to the topography of the Tibetan plateau (Clift et al., 2008; Licht et al., 2014; Liu and Yin, 2002; Molnar et al., 1993; Prell & Kutzbach, 1992). The onset of the modern Asian monsoonal system has been genetically associated with to development of high topographic relief of the Tibetan–Himalayan orogen (Molnar et al., 1993), likely resulting from a Neogene rapid surface uplift of the plateau. Our inference of a low (0.4–1.0 km) Eastern Kunlun Shan and moderate (0.4–1.5 km) Qilian Shan implies a substantial Neogene surface uplift (2–4 km) of the northern Tibet which would affect the regional circulation by disrupting the general west-to-east atmospheric flow and providing a heat source that warms the atmosphere over the plateau and further strengthens its southeast flow (Molnar et al., 1993).

The lower topographic relief in the northern Tibetan plateau during the Paleogene compared with today would also allow a warmer and more humid climate with enhanced physical erosion rate and silicate weathering rates (Figure 4b). Increased erosion patterns under a warmer and wetter climate could modulate Paleogene mountain building (Cheng, C. N. Garzione, Mitra, et al., 2019; West et al., 2005) and in turn, possibly affect deformation and surface uplift (Liu et al., 2020; McQuarrie et al., 2008) in northern Tibet. Our argument of a warmer and humid climate in the northern Tibet during the Paleogene is in agreement with the magnetic susceptibility records from the Xorkol basin (J Li et al., 2018) and oxygen isotope records from the lacustrine strata in the Qaidam basin (Li and Garzione, 2017; Li et al., 2017; Mao et al., 2014; Rieser et al., 2009)(Figure S1).

6. Conclusions

Flexural modeling results based on Paleogene isopach data from the Qaidam basin suggest a topographic load generated by a low (0.4–1.0 km) Eastern Kunlun Shan and a moderate (0.4–1.5 km) Qilian Shan is responsible for the subsidence of the Qaidam basin during the Paleogene. We attribute the difference in paleo-reliefs in the Eastern Kunlun Shan and the Qilian Shan to the lithospheric buckling, distinctive location of the Qilian Shan against the North China, and the pre-existing topographic relief. The significant variability of the along-strike relief within the Eastern Kunlun Shan reconciles the early Cenozoic exhumation of the Eastern Kunlun Shan with the existence of a wide depression in the northern Tibet. We further propose that Neogene surface uplift in the Eastern Kunlun Shan was more significant than in the Qilian Shan. The existence of a low-to-moderate topography implies a warmer and more humid climate which in turn affected the mountain building in North Tibet. In summary, this study offers a new approach that provides an independent constraint on the Paleogene topography of North Tibet, which improves our understanding of the growth of the Tibetan plateau and Asian paleoclimate.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data for the work in this paper can be downloaded from the https://osf.io/aundx/?view_only=0df85d504011448c92406a6d07ee5a72. Supplementary figures can be found in the Supporting Information.

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