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02 Cenozoic evolution of the Qaidam basin and implications for the growth of the northern Tibetan plateau: A review

 The corrections made in this section will be reviewed and approved by a journal production editor.

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[Instruction: Add a third affiliation to Feng Cheng. Thus, the authors and affiliation should be changed to: Feng Cheng^{a, b, c, *}, Marc Jolivet^d, Zhaojie Guo^a, Lin Wang^{e, *}, Changhao Zhang^f, Xiangzhong Li^g ^a *Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, School of Earth and Space Sciences, Peking University, Beijing, 100871, China* ^b *Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557, USA* ^c *Lhasa National Geophysical Observation and Research Station, Institute of Geology, China Earthquake Administration, Lhasa 850004, China* ^d *Laboratoire Géosciences Rennes, CNRS-UMR6118, Université Rennes 1, Observatoire des Sciences de l'Univers, Rennes, 35042, France* ^e *College of Engineering, Peking University, Beijing 100871, China* ^f *Qinghai Oilfield Company, PetroChina, Dunhuang, Gansu, 736202, China* ^g *Yunnan Key Laboratory of Earth System Science, Yunnan University, Kunming, 650500, China*]

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Abstract

As the largest depression in the Tibetan plateau, the Qaidam basin preserves over 10 km thick of Cenozoic sediments. Those sediments represent a unique archive of the evolution of the northern part of the Tibetan plateau and of intracontinental deformation in general. Yet, several critical issues associated with the evolution of the Qaidam basin remain controversial, preventing a full understanding of the evolution of the northern margin of Tibet during the Cenozoic. Here we comprehensively review these issues, synthesize records from structural geology, sedimentology, geochronology, and geophysics, and finally propose a holistic view of the Cenozoic evolution of the Qaidam basin. We infer that: 1) the traditional age model that assigned a Paleocene to Eocene basal age to the Cenozoic strata in the basin seems to fit reasonably well the deformation history obtained from combining growth-strata observations and thermochronology data across the basin; 2) basement-involved faults, with both dip-slip and strike-slip components, developed within the Qaidam basin. In particular, the Neogene initiation of strike-slip faulting along the south-dipping faults that roots into the Eastern Kunlun Shan played an important role in the evolution of the southern Qaidam basin; 3) The Eastern Kunlun Shan was already exhumed during the deposition of the Lulehe Formation, serving as a significant source of clastic material deposited in the Qaidam basin and separating the latter from the Hoh Xil basin to the south. We conclude that the Qaidam basin is a superimposed sedimentary basin that successively experienced flexural subsidence, outwards expansion, isolation and partitioning during the Cenozoic. Finally, the Cenozoic evolution of the basin results from a tight interplay between tectonics and climate.

Keywords:

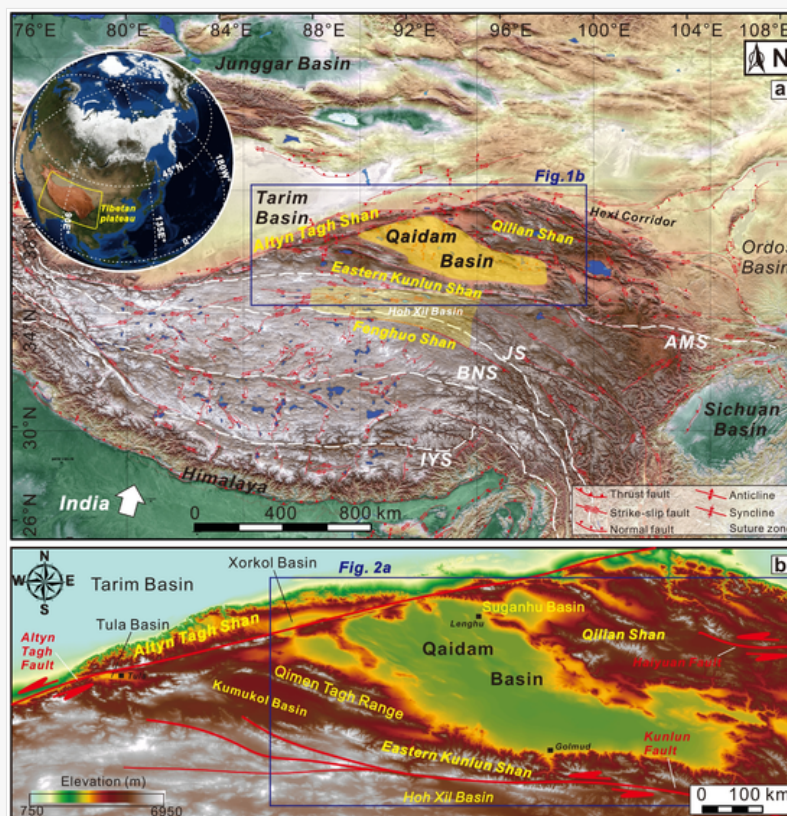
1 Introduction

Our knowledge of the growth of the Tibetan plateau has progressed over the last few decades, mostly by depicting in details the Cenozoic tectonic and topographic evolution of the several mountain belts and associated fault systems that compose the plateau (Ding et al., 2014; Hubbard and Shaw, 2009; Jolivet et al., 2001; Lease, 2014; Tapponnier et al., 2001; Wang et al., 2014; Yin et al., 2002). A particular interest has been addressed to the margins of the plateau – the locus of the outward expansion of the high-topography region – characterized by active tectonic deformation and sharp topographic and climatic gradients. Several substantial breakthroughs have been achieved in dating, describing and quantifying the Cenozoic deformation of the northern edge of the Tibetan plateau. One of the first widely accepted model argued that crustal deformation in the northern Tibetan plateau initiated during the Pliocene to Holocene, progressively propagating northward (Métivier et al., 1998; Meyer et al., 1998; Tapponnier et al., 2001). However, recent work highlights a protracted Cenozoic deformation history initiating during Early Cenozoic, progressing through the Oligocene to Early Miocene, and accelerating in the Middle Miocene to Holocene-Quaternary times (Cheng et al., 2015a; Clark et al., 2010; Dupont-Nivet et al., 2004; Duvall et al., 2013; Duvall et al., 2011; Jolivet et al., 2001; Lease et al., 2012; Yin et al., 2002; Zheng et al., 2010; Zhuang et al., 2011b). These new findings are in conflict with the progressively northward propagation model, highlighting an urgent need for a better understanding of the mechanisms that drove the growth of the plateau.

The northern Tibetan plateau is composed of a series of high topographic gradient mountain ranges surrounding the large and deep Qaidam sedimentary basin (Fig. 1). Being the largest Cenozoic sedimentary basin within the Tibetan plateau, the Qaidam basin is bordered by the Altyn Tagh Shan to the west, the Eastern Kunlun Shan to the south, and the Qilian Shan to the northeast (Figs. 1–2). Geological and subsurface surveys reveal that the basin preserves Cenozoic sedimentary successions reaching over 10 km in thickness (Cheng et al., 2018; Cheng et al., 2017; Wei et al., 2016; Xia et al., 2001; Yin et al., 2008b; Zhang et al., 2013a; Zhu et al., 2006). These clastic deposits contain some major hydrocarbon resources and the numerous field-derived and geophysical data resulting from exploration offer a unique opportunity to elucidate the evolution of the basin itself but also the growth history of the surrounding mountain belts. However, three critical issues associated with the tectonic and sedimentary evolution of the Qaidam basin remain controversial, leading to diverse and even competing models for the Cenozoic evolution of northern Tibet.

alt-text: Fig. 1

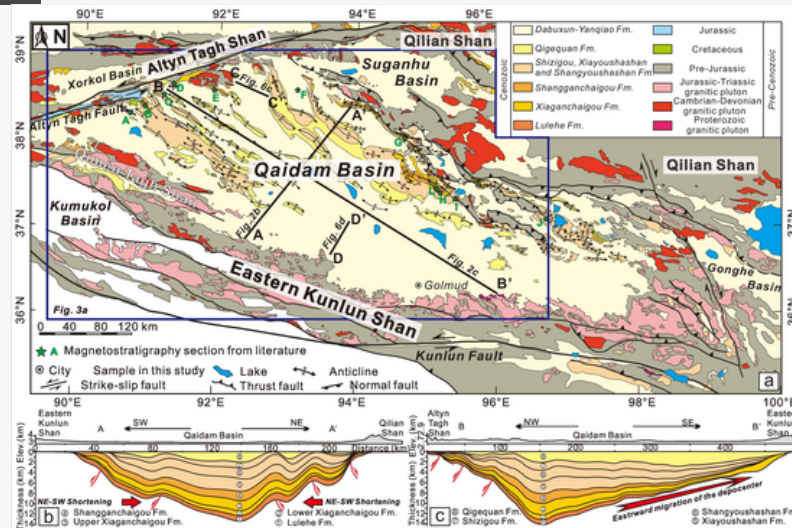
Figure 1. Fig. 1



(a) Topographic map of the Tibetan plateau, showing the main geological features. IYS, BNS, JS, AMS, refer to Indus Yalu, Bangong Nuijiang, Jinsha, Anymagen-Kunlun-Muztagh suture zones, respectively. (c) Topographic map of the Qaidam basin and the

alt-text: Fig. 2

Figure 2, Fig. 2



(a) Geological map of the Qaidam basin and the surrounding regions. (b) NE-SW- and (c) NW-SE-oriented profiles across the Qaidam basin, modified from Cheng et al. (2018). Note the NE-SW-directed crustal shortening across the Qaidam basin and eastward migration of the depocenter of the basin during the Cenozoic.

First, the age model for the Cenozoic strata within the Qaidam basin is highly debated. Most studies based on magnetostratigraphy, spore and pollen assemblages, fission-track and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of detrital grains as well as regional lithostratigraphic correlations assigned a Paleocene basal age (>50 Ma) to the Lulehe Formation (Fm.) that represents the lowermost part of the Cenozoic sequence (Chang et al., 2015; Fang et al., 2019; Fang et al., 2006; Fang et al., 2007; Ji et al., 2017; Ke et al., 2013; Lu and Xiong, 2009; Rieser et al., 2006a; Rieser et al., 2006b; Sun et al., 1999; Sun et al., 2005; Yang et al., 1992; Zhang, 2007). By contrast, a few recent studies proposed a Late Oligocene (~25–20 Ma) onset of sedimentation based on magnetostratigraphical constraints from two sections exposed along the northern margin of the basin (Fig. 2). When adopting the older age model with a Paleocene to Eocene deposition age of the Lulehe Fm., the Cenozoic onset time of faulting along the Altyn Tagh Fault and the northern Qaidam basin-Qilian Shan thrust belt becomes roughly coincident with the onset of India-Asian collision at 60–50 Ma (Cheng et al., 2019a; Cheng et al., 2019c; Cheng et al., 2015b; Cheng et al., 2016b; Cheng et al., 2019d; Dupont-Nivet et al., 2010; Hu et al., 2015; Yin et al., 2008a; Yin et al., 2008b). This inference of an Early Cenozoic deformation in the northern Tibetan plateau supports the argument that stress derived from India-Asia collision was transmitted rapidly to the northern edge of the plateau (Clark et al., 2010; Jolivet et al., 2001; Wang et al., 2017a; Yin et al., 2002; Zhuang et al., 2011b). Furthermore, if Paleocene to Eocene crustal shortening took place in the northern Tibetan plateau, mountain belts would probably have formed orographic barriers, starting to block the transfer of atmospheric moisture to the continental interior as early as the Early Cenozoic. This would be consistent with the already semi-arid to arid climate recorded in the Tarim basin during the Paleogene (Heilbronn et al., 2015; Jolivet et al., 2018; Sun and Wang, 2005). On the contrary, if considering an Oligocene deposition age for the Lulehe Fm., the onset time of deformation in the Altyn Tagh Shan and Qilian Shan would be similar to that of exhumation in the Eastern Kunlun Shan, Xining-Minhe-Longzhong basin complex and Dangchang basin (Clark et al., 2010; Dupont-Nivet et al., 2008; Dupont-Nivet et al., 2004; Horton et al., 2004). Based on this model, the initial deformation in the northern Tibetan plateau would start about 15–20 Ma later than the onset of India-Asia collision. This would fit with the model proposing a gradual northward propagation of the deformation in the plateau (Meyer et al., 1998; Tapponnier and Molnar, 1977; Tapponnier et al., 2001; Wang et al., 2017b). If topographic growth had remained limited in the northern Tibetan plateau during the Early Cenozoic, atmospheric circulation would probably not have been strongly affected, and the climate change in the Asian interior during the Early Cenozoic should be largely linked to other factors, such as the global climate variation or the retreat of the Paratethys sea (Bosboom et al., 2014; Dupont-Nivet et al., 2007; Meijer et al., 2019). As a consequence, it is of great importance to confirm the age model for the Cenozoic strata in the Qaidam basin.

Second, the source to sink and structural relations between the Eastern Kunlun Shan and the Qaidam basin (Figs. 1–2) has attracted geoscientists for decades because of their implications for the deformation pattern of the northern Tibetan

plateau (e.g., progressive northward, out of sequence, or pulsed deformation). Comparing the stratigraphic architecture of the Cenozoic strata in the Qaidam basin with those of the Hoh Xil basin immediately to the south, [Yin et al. \(2008b\)](#) proposed the existence of a wide Paleo-Qaidam basin. Their model suggested a vast Early Cenozoic depression bounded by the Qilian Shan to the north and by the Fenghuo Shan Thrust Belt to the south with negligible topographic relief in the Eastern Kunlun Shan. This model has been followed by many researchers ([Fig. 1](#)) ([McRivette et al., 2019](#); [Wu et al., 2019b](#)). However, other studies have indicated that the Eastern Kunlun Shan might have already been exhumed during the Early Cenozoic ([Cheng et al., 2016a](#); [Cheng et al., 2019a](#); [Wang et al., 2014](#)), which would suggest that the similar stratigraphic architecture of the Qaidam and Hoh Xil basins is only due to a similar depositional environment. Given that the crux of the debate is a dispute over the uplift history of the Eastern Kunlun Shan, it is of primary importance to document the evolution of the topography and the structural relation between the Qaidam basin and the Eastern Kunlun Shan.

The third open question is the Cenozoic evolution history of the Qaidam basin and the associated growth history of the northern Tibetan plateau. This issue is closely related to the abovementioned two issues. For instance, a Paleocene basal age (>50 Ma) for the Cenozoic strata in the basin would partly support the distributed shortening model ([Dewey and Bird, 1970](#); [England and Searle, 1986](#)). However, a late Oligocene basal age (~25–20 Ma) would support the outward growth or northward propagation model ([Métivier et al., 1998](#); [Meyer et al., 1998](#); [Tapponnier et al., 2001](#); [Wang et al., 2017b](#); [Zheng et al., 2017](#)). In addition, the Paleo-Qaidam basin model requires an Early Cenozoic onset of deformation in the Qilian Shan to the north and a Neogene initiation of the deformation in the Eastern Kunlun Shan to the south. This would imply deformation first in the northern margin of the Tibetan plateau, partially skipping the Eastern Kunlun Shan shortly after India-Asia collision ([Yin et al., 2008a](#); [Yin et al., 2008b](#)). On the other hand, other studies proposed a synchronous deformation in both the Eastern Kunlun Shan and the Qilian Shan to the north ([Cheng et al., 2016a](#); [Cheng et al., 2019a](#); [Wang et al., 2014](#)), again indicating distributed crustal deformation across the northern Tibetan plateau.

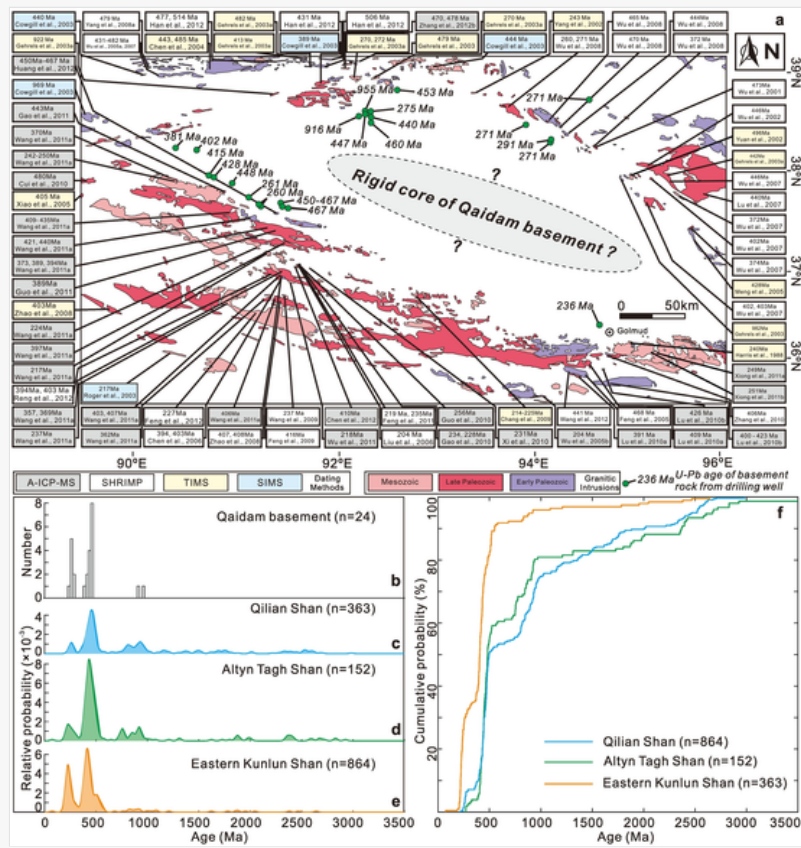
In this contribution, we focus on the first two critical issues by summarizing recent studies that provide different views on these issues and discussing the advantages and limitations of each hypothesis, and we propose future directions of investigation. We synthesize available information from subsurface data interpretation (i.e., seismic profiles and isopach maps of Cenozoic strata), sedimentology, stratigraphy, and basin analysis to present a holistic view of the Cenozoic evolution of the Qaidam basin.

2.2 Geological setting

The granitic and metamorphic crystalline basement of the Qaidam basin is covered by a relatively thin (less than 3 km) and discontinuous Mesozoic sedimentary sequence and a huge, as thick as 10 km Cenozoic sequence ([Figs. 2, 3a and 4](#)) ([Liu et al., 2007b](#); [Meng and Fang, 2008](#); [Rieser et al., 2006b](#); [Xia et al., 2001](#); [Yin et al., 2008a](#); [Yin et al., 2008b](#); [Zhou et al., 2006](#)). Recent studies showed that the Qaidam basin and the surrounding orogenic belts share a similar basement composition (i.e., similar geochemistry and U-Pb zircon age spectra) ([Cheng et al., 2017](#)) ([Fig. 3b–f](#)). The Qaidam crystalline basement was involved in at least Neoproterozoic, Early Paleozoic, and Late Paleozoic to Mesozoic tectono-magmatic episodes ([Cheng et al., 2017](#)). These recurrent thermo-mechanical events generated weaknesses in the Qaidam basement that should therefore not be considered as a mechanically strong crust. Detailed description of the basement is given in the Supplementary materials.

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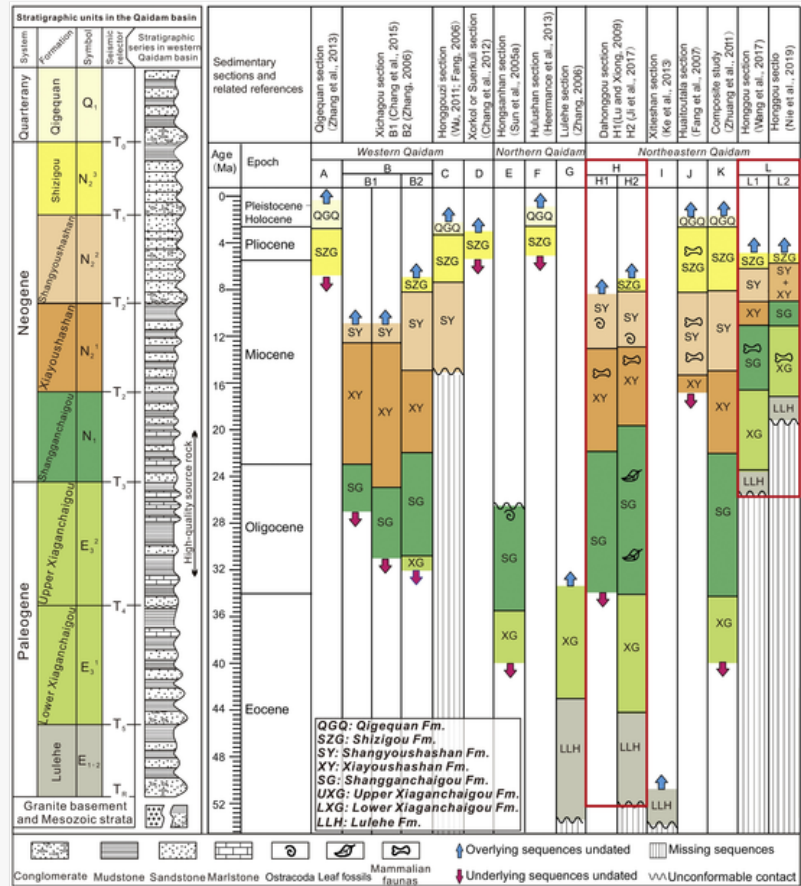
Figure 3, Fig. 3



(a) Zircon U-Pb ages for granitoids showing the distribution of Proterozoic to Mesozoic intrusions in the Qaidam basin and surrounding orogenic belts. Note the age of the Qaidam basement rocks along the edges of the basin (Cheng et al., 2017). The relative probability plot of the U-Pb zircon ages from basement rocks in the Qaidam basin (b), Qilian Shan (c), Altyn Tagh Shan (d), and Eastern Kunlun Shan (e). Cumulative probability plot for these data is shown in (f). Data and references listed are from Cheng et al. (2017) and references therein.

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Figure 4 Fig. 4



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Lithology, lithostratigraphic units, and age models of the Cenozoic strata in the Qaidam basin. The stratigraphic column is representative of the lithology in the western Qaidam basin, modified from Cheng et al. (2018). The multiple age models are modified from the compilation of (Wu et al., 2019b). These age models were established by previous work from different sections in the basin (Chang et al., 2012; Chang et al., 2015; Fang et al., 2006; Fang et al., 2007; Heermance et al., 2013; Ji et al., 2017; Ke et al., 2013; Lu and Xiong, 2009; Nie et al., 2019; Sun et al., 2005; Wang et al., 2017b; Wu, 2011; Zhang, 2007; Zhang et al., 2013b; Zhuang et al., 2011b). The location of each section is shown in Figure 2a. Images of typical outcrops and drill cores samples of Mesozoic to Cenozoic strata and basement rocks in the Qaidam basin. (a) Unconformities between the Jurassic and Cretaceous strata in the NE Qaidam basin. (b) Marginal lacustrine coal-bearing Jurassic strata in the NE Qaidam basin. (c) Drilling core samples in the NE Qaidam basin, showing coarse-grained sandstone in the Lulehe Fm. and granite basement rocks. (d) Conglomerates in the Lulehe Fm., eastern Qaidam basin. (e) Lacustrine limestone in the Lower Xiaganchaigou Fm., western Qaidam basin. (f) Organic rich layers in the Upper Xiaganchaigou Fm., western Qaidam basin. (g) Lacustrine to fluvial deposits in the Shangganchaigou Fm., eastern Qaidam basin. (h) Lacustrine sequences in the Xiayoushashan Fm., western Qaidam basin. (i) Mega-yardangs sculpted in mainly lacustrine Shizigou Fm. and fluvial Qigequan Fm., NE Qaidam basin.

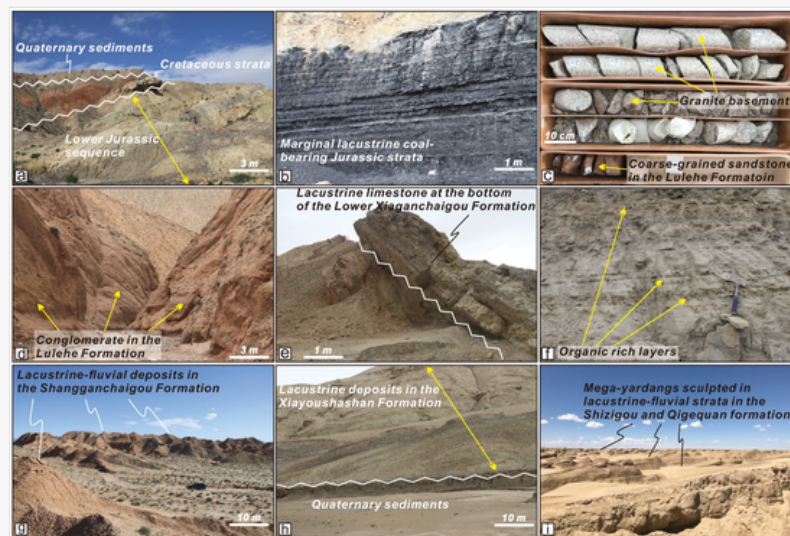
Mesozoic strata are Jurassic and Cretaceous in age (Cheng et al., 2019d; Meng et al., 2001; QBGMR, 1991; Ritts and Biffi, 2000; Ritts and Biffi, 2001; Ritts et al., 1999; Wu et al., 2011). These clastic, continental deposits mainly consist of sandstone intercalated with shale, coal, and conglomerate associated to fluvial to lacustrine depositional environments (Fig. 4a–b). The Mesozoic strata are essentially distributed in small sub-basins along the Altyn Tagh and the southern flank of the Qilian Shan in the NE Qaidam basin (Cheng et al., 2019d; Wu et al., 2011).

On the contrary, the Cenozoic strata are widely distributed throughout the basin with their main deposition center systematically located at the geometric center of the basin (Fig. 2) (Meng and Fang, 2008; Xia et al., 2001). According to the lithology and stratigraphy, the Cenozoic strata are classically subdivided into eight lithostratigraphic units, namely the Lulehe (Fm.), E_{1+2}^1 ; (2) the Lower Xiaganchaigou Fm., E_3^1 xg; (3) the Upper Xiaganchaigou Fm., E_3^2 xg; (4) the Shangganchaigou Fm., N_1 sg; (5) the Xiayoushashan Fm., N_2^1 xy; (6) the Shangyoushashan Fm., N_2^2 sy; (7) the Shizigou Fm., N_2^3 s; and (8) the Qigequan Fm. (Q_1 q). Integrating our own basin-scale field investigations and drill core observations with a compilation of previously published data (Fig. 4a–i), we propose a series of depositional environment maps and summarize the sedimentary features of these eight formations (Figure S1 in the Supplementary materials). The depositional ages for the Cenozoic strata are discussed in Section 4 (Fig. 5).

Q1

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Fig. 5



The Mesozoic and Cenozoic strata are cut by a series of NW- to WNW- trending faults also involving the basement (Fig. 2b–c) that must have participated in accommodating a significant amount of the Cenozoic crustal deformation in the northern Tibetan plateau (Cheng et al., 2014; Cheng et al., 2015c; Meng and Fang, 2008; Sun, 2019; Wang et al., 2010c; Wei et al., 2016; Wu et al., 2019c; Wu et al., 2014; Yin et al., 2008a; Yin et al., 2008b; Yin et al., 2007; Zhou et al., 2006). However, the geometry and kinematics of these faults have long remained debated (Burchfiel et al., 1989; Cheng et al., 2014; Huang et al., 2020; Métivier et al., 1998; Sun, 2019; Yin et al., 2007; Zuza and Yin, 2016), and will be discussed in Section 5.1.

3.3 Approaches

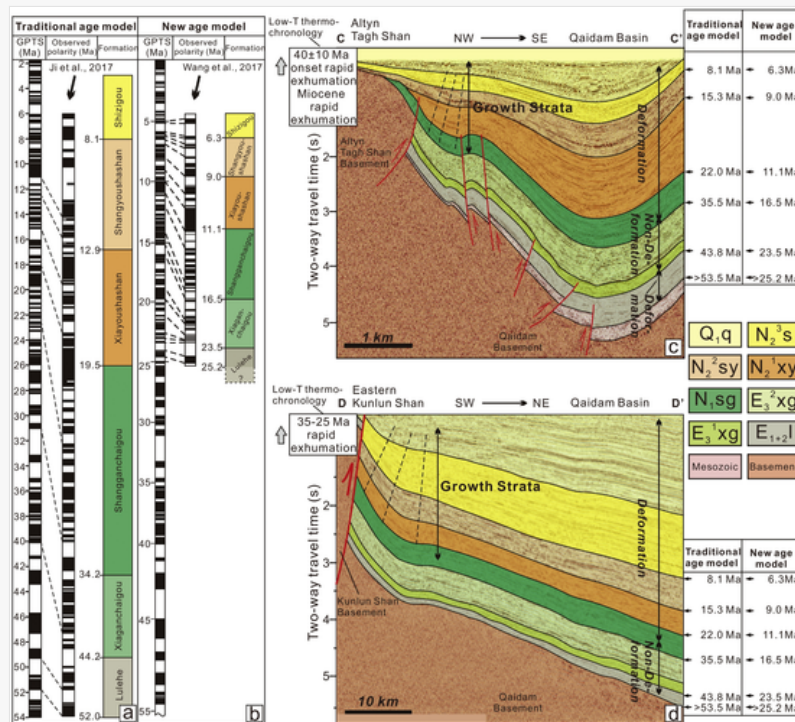
3.1.3.1 Age model

To evaluate the age model for the Cenozoic strata in the Qaidam basin, we first review the dating history and explain the details of the two above-mentioned debated age models, including their advantages and limitations (Fig. 5). We also select two seismic profiles in the southern and western parts of the basin that intersect the boundary faults (Fig. 6). After

superimposing the two age models to the growth strata on these seismic profiles, we compare the obtained deformation histories in the basin with the uplift and exhumation history of the mountain belts as inferred by existing low-temperature thermochronology data. We then discuss which age model provides a better match. A comprehensive analysis of the age model (Fig. 7) and a future perspective on the age model for the Cenozoic strata in the Qaidam basin are provided.

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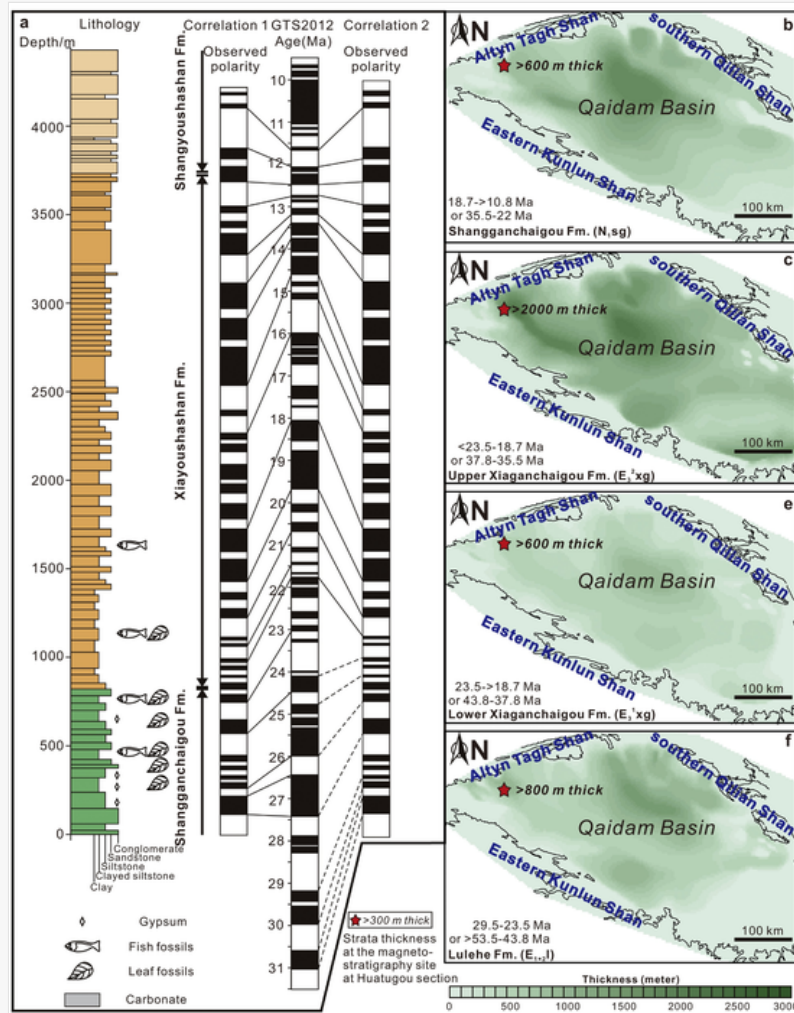
Figure 6 Fig. 6



Traditional (a) and new (b) age model for the Cenozoic strata in the Qaidam basin, represented by the work by Ji et al. (2017) and Wang et al. (2017b). Interpreted seismic profiles in the western (c) and southern (d) Qaidam basin. The section CC' is perpendicular to the strike of the Altn Tagh Shan (Cheng et al., 2016b) while section DD' is perpendicular to the strike of the Eastern Kunlun Shan (Cheng et al., 2018). The onset time of exhumation in the Altn Tagh Shan and Eastern Kunlun Shan is from previous low-temperature thermochronology studies (Clark et al., 2010; Jolivet et al., 2001; Wang et al., 2017a; Wang et al., 2015; Zhang et al., 2012). When following the “young ages” model (Wang et al., 2017b), the estimated onset time of deformation indicated by the growth strata conflicts with the onset time derived from the thermochronology data. When following the “old ages” model (Chang et al., 2012; Chang et al., 2015; Fang et al., 2007; Heemance et al., 2013; Ji et al., 2017; Ke et al., 2013; Lu and Xiong, 2009; Sun et al., 2005; Zhang, 2007; Zhang et al., 2013b), the estimated onset time of deformation indicated by the growth strata is consistent with the onset time derived from the thermochronology data. The location of each section is shown in Fig. 2a.

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Figure 7 Fig. 7



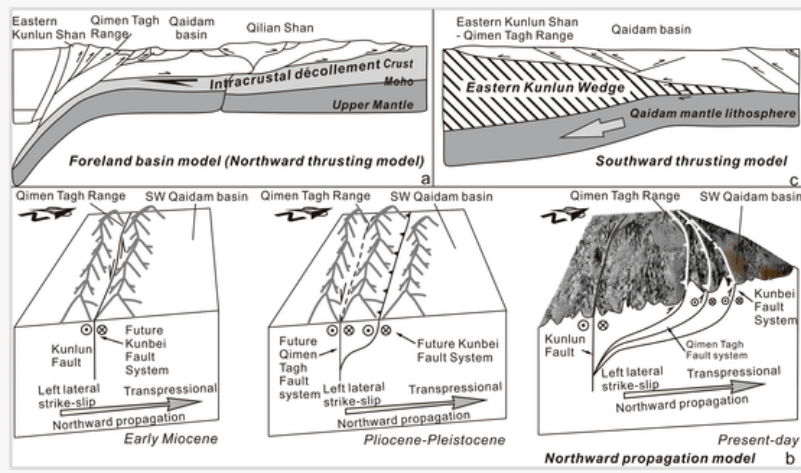
(a) Stratigraphic column and age model for the Cenozoic strata based on a magnetostratigraphy study in the western Qaidam basin, modified from [Chang et al. \(2015\)](#). Isochach map for the Cenozoic strata shows the thickness of the Shangganchaigou Fm. (b), Upper Xiaganchaigou Fm. (c), Lower Xiaganchaigou Fm. (d), and Lulehe Fm. (e) at this magnetostratigraphy site, respectively. Isochach data are from [Cheng et al. \(2018\)](#).

3.2.3.2 Interactions between the Qadaim basin and the Eastern Kunlun Shan

To understand the interactions between the Eastern Kunlun Shan and the Qaidam basin, two fundamental questions should be addressed: 1) What are the structural and kinematic relations between the Qaidam basin and the Eastern Kunlun Shan? ([Fig. 8](#)) and 2) What about the physiography of the northern Tibetan plateau margin in the Early Cenozoic? In other words, were the Qaidam and Hoh Xil basins part of a large Paleo-Qaidam basin or were they separated by a proto-Kunlun relief? To answer the first question, we first summarize the current debates on the fault geometry in the SW Qaidam basin. We then use seismic profiles ([Figs. 9–11](#)) and isochach data ([Fig. 10](#)) to document the structural evolution of the transition zone between the Qaidam basin and the Eastern Kunlun Shan. To answer the second question ([Fig. 12](#)), we analyze evidence provided by flexural modeling, sedimentary record (e.g., bulk petrology, detrital zircon geochronology) and subsurface data (seismic profiles, drill core samples, isochach maps) ([Figs. 14–17](#)) to document in details the source to sink relation between the Qaidam basin and the Eastern Kunlun Shan. Using the above-mentioned discussion as a guide, we propose a holistic view of the Cenozoic evolution of the basin.

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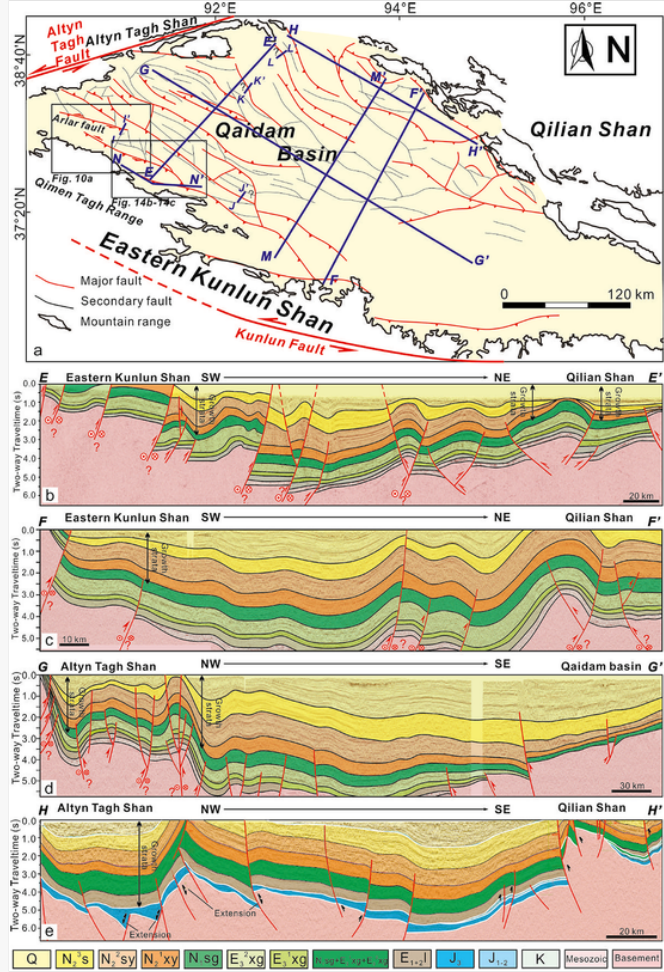
[Figure 8, Fig. 8](#)



Three typical models to describe the tectonic relation between the Qaidam basin and the Eastern Kunlun Shan. (a) Foreland basin model (northwards thrusting model)(Burchfiel et al., 1989). (b) Southwards thrusting model (Yin et al., 2008b; Yin et al., 2007). (c) Northward propagation model (Cheng et al., 2014).

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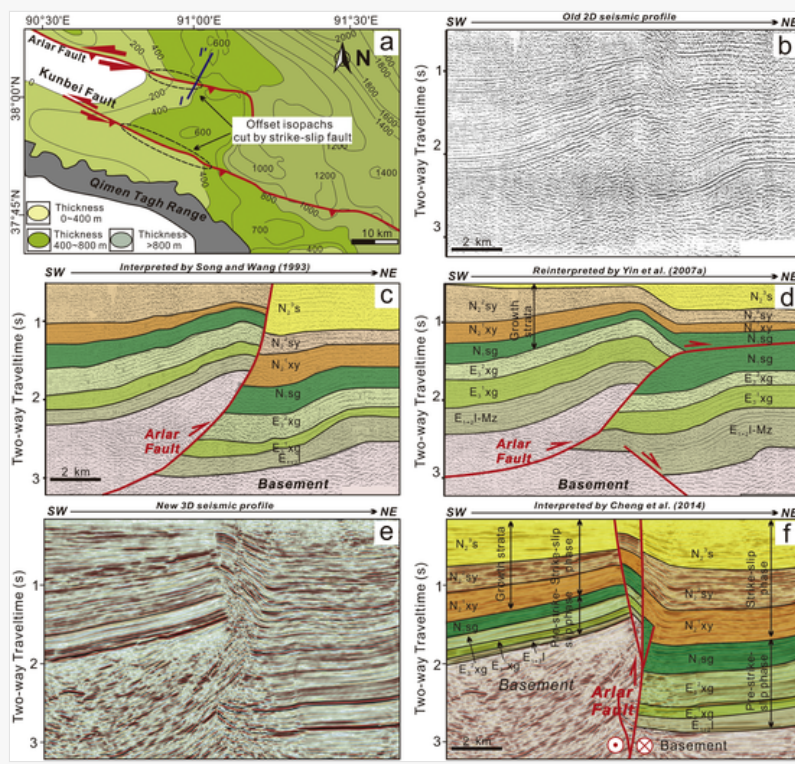
Figure 9, Fig. 9



(a) Distribution of the basement-involved faults in the Qaidam basin (data provided from the Qinghai Oil field, PetroChina). (b)–(e) interpreted seismic profiles across the Qaidam basin, compiled from previous studies (Cheng et al., 2015a; Cheng et al., 2019d; Cheng et al., 2017).

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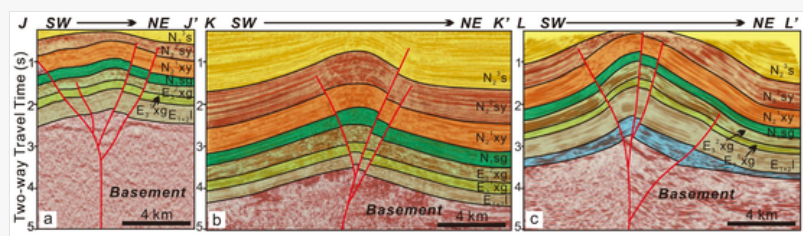
Figure 10, Fig. 10



(a) Isopach of the Upper Xiaganchaigou Fm., showing the Kunlun fault and Arlar fault (Cheng et al., 2014). The location of isopach map is shown in Fig. 9a. (b) 2D seismic profile of Song and Wang (1993), across the Arlar fault. (c) interpreted seismic profile by Song and Wang (1993). (d) Interpreted seismic profile by Yin et al. (2007). Uninterpreted (e) and interpreted (f) 3D seismic profile of across the Arlar fault (Cheng et al., 2014). Note that 3D seismic profiles show more obvious reflectors and flower structures are evidenced, indicating strike-slip faulting.

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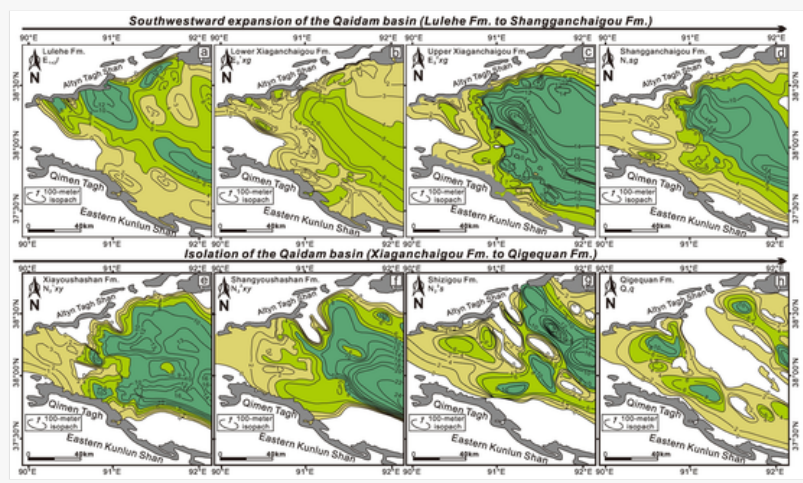
Figure 11, Fig. 11



Reinterpreted seismic profiles in the western Qaidam basin. Location of each profile is shown in Fig. 9a. Original profiles are listed in Liu et al. (2019). Note the flower structures, indicating the strike-slip components along these basement-involved faults. E₁₊₂¹xg; E₃¹xg; E₃²xg; N₁sg, N₂¹xy, N₂²sy, N₂³s, Q₁q are the abbreviated symbols for the Lulehe Fm., Lower Xiaganchaigou Fm., Upper Xiaganchaigou Fm., Shangganchaigou Fm., Xiayoushashan Fm., Shangyoushashan Fm., Shizigou Fm., Qigequan Fm., respectively.

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Figure 12, Fig. 12



4.4 Age model of Cenozoic strata in the Qaidam basin

4.4.1 Two debated age models

The first age model established for the Qaidam basin dates back to the late 1980s (Huo, 1990; Yang, 1988). A pioneering magnetostratigraphy study in the western and northeastern parts of the basin was then carried out by Yang et al. (1992), resulting in the following chrono-stratigraphic sequence: Paleocene to Early Eocene = Lulehe Fm., Late Eocene = Lower and Upper Xiaganchaigou Fms., Oligocene = Shangganchaigou Fm., Early to Middle Miocene = Xiayoushashan Fm., Middle to Late Miocene = Shangyoushashan Fm., Late Miocene to Pliocene = Shizigou Fm. Since then, a number of magnetostratigraphy studies have been conducted on the sparse exposures of Cenozoic strata of the Qaidam basin, leading to several different age models (Chang et al., 2012; Chang et al., 2015; Fang et al., 2006; Fang et al., 2007; Heermance et al., 2013; Ji et al., 2017; Ke et al., 2013; Lu and Xiong, 2009; Sun et al., 1999; Sun et al., 2005; Wang et al., 2017b; Zhang, 2007). Despite minor uncertainties in the absolute age of the boundaries between adjacent stratigraphic units, those models generally follow the model initially proposed by Yang et al. (1992) (Figs. 5–6). This stratigraphic framework, to some extent, is supported by the age controls from vertebrate fossils, ostracods, spore and pollen assemblages, fission-track and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of detrital grains as well as regional lithostratigraphic correlations (Chang et al., 2015; Fang et al., 2019; Fang et al., 2006; Fang et al., 2007; Ji et al., 2017; Ke et al., 2013; Lu and Xiong, 2009; Rieser et al., 2006a; Rieser et al., 2006b; Sun et al., 1999; Sun et al., 2005; Yang et al., 1992; Zhang, 2007).

On the other hand, as mentioned above, some recent publications reassigned the depositional age of the Cenozoic strata based on new magnetostratigraphy studies in the Honggou section (northeastern Qaidam basin) (Figs. 2 and 6b). This new age model claims for an Oligocene initial deposition of the Cenozoic strata, and proposes the following chrono-stratigraphic sequence: Oligocene = Lulehe Fm., Early Miocene = Lower and Upper Xiaganchaigou Fms., Middle Miocene = Xiaganchaigou Fm., Late Miocene = Shangyoushashan, and Shizigou Fms. (Fig. 5). Unlike the traditional age model, this new age model correlates their observed normal and reversed polarity zones at the Lulehe Fm. to the Late Oligocene to Early Miocene polarity zones at the Geomagnetic Polarity Time Scale (GPTS) (Fig. 6b). This new correlation is mainly based on: 1) Miocene vertebrate fossils found in the upper part of the section; 2) well-preserved and continuous strata without any unconformity or hiatus; 3) integrated detrital apatite fission track and detrital zircon geochronology data describing the source to sink relationships between the northeastern part of the Qaidam basin and the surrounding mountain belts; 4) a better match between the mean annual paleoprecipitation record in the Qaidam basin (Nie et al., 2019) and in the Chinese Loess Plateau (Nie et al., 2017) during the mid-Miocene climatic optimum (MMCO, 17–14.5 Ma) (Zachos et al., 2001).

However, some 20 km away from the Honggou section, in a laterally well connected section, Ji et al. (2017) performed a second magnetostratigraphic study, relying on biostratigraphic constraints, including palynological assemblages throughout the section, fossil leaves in the lower part of the section, ostracod assemblages, vertebrate fossils and detrital geochronology age constraints in the upper part of the section. Their results assign a Paleocene to Eocene depositional age for the basal part of the Lulehe Fm, completely different from the assignment by Wang et al. (2017b) and Nie et al. (2019), but consistent with the initial correlation of Yang et al. (1992). Given that these two sections are laterally connected and are situated on the same side of a fold in the NE Qaidam basin, these age models cannot be simultaneously correct.

4.4.2 Which age model is valid and can be better applied to other parts of the basin?

Both age models provide robust independent vertebrate fossil record at ~12–14 Ma as biostratigraphic age controls, suggesting convergence of the models for the post-middle Miocene strata and leaving open the debate on the pre-middle Miocene strata. Although fossil leaves were identified in the lower part of the section investigated by Ji et al. (2017), these leaves are not index fossils and thus cannot provide a tight age control. A lack of independent age constraints for the lower part of the Honggou section also makes the new age model debatable. Only by exclusively considering the correlation between the observed polarities zones and GPTS, the younger age model seems to provide a better match (Fig. 6b) further reinforced by the higher quality of the data with less gaps in the polarities correlations (Nie et al., 2019; Wang et al., 2017b).

However, we should still be cautious to assign a Late Oligocene age to the basal Cenozoic strata across the Qaidam basin. As shown on the seismic profiles (Fig. 9), the tectonic framework along the northwestern margin of the Qaidam basin is characterized by complex structures in the fold-thrust belt (Cheng et al., 2019c; Cheng et al., 2019d; Yin et al., 2008a; Yin et al., 2008b). Outcrops in the eastern part of the basin, especially along the southwestern front of the Qilian Shan usually contain much more complex lithostratigraphic units comparing with those exposed in the other parts of the basin (Fig. 2a). If the lithostratigraphic unit at the bottom of this section is truly the Lulehe Fm., it is worthy to carefully

recheck for potential unconformities, hiatus or faulted contacts along this section. More importantly, previous thermochronology studies have revealed an obvious Paleocene to Early Eocene tectono-thermal event in mountain belts surrounding the Qaidam basin (Chen et al., 2011; He et al., 2017; He et al., 2018; Jolivet et al., 2001; Lin et al., 2015; Pan et al., 2013; Staisch et al., 2020; Wang et al., 2010a; Wang et al., 2017a; Wang et al., 2007; Wang et al., 2015), roughly coincident with or shortly post-dating the onset of India-Asia collision. Therefore, crustal shortening and surface uplift in the northern Tibetan plateau might have already initiated in the Early Cenozoic. Materials eroded from these mountain belts undergoing exhumation would then be transported and finally deposited in the adjacent sedimentary basins. This prediction is supported by the occurrence of the well-dated Paleocene-Eocene strata in the Hoh Xil basin (Lin et al., 2020; Miao et al., 2016; Staisch et al., 2014; Wang et al., 2008) and the Eocene strata in the Yumen basin (Cheng et al., 2019b; Dai et al., 2005; Wang et al., 2016b) and Xorkol basin (Li et al., 2018). As a consequence, even if the new age model is valid for the Honggou section, it is likely that these lithostratigraphic units might not be representative of the initial Cenozoic initial subsidence of the Qaidam basin.

Another way to test these two debated age models is to try to tie them to the independent chronology of deformation events recorded in both the basin and surrounding mountain belts (Fig. 6). To establish that chronology, we used the growth strata developed along the margins of the basin and compared the onset time of deformation evidenced from growth strata with the increase in exhumation rate derived from thermochronology data in the hanging wall of boundary reverse faults in the various ranges. Previous thermochronology studies suggested that the Altyn Tagh Shan experienced a first rapid exhumation during the Eocene (40 ± 10 Ma) followed by a renewed, strong exhumation since the Miocene (Jolivet et al., 2001; Wang et al., 2006; Wang et al., 2015; Yu et al., 2019a; Yu et al., 2019b; Zhang et al., 2012). Seismic profiles in the northwest margin of the Qaidam basin display well-developed growth strata in the footwall of major thrust faults (Fig. 6c). When following the “old ages” model (Chang et al., 2012; Chang et al., 2015; Fang et al., 2006; Fang et al., 2007; Heermance et al., 2013; Ji et al., 2017; Ke et al., 2013; Lu and Xiong, 2009; Nie et al., 2019; Sun et al., 2005; Wu, 2011; Zhang, 2007; Zhang et al., 2013b; Zhuang et al., 2011b), the Altyn Tagh Shan would have experienced a first Paleocene to Eocene exhumation followed by a second Oligocene to Miocene exhumation, roughly consistent with the thermochronology studies. However, by following the “young ages” model, seismic profiles would show two exhumation pulses at ~ 25 to 24 Ma and 17 – 6.3 Ma separated by a period of tectonic quiescence from 24 Ma to 17 Ma. This second scenario does not fit the information provided by available thermochronology data (Fig. 6c). Another set of thermochronology studies suggested that the Southern Qaidam Thrust initiated at 35 – 25 Ma (Clark et al., 2010; Jolivet et al., 2001; [Instruction: Li et al., 2020 should be changed to Li et al., 2021] Li et al., 2020; Mock et al., 1999; Wang et al., 2017a), associated with the simultaneous exhumation of the Eastern Kunlun Shan basement. Seismic profiles from the southern Qaidam basin show well-developed growth strata in the footwall of the Southern Qaidam Thrust that separates the Eastern Kunlun Shan from the Qaidam basin. When following the “old ages” model, the observed pre-growth strata were deposited from the Paleocene to the Eocene, and the growth strata initiated during the Oligocene. The inference of an Oligocene onset of the Southern Qaidam Thrust activity is consistent with the ~ 35 – 25 Ma onset time of initial activity that has been proposed based on thermochronology data. However, if adopting the “young ages” model, the deposition of the pre-growth strata lasted from ca. 25.2 Ma to 16.5 Ma, and the growth strata initiated at the 16.5 Ma (Fig. 6d). The “young ages” model would thus indicate a middle Miocene initiated faulting along the Southern Qaidam Thrust, conflicting with the ~ 35 – 25 Ma age derived from thermochronology (Fig. 6). Based on the obvious discrepancies described above between the established exhumation history in the mountain ranges surrounding the Qaidam basin and the sequence of events implied by the young age model proposed by Wang et al. (2017b) and Nie et al. (2019), we propose that the latest should not be applied to the northwestern and southern parts of the Qaidam basin.

Moreover, combined magnetostratigraphic data with independent age constraints provided by fossils, Chang et al. (2015) indicates an Oligocene Shangganachaigou Fm., Early to Middle Miocene Xiayoushashan Fm., Middle to Late Miocene Shangyoushashan Fm., respectively (Fig. 7a). According to the isopach map of the Cenozoic strata in the Qaidam basin, the Shangganachaigou Fm. is over 600 m thick at the Honggou magnetostratigraphy study site (Fig. 7b). Moreover, over 2000 m thick upper Xiaganachaigou Fm., over 600 m thick Lower Xiaganachaigou Fm., and over 800 m thick Lulehe Fm. are also developed (Fig. 7c–f). Considering these additional >3000 m thick underlying the Shangganachaigou Fm., the initial depositional age of the Cenozoic strata in that section should be much older than the Oligocene, unless the sedimentation rate was dramatically higher during that period, which is not reflected by the sediment facies (Fig. S1). In other words, the new age model does not fit the entire sedimentary record in the western part of the Qaidam basin and the classic old age model seems to provide a much better match.

The “old ages” model thus seems to fit reasonably well the deformation history obtained from combining growth-strata observations and thermochronology data in the northern and southern Qaidam basin. However, when this issue is examined in more detail, it is likely that the Cenozoic lithostratigraphic units in the Qaidam basin are diachronous from one section to the other and have no basin-wide chronostratigraphic significance. A good example of such diachronicity in foreland deposits is given by the Xiyu Fm. in the Tarim and Junggar basins (Fig. 1). Indeed, these alluvial fans once considered to be synchronous and dated as Early Pleistocene in age (Chen et al., 1994; Feng and Dai, 2004; Gaborardi et al., 2005; Zhu et al., 2004), were later demonstrated to be largely diachronous, spanning at least

from 15 Ma to 1.7 Ma (Charreau et al., 2009a; Charreau et al., 2005; Charreau et al., 2009b; Cheng et al., 2018; Heermance et al., 2007; Huang et al., 2010; Sun et al., 2009; Sun et al., 2007).

4.3.4.3 Future perspective

As shown above, the Cenozoic strata preserved in the Qaidam basin record the Cenozoic deformation history of the northern margin of the Tibetan plateau (Meng and Fang, 2008; Métivier et al., 1998; Meyer et al., 1998; Xia et al., 2001; Yin et al., 2008a; Yin et al., 2008b; Yin et al., 2002). In particular, the Lulehe Fm., marking the onset of Cenozoic deposition in the basin, clearly corresponds to the onset of topographic growth of the surrounding mountain belts (Cheng et al., 2019a; Wang et al., 2017b; Xia et al., 2001; Yin et al., 2008a; Yin et al., 2008b; Yin et al., 2007; Yin et al., 2002). The uncertainties in the depositional age of this key formation have major consequences on our understanding of the initial deformation pattern along the northern edge of the plateau. On a larger scale, it also affects our understanding of the mechanisms of crustal deformation in the entire plateau, and finally of the possible interaction between plateau growth and climate change (Bush et al., 2016; Cheng et al., 2019a; Cheng et al., 2019c; Dupont-Nivet et al., 2008; Fu et al., 2012; Wang et al., 2017b; Zhang et al., 2013a). Given the importance of constraining the age model of the Cenozoic strata within the Qaidam basin, increased investigations are thus urgently needed.

First, as pre-Quaternary strata are largely covered by younger deposits in the western Qaidam basin, magnetostratigraphy study could be carried out on the deep drilling cores obtained by the Qinghai Oilfield Company, PetroChina. Second, a recent detrital zircon geochronology study in the southwestern part of the Qaidam basin reported Cenozoic U-Pb zircon ages (e.g. 37 Ma and 56 Ma) from the Miocene and Pleistocene strata in the southern part of the basin (Cheng et al., 2016a). This indicates that Early Cenozoic volcanic ash might have been deposited in some parts of the Qaidam basin. Finding and dating those ashes would indeed bring robust constraints to the age model. Third, U-Pb dating of authigenic carbonate minerals from lacustrine strata in nonmarine systems are now widely used to determine the depositional ages (Drost et al., 2018; Finzel and Rosenblume, 2020; Rasbury and Cole, 2009). The well-developed limestones and marls in the Lulehe Fm. to Shangganhaigou Fms. (Chang et al., 2015; Cheng et al., 2019a; Cheng et al., 2019c; Meng and Fang, 2008; Miao et al., 2011; Rieser et al., 2009a; Xia et al., 2001) are suitable materials that hold great potential for determining such depositional ages. Using outcrops and the dense drill core network, a detailed U-Pb dating of carbonate samples from the Xiaganhaigou to the Shangganhaigou Fms. across the basin would not only provide independent age controls for the corresponding magnetostratigraphy studies but also bring detailed constraints on the potential diachronicity of the units inside the basin. Fourth, Re-Os geochronometry has been widely used as a proxy for determining precise and accurate depositional ages of marine organic-rich rocks (Rooney et al., 2020; Selby and Creaser, 2003; Tripathy et al., 2015) and is now successfully applied to similar deposits in lacustrine nonmarine systems (Cumming et al., 2012; Cumming et al., 2014; Meng et al., 2020). As the largest petroliferous basin in the Tibetan plateau, the Qaidam basin contains abundant rocks that are rich in organic matter, especially the lacustrine source rocks in the Xiaganhaigou Fm. and Shangganhaigou Fm. (Fu et al., 2015; Jin et al., 2002; Pang et al., 2004). An extensive, basin-wide Re-Os geochronology study would again enhance our understanding of the depositional age of the corresponding Cenozoic strata pointing out potential stratigraphic diachronicity.

Finally, a better understanding of the tectonic and sedimentary interactions between the Qaidam basin and the surrounding belts would contribute to a better knowledge of the basin fill history, which, in turn, would help assessing the degree of reliability of the age model proposed through the above-mentioned geochronometer. Although datasets on the sedimentation and deformation history of the Tibetan plateau (e.g., low- and high- temperature geochronology, provenance data, isotopic data, palynology, seismic profiles) have improved significantly over the last few decades, the understanding of the interaction between the Qaidam basin and the surrounding belts is still hampered by the incomplete coverage of these datasets, especially from remote and often inaccessible regions (Wu et al., 2019a; Yin et al., 2007).

5.5 Interactions between the Eastern Kunlun Shan and the Qaidam basin

5.1.5.1 Tectonic relation between the Qaidam basin and the Eastern Kunlun Shan

5.1.1.5.1.1 South-dipping vs north dipping boundary fault in the southern Qaidam basin

The debate on the upper crustal structural relation between the Eastern Kunlun Shan and the Qaidam basin has become particularly heated during the last two decades. Although several models have been proposed (Burchfiel et al., 1989; Cheng et al., 2014; Huang et al., 2020; Jolivet et al., 2003; Meng and Fang, 2008; Meyer et al., 1998; Mock et al., 1999; Tapponnier et al., 2001; Wang et al., 2006; Xia et al., 2001; Yin et al., 2007), three typical models (Fig. 8) that describe the tectonic structure in the Eastern Kunlun Shan and in the SW Qaidam basin are representative of the key questions that remain debated: (1) Northward thrusting model, (2) Northward propagation model, (3) Southward thrusting model.

First, the northward thrusting model dates back to the 1980s. Burchfiel et al. (1989) proposed that the Qaidam basin is bounded to the south by a south-dipping fault. North-directed motion of the southern block would induce thrusting of the Eastern Kunlun Shan crust onto the Qaidam basin leading to the uplift of the Eastern Kunlun Shan (Fig. 8a).

Following this model, [Mock et al. \(1999\)](#) further argued that, from the Oligocene to the Early Miocene, this north-directed thrusting would be associated with the formation of a crustal wedge in the Eastern Kunlun Shan. Therefore, this model considers the southwestern part of the Qaidam basin as a foreland basin of the Eastern Kunlun Shan. [Meng and Fang \(2008\)](#) proposed that the Cenozoic tectonic subsidence of the Qaidam basin may result from crustal buckling in response to regional NE-trending compression. In this model, north-directed thrusting, initiating during the Miocene along the south-dipping boundary fault, may have controlled the exhumation of the Qimen Tagh Range, the western segment of the Eastern Kunlun Shan ([Fig. 2](#)) ([Cheng et al., 2014](#)). The second type of models emphasizes the role of sinistral strike-slip faults in the Eastern Kunlun Shan. The structural pattern of the range would be characterized by a large transpressional system, including the left-lateral strike-slip Kunlun fault to the south and a series of south-dipping thrusts to the north ([Jolivet et al., 2003](#); [Meyer et al., 1998](#); [Tapponnier et al., 2001](#); [Wang et al., 2006](#)). [Cheng et al. \(2014\)](#) further developed this model and proposed a northward propagation model ([Fig. 8b](#)). This model emphasizes the Neogene northward bending and propagation of the fault system initiating as strike-slip lineaments along the Kunlun fault and progressively switching to thrusts, forming a northward growing crustal wedge ([Fig. 8b](#)). In the meantime, [Yin et al. \(2007\)](#) proposed a quite different model arguing that several south-directed thrusts rooted into the Qilian Shan to the north propagated southward, carrying the low-elevation Qaidam basin to the high-elevation Eastern Kunlun Shan ([Fig. 8c](#)). This southward thrusting model has been adopted by some recent studies ([Shi et al., 2009](#); [Wang et al., 2011](#); [Wu et al., 2019b](#); [Zuza and Yin, 2016](#)), attracting a growing attention from the Asian tectonics community in recent years.

The abundant, high quality subsurface data acquired by the oil industry in recent years enable a re-evaluation of these three competing models. First, isopach maps show that the Cenozoic strata (including the Lulehe, Lower and Upper Xiaganchaigou, and Shangganchaigou formations) generally thicken from the southern margin of the basin ~~towards~~[toward](#) its center ([Figs. 2b–c, 12](#)) ([Cheng et al., 2018](#); [Mao et al., 2014a](#); [Meng and Fang, 2008](#); [Yin et al., 2008b](#)). This pattern opposes the classic tectonically subsiding foreland-basin model that requires the depocenter to be situated next to the bounding fault ([Jordan, 1981](#)). To this end, the foreland basin model (northwards thrusting of the Eastern Kunlun Shan) ([Burchfiel et al., 1989](#); [Mock et al., 1999](#)) does not seem to explain the structural relation between the Eastern Kunlun Shan and the Qaidam basin.

On the other hand, the south-directed thrusting model put forward by [Yin et al. \(2007\)](#) was mainly based on: 1) observation of an unconformity between the north-dipping Pliocene-Quaternary strata and the Ordovician to Carboniferous strata of the Eastern Kunlun Shan; 2) evidence for south-directed thrusting in the Carboniferous strata; 3) observation, on 2D seismic profiles, of several south-directed reverse faults beneath the southwestern part of Qaidam basin; 4) the reporting of several north-dipping faults in the Eastern Kunlun Shan on existing geological map ([Liu, 1988](#)) and in fieldwork reports of ([Dewey et al., 1988](#)). We acknowledge the importance of the observed unconformity between the Pliocene-Quaternary strata and the Ordovician to Carboniferous basement rocks of the Eastern Kunlun Shan. Yet this observation may just indicate the exhumation of the Eastern Kunlun Shan during or before the deposition of Pliocene-Quaternary strata. The geological map by [Liu \(1988\)](#) is 1: 1,500,000 scale and cannot display subtle key information on faults geometry, whereas the field investigation performed by [Dewey et al. \(1988\)](#) is limited to a narrow strip along the Golmud to Lhasa road, covering only a small portion of the Eastern Kunlun Shan near the Golmud ([Kidd et al., 1988](#)). More recent geological maps (1: 250,000 scale) report several major north-directed thrust faults in the Qimen Tagh Range, forming the western part of the Eastern Kunlun Shan ([I.G.S.Q.P., 2004](#); [I.G.S.S.P., 2003](#)). These faults might support the northward thrusting model, contradicting the southward thrusting hypothesis. More importantly, several newly acquired 2D and 3D high-quality seismic profiles display series of south-dipping faults beneath the southwestern part of Qaidam basin ([Fig. 9b–c](#)). On NE-trending seismic profiles EE' and FF', these thrusts are high angle basement-involved faults defining a block-like structure ([Fig. 9b](#)). These faults cut the Cenozoic sediments rooting into the Eastern Kunlun Shan and Qaidam basement. On seismic profile EE', the thickness of the Lower Cenozoic lithostratigraphic units (Lulehe Fm. to Xiaganchaigou Fm.) in the footwall do not match with those of the hanging wall. The post-Xiaganchaigou Fm. strata taper toward the faults, forming growth strata ([Fig. 9c](#)). On seismic profile FF', the post-Xiaganchaigou Fm. in the SW Qaidam basin again taper toward the faults, forming growth strata that indicate the onset of deformation accommodated along these faults ([Fig. 9c](#)). Based on a 2D low-resolution seismic profile ([Fig. 10a–b](#)), [Song and Wang \(1993\)](#) suggested that the Arlar fault cuts through all the Cenozoic strata up to earth surface. They interpreted such fault as a long-lived purely reverse fault that initiated during the Early Cenozoic ([Fig. 10c](#)). However, [Yin et al. \(2007\)](#) reinterpreted the same 2D seismic profile by describing a fault-bend fold above the Arlar fault. In that second model, this basement-involved fault cuts through the Mesozoic to Early Cenozoic strata (Lulehe, Lower and Upper Xiaganchaigou Fms.) and forms a footwall flat within the Shangganchaigou Fm. ([Fig. 10d](#)). The growth strata started to develop during the deposition of the Shangganchaigou Fm. suggesting that the Arlar fault initiated at this time. Finally, based on a newly acquired much higher resolution 3D seismic profile from the same location ([Fig. 10e](#)), [Cheng et al. \(2014\)](#) proposed that the Arlar fault is characterized by a positive flower structure, indicating strike-slip displacement along the fault ([Fig. 10f](#)). The isopachs of the Upper Xiaganchaigou Fm. show over 20 km lateral offset across the Arlar and Kunbei faults ([Fig. 10a](#)), indicating sinistral strike-slip movements along these two faults. Growth strata associated with the flower structure initiated during the deposition of the Xiayoushashan Fm., probably dating the onset time of left-lateral faulting along the Arlar fault ([Fig.](#)

10f). We thus propose that left-lateral faulting along these structures (including the Arlar and Kunbei faults) in the southwestern part of the Qaidam basin initiated during the deposition of the Shangganhaigou Fm. to Xiayoushashan Fm. (Fig. 10). Some of the basement-involved faults within the basin also display a major strike-slip component reflected by flower structures on the seismic profiles (Fig. 11) (Liu et al., 2019). These flower structures reveal transpressional deformation within the basin, indicating that the N-S contraction in the northern Tibetan plateau was slip-partitioned along these WNW-striking faults in the Qaidam basin.

Moreover, isopach maps show that the depocenters of the southwestern part of the Qaidam basin are located next to the Eastern Kunlun Shan during deposition of Xiayoushashan and Shangyoushashan Fms. (Fig. 12e–f), coincident with the Oligocene to Miocene rapid exhumation of the Eastern Kunlun Shan revealed by low-temperature thermochronology (Dai et al., 2013; Duvall et al., 2013; Jolivet et al., 2001; Jolivet et al., 2003; McRivette et al., 2019). As a consequence, the southwestern part of the Qaidam basin might be considered as a foreland/flexural basin of the Eastern Kunlun Shan during deposition of the Xiayoushashan and Shangyoushashan Fms. In summary, these newly acquired subsurface data allow us to interpret the basement-involved faults as south-directed dipping thrusts, rooting into the Eastern Kunlun Shan (Cheng et al., 2014; Cheng et al., 2015c; Sun, 2019; Wu et al., 2014), ruling out the north-directed thrusting model.

5.1.2.5.1.2 The northward propagation model

The structural pattern discussed above can be summarized as: 1) a series of south-dipping faults control the general tectonic pattern of the southwestern part of the Qaidam basin; 2) these faults have a sinistral strike-slip component accommodated during the deposition of the Shangganhaigou to Xiayoushashan Fms. Based on the evidence of a southwards younging of the onset of sinistral strike-slip motion on the faults from the SW Qaidam basin to the Qimen Tagh Range and to the modern Kunlun fault, Cheng et al. (2014) proposed a northward fault-propagation model. This model considers the faults beneath the southwestern part of the Qaidam basin and the faults within the Qimen Tagh Range as the former western segments of the Kunlun fault. These faults were once located further south in the present-day location of the Kunlun fault and gradually migrated northward since the deposition of the Shangganhaigou to Xiayoushashan Fm., while their kinematics changed from sinistral strike-slip motion to NE-SW contraction. We believe that the distinctive distribution of Cenozoic strata and the geometry of the faults in the southwestern part of the Qaidam basin can be reconciled with this northward propagation model (Cheng et al., 2014). Indeed, it better explains the kinematics framework by taking the Neogene northward bending and propagation of the successive strike-slip faults into consideration. During the deposition of the Lulehe to Xiaganhaigou Fms., tectonic activity in the Eastern Kunlun Shan and the southwestern part of the Qaidam basin was null or very low. Since the deposition of the Shangganhaigou to Xiayoushashan Fm., the south-dipping basement-evolved faults gradually migrated northward. Their sinistral strike-slip motion gradually changed to the NE-SW contraction which controlled the deposition of the Neogene sediments in the SW Qaidam basin.

5.1.3.5.1.3 Uncertainties of fault geometry and further work

Despite the improvements brought by the newly available geophysical data on our understanding of the structural pattern along the SW margin of the Qaidam basin, it should still be noted that the strong seismic noise in the region adjacent to the mountain ranges prevents clear imaging of that key boundary region (Cheng et al., 2014; Cheng et al., 2015c; Sun, 2019; Wang et al., 2010c; Wu et al., 2014). The interpretation of either a north-directed (Mock et al., 1999; Sun, 2019) or a south-directed décollement (Yin et al., 2007) beneath the Cenozoic strata in the Qaidam basin remains speculative. Analyzing the earthquake focal mechanisms and focal-depth distribution within the Eastern Kunlun Shan, Chen et al. (1999) proposed that the southern Qaidam basin is bounded by a south-dipping thrust fault to the south. However, as Yin et al. (2007) pointed out, projecting the earthquake data collected from over 1000 km along the Eastern Kunlun Shan on a single cross-section is problematic. Besides, focal mechanisms for reverse or normal faults would have two opposite nodal planes difficult to relate to true faults in the absence of additional field evidence (Yin et al., 2007). Therefore, despite the improvement of the quality of the seismic reflection data in the southwestern part of the Qaidam basin (Cheng et al., 2014; Cheng et al., 2015c; Sun, 2019; Wu et al., 2014) and increased field-based geologic mapping in the remote Eastern Kunlun Shan (Staisch et al., 2020; Wu et al., 2019a), further geological and geophysical work is needed. The researches should especially focus on determining which are the major boundary faults and which are associated back-thrusts.

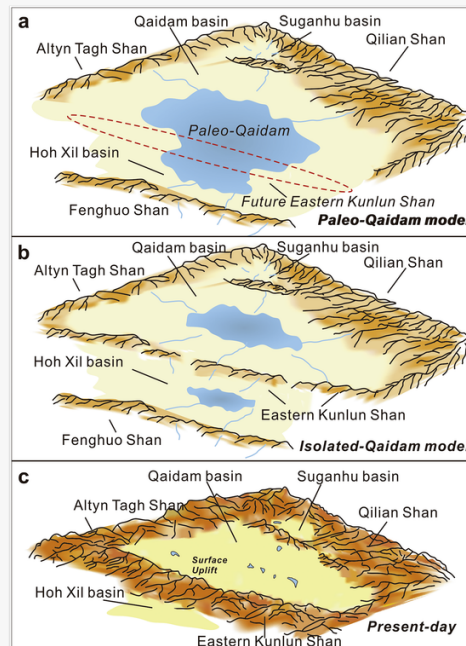
5.2.5.2 Was there a large depression in the northern Tibetan plateau during the Early Cenozoic?

Besides the structural relation between the Eastern Kunlun Shan and the Qaidam basin, another important issue associated with the Cenozoic evolution of the northern Tibetan plateau is the source to sink relationship between the Eastern Kunlun Shan and the Qaidam basin. As described above, the isopach maps (Fig. 11e–f) indicate that the Neogene (post-Xiayoushashan Fm.) SW Qaidam basin can be described as a foreland basin, a geometry supported by the Miocene rapid exhumation of the Eastern Kunlun Shan (See discussion in Section 5.2.3) as revealed by the low-temperature thermochronology (Fig. 12) (Dai et al., 2013; Duvall et al., 2013; Jolivet et al., 2001; Jolivet et al., 2003; Mao et al., 2014a; McRivette et al., 2019). However, this geometry does not seem to have prevailed during the Early

Cenozoic and the occurrence of a Paleogene Paleo-Qaidam basin encompassing the Qaidam and Hoh Xil depressions (Yin et al., 2008b) remains speculative (Figs. 1a and 13a). This hypothesis is based on similarities in stratigraphic characteristics of the Cenozoic strata in the Qaidam and Hoh Xil basins and the rapid Miocene exhumation of the Eastern Kunlun Shan that would have ultimately separated the two depressions. In this model, the minor depocenter in the southern Qaidam basin during the deposition of Lulehe Fm. was interpreted as a syncline creating a local sub-depocenter. If correct, this model suggests no or little paleo-relief in the Eastern Kunlun Shan during the Early Cenozoic and out-of-sequence deformation (i.e., Paleogene deformation in the Qilian Shan to the north with Neogene deformation in the Eastern Kunlun Shan to the south) in the northern Tibetan plateau, which will largely affect our understanding of the growth pattern of the entire Tibetan plateau. The key to answering these questions is whether the Eastern Kunlun Shan was exhumed during the Early Cenozoic. Indeed, several lines of evidence challenge the burial of the Eastern Kunlun Shan during the Early Cenozoic.

alt-text: Fig. 13

Figure 13, Fig. 13



Two scenarios for the evolution of the Qaidam basin and the Eastern Kunlun Shan during the Cenozoic. (a) Paleo-Qaidam model, forming a large depression in the northern Tibetan plateau (Mao et al., 2014a; Yin et al., 2008b). (b) Isolated-Qaidam model, showing the minor topographic relief in the Eastern Kunlun Shan, cutting off the link between the Qaidam basin and the Hoh Xil basin (Cheng et al., 2016a; Cheng et al., 2019c). (c) Modern topography of the Qaidam basin and surrounding regions.

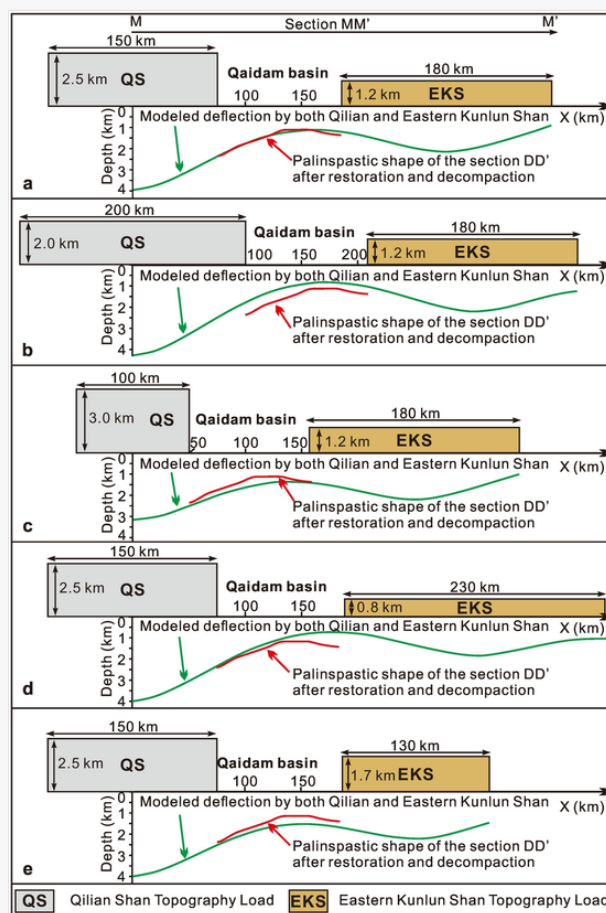
5.2.1.5.2.1 Flexural modeling evidence

Using seismic profiles and isopach maps, Cheng et al. (2019a) reconstructed the original shape of a NE-trending section across the Qaidam basin at the time of deposition of the Lulehe Fm. after conducting the balanced cross-section restoration and decompaction. The authors subsequently modeled the shape of this profile using flexural modeling (Fig. 14). Comparing this model with the restored cross-section, it appears clearly that the topographic load induced by the Qilian Shan alone cannot create a sufficient load to cause the observed deflection of the Qaidam basement during the deposition of the Lulehe Fm. (Fig. 14a). Changing the size (equivalent to the topographic load) of the Eastern Kunlun Shan and Qilian Shan cannot provide a better fit between the modeled deflection of the Qaidam basement and the original shape of the Qaidam basin restored from geological data (Fig. 14b–e). In other words, both the Eastern Kunlun Shan and the Qilian Shan basements should be exhumed during the deposition of the Lulehe Fm., and the associated overload was responsible for the flexural deflection of the Qaidam basement. Following this methods, Wang et al.

(2021) analyzed four additional NE-trending sections across the Qaidam basin at the time of deposition of the Lulehe Fm. and further documented the variable along-strike relief of the Eastern Kunlun Shan at that time. Based on these information, we thus conclude that, during deposition of the Lulehe Fm., a non-negligible paleo-Kunlun relief was present, separating the SW Qaidam from the Hoh Xil basins.

alt-text: Fig. 14

Figure 14, Fig. 14



Two-load beam flexural modeling results, showing that both Eastern Kunlun Shan topographic loads are responsible for the flexural of the Qaidam basement, modified from Cheng et al. (2019a). The location of this section MM' is given in Fig. 9a. Note that changing the size of the Eastern Kunlun Shan and Qilian Shan cannot provide a better fit between the modeled deflection of the Qaidam basement (green curve) and the original shape of the Qaidam basin (red curve) that restored after decompaction and the cross-section shortening restoration. See Cheng et al. (2019a) for the detailed flexural modeling experiment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

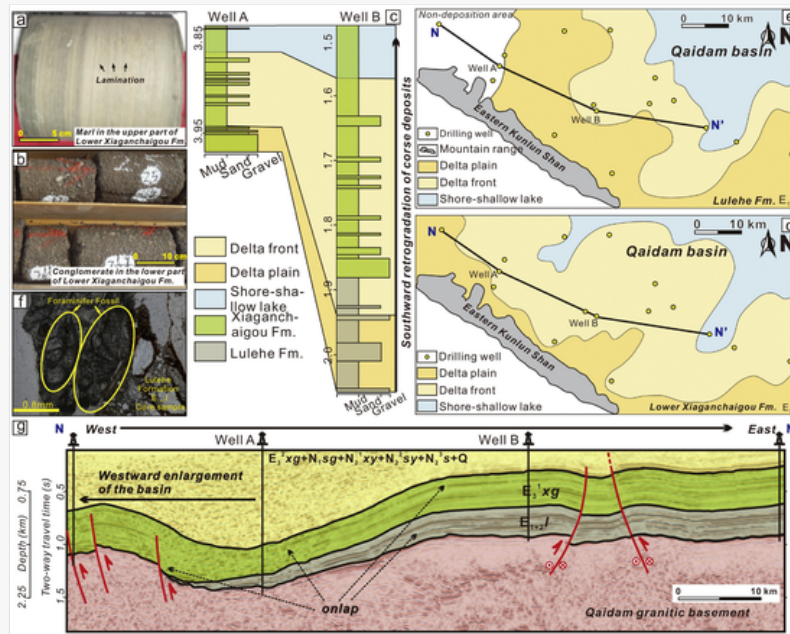
5.2.2.5.2.2 Sedimentary records

Based on sediment samples obtained from drill cores in the southern Qaidam basin, the Lulehe Fm. in the southern Qaidam basin is described as boulder-to cobble-sized clast-supported conglomerate (Fu et al., 2012; Gong et al., 2012; Ma and Wang, 2015; Mu, 2002; Sun et al., 2005; Zhang et al., 2013a). However, fine-grained fluvial and lacustrine deposits have also been observed in the Lulehe Fm. in the southwestern part of Qaidam basin, indicating a complex depositional environment pattern (Cheng et al., 2019a; Cheng et al., 2019c). Cheng et al. (2019a) carried out an extensive study based on the core samples obtained from a wide range of drill wells to document the sedimentary characteristics of the Lulehe Fm., indicating both proximal and distal deposits (Fig. 15a–e). Meanwhile, heavy mineral analysis on the Lulehe Fm. core samples collected from the drilling wells along the southern margin of the basin also revealed a dominating zircon-leucoxene-garnet-sphene assemblage. This result indicates that the Lower Paleozoic and Lower Mesozoic igneous rocks in the Qimen Tagh Range were likely the sources of material deposited in the southwestern part of the Qaidam basin (Li et al., 2015a; Zhu et al., 2017). In addition, unstable minerals, such as the epidote, were well-preserved in those samples. Given that these unstable minerals are unlikely to have been preserved under long-distance transport from the Altyn Tagh Shan or Qilian Shan, the Eastern Kunlun Shan should be the primary source region for the southwestern part of Qaidam basin during that period (Fu et al., 2013; Li et al., 2015a; Zhu et al., 2017). Moreover, Cheng et al. (2016a), reported foraminifera-bearing carbonate fragments are preserved within Lulehe Fm. conglomerates in the SW Qaidam basin (Fig. 15f). Given that foraminifera are generally found in marine environments (Rohling et al., 1998) and carbonate fragments are not transported over long distances (Mack and Rasmussen, 1984; Zuffa, 1980), a simple explanation for these carbonate fragments is that they were derived from the

foraminifera-abundant Carboniferous sequences in the western segment of the Eastern Kunlun Shan. This further demonstrates that the Eastern Kunlun Shan was the primary source region for the southwestern part of Qaidam basin.

alt-text: Fig. 15

Figure 15. Fig. 15



Photographs of the core samples collected from the SW Qaidam basin, showing the laminated marls in the Lower Xiaganchaigou Fm. (a) and the conglomerates in the Lulehe Fm. (Cheng et al., 2019c) (b). (c) Well-correlation diagram of the Lulehe Fm. and Lower Xiaganchaigou Fm. strata based on well-log and drill core data in the SW Qaidam basin. Distribution of facies during the deposition of the Lulehe Fm. (d) and Lower Xiaganchaigou Fm. (e) in the SW Qaidam basin (Cheng et al., 2019c). The location of facies map is shown in Fig. 9a. (f) Plane polarized light microphotograph of core samples collected from the Lulehe Fm. in the SW Qaidam basin, from Cheng et al. (2016a). Note the foraminifera fossils in carbonate debris within conglomerates. (g) Interpreted seismic profile in the SW Qaidam, displaying the successive westward (mountain-ward) onlap of the Lulehe and Lower Xiaganchaigou formations, modified from Cheng et al. (2019c). The location of section is shown in Fig. 9a.

5.2.3.5.2.3 Low-temperature thermochronology record

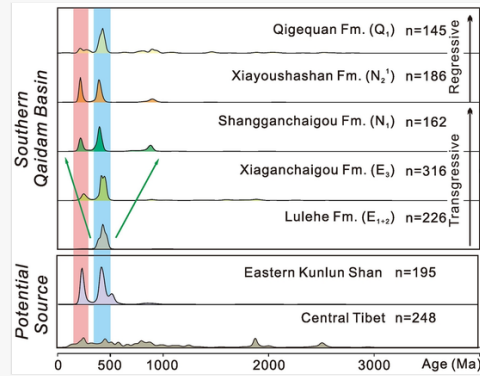
Published low-temperature thermochronology data reveal that the Eastern Kunlun Shan might have experienced a two-stage exhumation history during the Cenozoic: (1) Paleocene to Early Oligocene initial exhumation and (2) Late Oligocene to Miocene rapid exhumation. Thermochronology data and modeling in the Eastern Kunlun Shan show initial rapid exhumation as early as ca. 55–40 Ma (Clark et al., 2010; Jolivet et al., 2001; Shi et al., 2018; Staisch et al., 2020; Wang et al., 2017b; Wu et al., 2020). More specifically, apatite and zircon fission track and (U-Th)/He thermochronology studies on the crystalline rocks of the Eastern Kunlun Shan revealed that the exhumation of the Eastern Kunlun Shan might have initiated at 40 ± 10 Ma in response to the India-Asia collision (Clark et al., 2010; Jolivet et al., 2001; Staisch et al., 2020; Wang et al., 2017b). Meanwhile, (U-Th)/He thermochronology studies on detrital apatite from upper Eocene to Pliocene strata within the Eastern Kunlun Shan indicated that high mountain ranges in the Eastern Kunlun Shan might have formed at or before ~40 Ma (Shi et al., 2018). On the other hand, the rapid exhumation of the Eastern Kunlun Shan during the Oligocene to Miocene has been inferred by a number of low-temperature thermochronology studies (Dai et al., 2013; Duvall et al., 2013; Jolivet et al., 2001; Li et al., 2021; Liu et al., 2017; McRivette et al., 2019; Staisch et al., 2020; Wang et al., 2018; Wu et al., 2020; Yuan et al., 2003).

Although it is obvious that a Paleogene relief existed in the Kunlun region, it is also undeniable that strong similarities existed between the sediment facies in both basins (Yin et al., 2008b). Following that observation, the question whether the two basins were completely disconnected or not still remains open. On seismic profile MM' (Fig. 15g), the successive westward onlaps of the Lulehe and Lower Xiaganchaigou Fm. suggest a mountainward expansion of the Qaidam basin during the Paleocene – Early Eocene. This inference of a progressive expansion of the drainage area in the SW Qaidam basin is further supported by the progressively westward retrogradation of the fluvial-deltaic deposits (Fig. 15e–d) and by the westward expansion of the Lulehe to Shangganchaigou deposits (Fig. 12a–d). Moreover, the increasing proportion of Mesozoic to Late Paleozoic and Precambrian U-Pb detrital zircon ages in samples from the Lulehe Fm. to the Shangganchaigou Fm. further suggest a widening of the source regions, again supporting the expansion of the drainage system in the SW Qaidam basin (Fig. 16). These observations thus suggest that while some relief existed in the Eastern Kunlun Shan area during the Paleogene, the Qaidam basin drainage area nonetheless might have expanded progressively during that period, likely merging with that of the Hoh Xil basin to the south (Fig. 13b). This connection was cut off during the Miocene due to the rapid exhumation of the Eastern Kunlun Shan. This

inference of a Late Oligocene to Miocene isolation of the Qaidam basin is consistent with the reduction of the deposition area observed on the isopach maps (Fig. 12e–h).

alt-text: Fig. 16

Figure 16, Fig. 16



Detrital zircon age spectra for Cenozoic sandstone samples from the SW Qaidam basin and relative probability plot of granitoid pluton ages in the Eastern Kunlun Shan and the Central Tibet. Zircon ages from the Cenozoic sandstone and basement rocks of potential source regions are mainly compiled from (Cheng et al., 2016a; Cheng et al., 2017; Dai et al., 2012). The green arrows show that the distribution of the zircon ages becomes more diverse from the Lulehe Fm. sample to the Shangganchaigou Fm., probably indicate the expansion of the drainage area of the Qaidam basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In summary, flexural modeling, sedimentology and low-temperature thermochronology evidence demonstrate that no single large depression developed during the Paleocene and that the Eastern Kunlun Shan was exhumed during the Paleocene to Early Oligocene, feeding clastic material to the Qaidam basin. In the same time, the southwestern part of the Qaidam basin drainage area was expanding southward toward the Hoh Xil basin depression implying that the relief in the Eastern Kunlun Shan area was limited. This inference of an existing minor exhumation in the Eastern Kunlun Shan during the Early Cenozoic has been adapted to the tectonic evolution model of the northern Tibetan plateau by McRivette et al. (2019).

6.6 Implication for the Cenozoic evolution of the Qaidam basin

Based on the various arguments discussed above, we propose a holistic view of the Cenozoic evolution of the Qaidam basin. Given the debates on the age model for the Cenozoic strata in the Qaidam basin, the lithostratigraphic units are used to describe the corresponding time period without reference to an absolute time-scale. We propose a three-stages evolution model including: 1) initial flexural subsidence; 2) basin-scale expansion; 3) isolation.

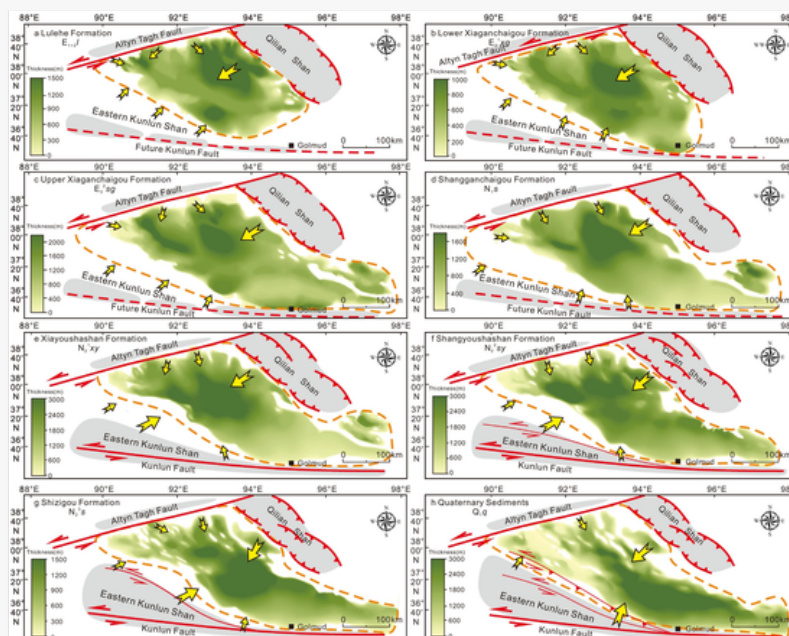
6.1.6.1 Flexural subsidence of the Qaidam basin

Thermochronology studies (e.g., $^{40}\text{Ar}/^{39}\text{Ar}$ dating and apatite fission track) have revealed several Mesozoic tectono-thermal events in the Altyn Tagh Shan, Eastern Kunlun Shan, and Qilian Shan, indicating substantial crustal deformation in the northern Tibetan plateau during the Mesozoic (Arnaud et al., 2003; Baotian et al., 2013; Chen et al., 2003; Chen et al., 2009; Cheng et al., 2016c; Dai et al., 2013; Du et al., 2018; He et al., 2017; He et al., 2018; Jian et al., 2018; Jolivet et al., 2001; Jolivet et al., 1999; Li et al., 2019; Lin et al., 2019; Liu et al., 2007a; Liu et al., 2005; Liu et al., 2007b; Mock et al., 1999; Pan et al., 2013; Qi et al., 2016; Rieser et al., 2006b; Rieser et al., 2009b; Sobel et al., 2001; Tian et al., 2020; Wang et al., 2016a; Wang et al., 2004; Wang et al., 2005; Wang et al., 2018; Wang et al., 2015; Wu et al., 2019c; Yuan et al., 2006; Zhang et al., 2017; Zhuang et al., 2018). This multi-pulse crustal deformation resulted in the exhumation and uplift of the mountain belts, forming pre-existing topographic reliefs in the northern Tibetan plateau. Provenance analyses on the Mesozoic sedimentary records in the Qaidam basin (Cheng et al., 2016a; Cheng et al., 2016b; Ritts and Biffi, 2000; Ritts and Biffi, 2001; Ritts et al., 1999; Robinson et al., 2003; Wu et al., 2011; Yu et al., 2017; Zhang et al., 2020; Zhao et al., 2020a; Zhao et al., 2020b), Hoh Xil basin (Staisch et al., 2020; Staisch et al., 2014; Wu et al., 2019b), Suganhu basin (Cheng et al., 2019d), Jiuquan basin (Chen et al., 2014; Cheng et al., 2019b), also demonstrated the existence of inherited relief in the northern Tibetan plateau. As shown by the detrital zircon geochronology, paleocurrent measurement, heavy mineral analysis, and petrology studies, pre-existing reliefs in the Eastern Kunlun Shan and the Qilian Shan shed materials into the southwestern and northeastern parts of the Qaidam basin during deposition of the Lulehe Fm. (Cheng et al., 2016a; Cheng et al., 2016b; Wang et al., 2020a; Wu et al., 2011; Yu et al., 2017; Zhao et al., 2020a). These pre-existing reliefs in the Eastern Kunlun Shan and the Qilian

Shan were resulting in topographic load induced basement deflection of the Qaidam basin during the deposition of the Lulehe Fm. An early stage of exhumation of the Qilian Shan and the Altyn Tagh Shan is also supported by the growth strata shown on the seismic profile in the northwestern and northeastern edges of the basin (Cheng et al., 2019a; Cheng et al., 2019c; Cheng et al., 2019d; Yin et al., 2008a; Yin et al., 2008b). As shown on the isopach map of the Lulehe Fm. strata (Figs. 7, 12, 17a), the major depocenter was adjacent to the Qilian Shan while a few secondary depocenters were located along the southern and western margins of the basin. Despite uncertainties, the synchronous deformation along the western edge of the Qaidam basin might be associated with the initial left-lateral strike-slip faulting along the Altyn Tagh Fault (Cheng et al., 2015a; Cheng et al., 2016b; Yin et al., 2002).

alt-text: Fig. 17

Figure 17. Fig. 17



Sketched tectonic features in the Qaidam basin and surrounding orogenic belts on the isopach maps of the Cenozoic strata. The yellow arrows refer to the direction of the drainage system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Integrated provenance analysis based on sedimentology evidence and detrital zircon geochronology show that the pre-Cenozoic exhumed Eastern Kunlun Shan (including basement-exposed topographic highs) served as the dominant source of detrital materials for the Qaidam basin during the deposition of the Lulehe Fm. (Fig. 17a) and separated the Qaidam basin from the Hoh Xil basin to the south. Despite the existence of this relief, the Lulehe Fm. along the northern front of the Eastern Kunlun Shan is composed of distal fluvial to marginal lacustrine deposits and proximal fluvial deposits (Cheng et al., 2019a; Cheng et al., 2019c), indicating that the relief of the Eastern Kunlun Shan was limited and was likely located further south than its modern position. This inference of limited topography of the Eastern Kunlun Shan is consistent with flexural modeling results (Cheng et al., 2019a; Wang et al., 2021). Wang et al. (2021) applied flexural modeling to reconstructed the Paleogene isopach pattern obtained from seismic imaging of the Qaidam basin. Modeling result shows that the topographic load of the Eastern Kunlun Shan was much smaller than that of the Qilian Shan (Fig. 14a). Based on these lines of evidence, we proposed that the Qaidam basin should be considered as a flexural basin during the deposition of the Lulehe Fm.

6.2.6.2 Basin-scale expansion of the Qaidam basin drainage system

Based on the information derived from the isopach maps, seismic profiles, sedimentology, and detrital zircon geochronology, we propose a basin-scale expansion of the Qaidam basin from the deposition of the Lower Xiaganchaigou Fm. to that of the Shangganchaigou Fm. This expansion is characterized by the landward migration/retrogradation of the alluvial-fluvial facies deposits along the edges of the Qaidam basin (Fig. 15c-e)(Cheng et al., 2019c). Inside the basin, expansion of the drainage and deposition system translates into landward-onlapping reflectors shown on the seismic reflection profiles (Fig. 15g) (Cheng et al., 2016a; Cheng et al., 2019c), the outwards widening of the sediment deposition area as shown on the isopach maps (Figs. 5, 11, 17b-d), and the more diverse age distribution shown on detrital zircon age spectra (Fig. 16) (Cheng et al., 2016a; Cheng et al., 2019c).

Despite that left-lateral strike-slip faulting along the Altyn Tagh Fault might locally create extension along the fault zone, seismic profiles across the basin indicate a continuous contractional setting affecting the Qaidam basin, the Qilian Shan, and the Eastern Kunlun Shan throughout the Cenozoic (Cheng et al., 2016a; Cheng et al., 2019a; Cheng et al., 2019c; Cheng et al., 2016b; Cheng et al., 2017; Wei et al., 2016; Wu et al., 2014; Yin et al., 2008a; Yin et al., 2008b;

Yin et al., 2007; Zhou et al., 2006). Continuous formation of growth strata can be observed in the Lower Xiaganchaigou, Upper Xiaganchaigou, and Shangganchaigou Fms. of the northern Qaidam basin (Fig. 9), indicating a contemporaneous uplift of the Qilian Shan seemingly incompatible with an overall widening of the basin (Cheng et al., 2019c). On the other hand, the depositional facies datasets provided by the Qinghai Oilfield, PetroChina, shows a distinct basin-ward shift of lithofacies associations, from proximal alluvial fan facies to distal lacustrine facies in plan view (Cheng et al., 2019c). Vertically, the coarse-grained alluvial fan and braided river deposits retrograded northward, from the deposition of the Lulehe Fm. to that of the Shangganchaigou Fm. In details, the alluvial fan facies of the Lulehe Fm. gradually evolved upward to braided river facies in the Lower Xiaganchaigou and Shangganchaigou Fms. As a consequence, in such a contractional setting, climate likely played a major role in reducing the formation of topographic relief, allowing for the expansion of drainage and deposition areas. A negative shift in $\delta^{18}\text{O}$ values of marls/limestones from the Lower Xiaganchaigou Fm. to the Shangganchaigou Fm. (Cheng et al., 2019c; Li et al., 2016; Li et al., 2017; Mao et al., 2014b; Rieser et al., 2009a) and the discovery of the fishes living in warm freshwater environments (Yan et al., 2018; Yang et al., 2018), suggest that the regional climate was relatively wet climate with considerable precipitation at that time.

We thus propose that during the deposition of the Lower Xiaganchaigou Fm. to Shangganchaigou Fm., the regional climate changed toward wetter conditions triggering erosion in the uplifting ranges around the basin and allowing a landward expansion of the basin drainage area and deposition area. Although the southward basin expansion would lead to a potential connection between the Qaidam basin and the Hoh Xil basin to the south at that time (Cheng et al., 2016a; Cheng et al., 2019c; Mao et al., 2014a; McRivette et al., 2019; Yin et al., 2008b), the Eastern Kunlun Shan might still be partly uplifted. Except for a few minor depocenters in the western or eastern part of the basin, the major depocenter was consistently located near the geometric center of the basin. This continuous accumulation of materials derived from the surrounding mountain belts increased the sedimentation load, which further drove the subsidence, allowing for continuous sediment accommodation space (Fig. 17b–d) (Cheng et al., 2017; Métivier et al., 1998; Meyer et al., 1998).

6.3.6.3 Isolation of the Qaidam basin

From the deposition of the Xiayouoshashan Fm., the Qaidam basin has been gradually shrinking, as shown on the isopach maps by a reduction in sediment distribution area (Figs. 5, 17e–h). The most prominent change is that the southern edge of the basin migrated northwards compared to the previous period. This motion is reflecting the rapid uplift of the Eastern Kunlun Shan during deposition of the Xiayouoshashan Fm. This is further supported by growth strata forming during the same period in the southern Qaidam basin (Cheng et al., 2016a; Cheng et al., 2018; Cheng et al., 2019a; Cheng et al., 2014; Cheng et al., 2017; Cheng et al., 2015c; Huang et al., 2020; Mao et al., 2014a; Wang et al., 2010b; Wu et al., 2014) and the increase in cooling rates evidenced by low-temperature thermochronology data in the Eastern Kunlun Shan (Dai et al., 2013; Duvall et al., 2013; Jolivet et al., 2001; Jolivet et al., 2003; Mao et al., 2014a; McRivette et al., 2019; Staisch et al., 2020; Wu et al., 2019a). Northwest and northeast of the basin, the tectonic uplift of the Altyn Tagh Shan and Qilian Shan, evidenced by low-temperature thermochronology data (Chen et al., 2009; Cheng et al., 2016c; Jolivet et al., 1999; Li et al., 2015b; Lin et al., 2015; Liu et al., 2007a; Pang et al., 2019a; Pang et al., 2019b; Wang et al., 2006; Wang et al., 2020b; Yin et al., 2002; Yu et al., 2019a; Yu et al., 2019b) and the development of growth strata along the margins of the Qaidam basin (Figs. 6a and 7d), forced the depocenter of the basin to gradually migrate eastward during the deposition of the Xiayouoshashan, Shangyoushashan, Shzigou, and Qigequan Fms. (Cheng et al., 2015a; Cheng et al., 2015b; Cheng et al., 2016b; Cheng et al., 2019d; Meng and Fang, 2008; Wang et al., 2010b; Wang et al., 2010c; Wu et al., 2019d)(Fig. 2c). The deposition of the Shangyoushashan Fm., marks the onset of noticeable internal deformation in the Qaidam basin that will lead to partitioning during the Neogene (uplifted zone during the Neogene are represented by non-deposition areas on the isopach maps) (Fig. 17f–g). Seismic profiles show that these structures formed during the period extending from the deposition of the Xiayouoshashan Fm. to that of the Qigequan Fm. (Figs. 6, 9–11). This internal deformation, added to the topographic growth of the surrounding ranges, further increased the shrinking of the Qaidam basin. However, during the same period, the regional climate became more arid (Heermance et al., 2013; Li et al., 2016; Miao et al., 2019; Zhuang et al., 2011a), and we might not rule out the possibility that the decrease in rainfall, by reducing the erosion rates, limited the sediment discharge in the basin, favoring its reduction in size. The Late Cenozoic evolution of the Qaidam basin was thus controlled by a complex combination of tectonic crustal thickening and relief building associated to a climate-driven reduction in erosion rates.

Overall, the Qaidam basin should be considered a superimposed basin, controlled during the Cenozoic by the major fault systems in the Altyn Tagh Shan, Qilian Shan, and Eastern Kunlun Shan. It cannot be simply summarized as a foreland basin, strike-slip full-part basin, or any other type of sedimentary basin. Given the multiple pulses of contractional deformation in the surrounding regions, the Qaidam basin might have experienced at least three stages of evolution during the Cenozoic, from a flexural basin during the deposition of the Lulehe Fm., to an expanding “cratonic basin” during the deposition of the Lower Xiaganchaigou, Upper Xiaganchaigou, and Shangganchaigou Fms., and finally to a completely isolated and partitioned endoreic basin from the deposition of the Xiayouoshashan Fm. to the present. Besides the tectonics, climate change toward a wetter climate condition during the Paleogene contributed

to the expansion of the basin, a trend that was inverted during the Neogene due to the superimposed effects of increased crustal shortening and aridity-driven decrease in erosion rates.

7.7 Conclusion

The compilation of the available sedimentology, tectonics, thermochronology, geochronology, and geophysical data in the Qaidam basin highlights the following points:

- (1) Although the most recent “young ages” model for the Cenozoic strata in the Qaidam basin might work for the northeastern part of the basin, the traditional “old ages” model seems to fit reasonably well the deformation history obtained from combining growth-strata observations and thermochronology data in the northern and southern Qaidam basin. The Cenozoic lithostratigraphic units within the basin might be probably time-transgressive, but further investigation is urgently needed.
- (2) The Neogene initiation of strike-slip faulting along the south-dipping faults that roots into the Eastern Kunlun Shan played an important role in the evolution of the southern Qaidam basin. The Eastern Kunlun Shan has been exhumed since the deposition of the Lulehe Fm., serving as a significant source to the sediments deposited in the Qaidam basin. The topographic relief in the Eastern Kunlun Shan separated the Qaidam basin from the Hoh Xil basin to the south.
- (3) The Qaidam basin is a superimposed sedimentary basin, which experienced three stages of evolution during the Cenozoic, from a flexural basin setting during the deposition of Lulehe Fm. Then the Qaidam basin became an outward expanding “cratonic basin” during the deposition of Lower Xiaganchaigou, Upper Xiaganchaigou, and Shangganchaigou formations, and finally became an isolated, partitioned, and closed basin from the deposition of the Xiayoushashan Fm. to the present. Both tectonics and climate play an important role in the evolution of the basin during the Cenozoic.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Q12 ~~Appendix A~~ Appendix A Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.earscirev.2021.103730>.

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 The corrections made in this section will be reviewed and approved by a journal production editor. The newly added/removed references and its citations will be reordered and rearranged by the production team.

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Highlight Highlights

- The old age model fits well the deformation history in the northern Tibetan plateau
- Cenozoic lithostratigraphic units of the Qaidam basin could be time-transgressive
- Basement-involved faults accommodate deformation and control basin evolution
- Qaidam basin has experienced flexural subsidence, outwards expansion, and isolation
- The interplay between the tectonics and climate determines the basin evolution

Appendix A Supplementary data

[Media Component 1](#)

Supplementary material

alt-text: Image 1

Queries and Answers

Q1

Query: Please provide caption for Fig. 5.

Answer: Caption for Fig. 5

Images of typical outcrops and drill cores samples of Mesozoic to Cenozoic strata and basement rocks in the Qaidam basin. (a) Unconformities between the Jurassic and Cretaceous strata in the NE Qaidam basin. (b) Marginal lacustrine coal-bearing Jurassic strata in the NE Qaidam basin. (c) Drilling core samples in the NE Qaidam basin, showing coarse-grained sandstone in the Lulehe Fm. and granite basement rocks. (d) Conglomerates in the Lulehe Fm., eastern Qaidam basin. (e) Lacustrine limestone in the Lower Xiaganchaigou Fm., western Qaidam basin. (f) Organic rich layers in the Upper Xiaganchaigou Fm., western Qaidam basin. (g) Lacustrine to fluvial deposits in the Shangganchaigou Fm., eastern Qaidam basin. (h) Lacustrine sequences in the Xiayouhashan Fm., western Qaidam basin. (i) Mega-yardangs sculpted in mainly lacustrine Shizigou Fm. and fluvial Qigequan Fm., NE Qaidam basin.

Q2

Query: Your article is registered as belonging to the Special Issue/Collection entitled “Tethyan Tectonics”. If this is NOT correct and your article is a regular item or belongs to a different Special Issue please contact p.rajendran.1@elsevier.com immediately prior to returning your corrections.

Answer: Yes

Q3

Query: Please confirm that given names and surnames have been identified correctly and are presented in the desired order, and please carefully verify the spelling of all authors' names.

Answer: Yes

Q4

Query: The author names have been tagged as given names and surnames (surnames are highlighted in teal color). Please confirm if they have been identified correctly.

Answer: Yes

Q5

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Answer: I confirm that the provided email is the correct address.

Q6

Query: Please check whether the designated corresponding author is correct, and amend if necessary.

Answer: Yes. The designated two corresponding authors are correct.

Q7

Query: Please check the hierarchy of the section headings and confirm if correct.

Answer: Yes, it is correct.

Q8

Query: The citation "Rieser et al., 2006c" has been changed to "Rieser et al., 2006b" to match the author name/date in the reference list. Please check if the change is fine in this occurrence and modify the subsequent occurrences, if necessary.

Answer: I am fine with this change.

Q9

Query: Citation "Pan et al., 2013" has not been found in the reference list. Please supply full details for this reference.

Answer: The full details for this reference is given below:

Pan, B., Li, Q., Hu, X., Geng, H., Liu, Z., Jiang, S., Yuan, W., 2013. Cretaceous and Cenozoic cooling history of the eastern Qilian Shan, north-eastern margin of the Tibetan Plateau: evidence from apatite fission-track analysis. *Terra Nova* 25, 431-438.

Q10

Query: Have we correctly interpreted the following funding source(s) and country names you cited in your article: "Lhasa National Geophysical Observation and Research Station; Chinese Academy of Geological Sciences, China; CAS; National Natural Science Foundation of China, China".

Answer: The third funding source is State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, CAS

Q11

Query: Supplementary caption was not provided. Please check the suggested data if appropriate, and correct if necessary.

Answer: I am fine with the suggested data. Thanks.

Q12

Query: Supplementary caption was not provided. Please check the suggested data if appropriate, and correct if necessary.

Answer: I am fine with the suggested data. Thanks.

Q13

Query: Ref. Pan et al. (2013) was a duplicate and was thus removed from the Reference list. Please check if appropriate.

Answer: The reference is:

Pan, B., Li, Q., Hu, X., Geng, H., Liu, Z., Jiang, S., Yuan, W., 2013. Cretaceous and Cenozoic cooling history of the eastern Qilian Shan, north-eastern margin of the Tibetan Plateau: evidence from apatite fission-track analysis. *Terra Nova* 25, 431-438.

Q14

Query: Please provide the volume number and page range for the bibliography in Finzel and Rosenblume, 2020.

Answer: volume number: 49

page range: 294-298

Finzel, E.S., Rosenblume, J.A., 2020. Dating lacustrine carbonate strata with detrital zircon U-Pb geochronology. *Geology* 49, 294-298.

Q15

Query: Please provide the volume number and page range for the bibliography in Li et al., 2020.

Answer: This is an error. This reference should be deleted and all Li et al., 2020 in the main text should be changed to Li et al., 2021

Q16

Query: Please provide the volume number and page range for the bibliography in Meng et al., 2020.

Answer: Volume: 18

Page range: 1-9

Meng, Q.-A., Wang, X., Huo, Q.-L., Dong, Z.-L., Li, Z., Tessalina, S.G., Ware, B.D., McInnes, B.I.A., Wang, X.-L., Liu, T., Zhang, L., 2021. Rhenium–osmium (Re–Os) geochronology of crude oil from lacustrine source rocks of the Hailar Basin, NE China. *Petroleum Science* 18, 1-9.

Q17

Query: Ref. Rieser et al. (2006c) was a duplicate and was thus removed from the Reference list. Please check if appropriate.

Answer: No problem of removing it.

Q18

Query: Please provide the volume number and page range for the bibliography in Yu et al., 2019a.

Answer: Volume: 15

Page: 423-432

Yu, J., Pang, J., Wang, Y., Zheng, D., Liu, C., Wang, W., Li, Y., Li, C., Xiao, L., 2019. Mid-Miocene uplift of the northern Qilian Shan as a result of the northward growth of the northern Tibetan Plateau. *Geosphere* 15, 423-432.