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Three main stages in the uplift of the Tibetan Plateau during the Cenozoic period and its possible effects on Asian aridification: A review

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Abstract: The Tibetan Plateau uplift and its linkages with the evolution of the Asian climate during the Cenozoic are a research focus for numerous geologists. Here, a comprehensive review of tectonic activities across the Tibet shows that the development of the Tibetan Plateau has undergone mainly three stages of the uplift: the near-modern elevation of the central Tibet and significant uplift of the northern margins (~55-35 Ma), the further uplift of the plateau margins (30-20 Ma), and a rapid uplift of the plateau margins again (15-8 Ma). The first uplift of the plateau during ~55-35 Ma forced the long-term westward retreat of the Paratethys Sea. The high elevation of the central Tibet and/or the Himalayan would enhance rock weathering and erosion contributing to lowering of atmospheric CO_2 content, resulting in global cooling. The global cooling, sea retreat coupled with the topographic barrier effect of the Tibetan Plateau could have caused the initial aridification in central Asia during the Eocene time. The second uplift of the northern Tibet could have resulted in the onset of the East Asian winter monsoon as well as intensive desertification of inland Asia, whereas the central-eastern in China became wet. The further strengthening of the East Asian winter monsoon and the inland Asian aridification during 15-8 Ma was probably associated with the Tibetan Plateau uplift and global cooling. Therefore, the uplift of the Tibetan Plateau plays a very important role in the Asian aridification.

Keywords: Tibetan Plateau, Asian aridification, uplift , India-Asia collision

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1. Introduction

The collision between India and Asia during the Cenozoic period created the high Himalaya Mountains and the Tibetan Plateau, which profoundly affected the global Cenozoic climate (e.g., Garzione, 2008; Molnar et al., 2010; Raymo and Ruddiman, 1992) and the geochemical composition of the ocean as a result of input fluxes of dissolved salts from the Tibetan Plateau to the sea (e.g., Chatterjee et al., 2013; Misra and Froelich, 2012). Reconstructing the uplifting processes of the Tibetan Plateau and its relationship with crustal deformation is of wide-ranging importance to understand the lithospheric evolution, surface uplift and global climate changes.

The Tibetan Plateau covers an area of more than 2.5 million km^2 with an average elevation of about 5000 m. In general, the Tibetan Plateau consists of six nearly west-east stretching tectonic blocks including the Himalayan, Lhasa, Qiangtang, Songpan-Ganzi-Hoh-Xil, Kunlun-Qaidam and Qilian blocks from south to north, separated by Indus-Yarlung suture (IYS), Bangong-Nujiang suture (BNS), Jinshajiang suture (JS), Anyimaqen-Kunlun-Mutztagh suture (AKMS) and South Qilian suture (SQS), respectively (Li et al., 2015; Yin and Harrison, 2000) (Fig. 1). The Lhasa and Qiangtang blocks are characterized by the main flat plateau with an average elevation of about 5000 m including several sedimentary basins. The plateau margins are a series of orogenic belts, with an average elevation ranging from 5500 to 6500 m, and sedimentary basins, such as the Qilian Mountains and Qaidam basin to the north, the Longmen Shan and Sichuan basin to the east (Fig.1). Based on seismic velocity models and wide-angle seismic profiles, the average crust thickness was interpreted as about 70-75 km under the southern Tibet, ~60-65 km under the plateau margins, and approximately 36 to 40 km beneath the Sichuan basin to the east and Tarim basin to the north (Jiang et al., 2006; Owens and Zandt, 1997; Tseng et al., 2009; Wang et al., 2007).

The timing of the initial contact and main India-Asia collision is still ambiguous with suggestions ranging from 70 to 34 Ma (Aitchison et al., 2007; DeCelles et al., 2014; Ding et al., 2005; Hu et al., 2015; Leech et al., 2005; Meng et al., 2012; Najman et al., 2010; Van Hinsbergen et al., 2012; Zhu et al., 2013), and it is probable that the main collision was not simultaneous along the entire convergent belt. Van Hinsbergen et al. (2012) proposed a two-stage India-Asia collision with phases at ~52 and 25-20 Ma based on the compilation of palaeomagnetic data from Lhasa and Tethyan Himalaya terranes. Based on the radiolarian and nannofossil biostratigraphy coupled with detrital zircon U-Pb geochronology from the Sangdanlin region in south Tibet, Hu et al. (2015) suggested that the onset of the India-Asia collision was at 59±1 Ma. Provenance analysis from upper Cretaceous-Paleocene strata in the Tethys Himalaya was proposed for the closure time of the Neo-Tethys Ocean and the India-Asia collision between 70 and 58±0.6 Ma (Cai et al., 2011; DeCelles et al., 2014). However, most of evidence based on geological, geophysical and geochemical data indicates that the main Indian subcontinent-Asia collision occurred between 55 and 50 Ma inferred by the following reasons: 1) the initiation of substantial faunal exchange of medium-to large-sized mammals during 53.3-50 Ma or a little earlier between India and Asia block (e.g., Clementz et al., 2010; Clyde et al., 2003); 2) the plate motion of India decreased dramatically during 55-50 Ma (e.g., Guillot et al., 2003; Shellnutt et al., 2014; van Hinsbergen et al., 2011b), indicating the initial India-Asia collision (Li et al., 2015) or the slab breakoff of the subducting Neo-Tethyan oceanic lithosphere (Ji et al., 2016; Zhu et al., 2015); 3) a pronounced flare up in magmatic activities and the ultrahigh-pressure metamorphism around 55-50 Ma (Ding et al., 2016; Donaldson et al., 2013; Guan et al., 2012; Zhu et al., 2015); 4) the provenance change of the Himalayan foreland basin resulted from the first arrival of the Lhasa detritus (Green et al., 2008; Najman et al., 2010; Wang et al., 2011; Zhu et al., 2005); 5) Paleomagnetic studies show that the initial contact of the India-Asia collision occurred around 55-50 Ma or a little earlier (e.g., Chen et al., 2010; Huang et al., 2015; Meng et al., 2012; Najman et al., 2010; Sun et al., 2010a). Tan et al. (2010) proposed a younger collision age of 43 Ma based on the paleomagnetic results from the late Cretaceous red beds, lava flows and Eocene tuffs in the Lhasa block, but Najman et al. (2010) suggested that the sampled volcanic tuffs were a short-term large eruption that only recorded a snapshot record of the Earth magnetic field at high inclination, therefore its paleomagnetic inclination should be taken caution. Therefore, we preferred an age of ~55-50 Ma of initial India-Asia collision in this study.

After the initiation of the India-Asia collision, the Tibetan Plateau has experienced two basically deformational styles. One is N-S crustal shortening and the tectonic uplift of the adjoining mountains. The E-W extension and related N-S trending rifts are another deformation pattern of the plateau. These two deformational styles accommodated most of India-Asia convergence. However, it is still uncertain how much of the total convergence between India and stable Asia after their initial collision was absorbed by the crustal shortening and E-W extension since the India-Asia collision (Dupont-Nivet et al., 2010; Guillot et al., 2003; Li et al., 2015; Tan et al., 2010; van Hinsbergen et al., 2011a, 2011b; Yin and Harrison, 2000). Based on the available paleomagnetic data, Guillot et al. (2003) estimated a total India-Asia convergence of 3215±496 km and ~1100 km shortening of Himalayan since 55 Ma. Dupont-Nivet et al. (2010) estimated 2900±600 km subsequent latitudinal convergence between India and Asia, divided into 1100±500 km within Asia and 1800±700 km within India inferred from the apparent polar wander paths of India and Asia. Some paleomagnetic results indicate that the Himalayan region experienced at least 1500±480 km of post-collisional crustal shortening and 2000±550 km within Asia since the collision (Sun et al., 2010a). According to the marine magnetic anomalies and the Eurasia-India plate circuit, van Hinsbergen et al. (2011a) argued that the convergence was up to 3200-4000 km for the India-Asia collision since 55 Ma. Recently, Li et al. (2015) concluded that ~1630 km of shortening occurred across the Tibetan Plateau with more than ~1400 km accommodated by large-scale thrust belts since 55 Ma based on a comprehensive review of published geological and simulated data. Although the amount of India-Asia convergence accommodated by the large-scale thrust belts is still uncertain, the large-scale thrust belts not only contribute to the crustal shortening in central Tibet but also cause the uplift of the plateau margins (e.g., DeCelles et al., 2002; Li et al., 2015; Tapponnier et al., 2001; Yin and Harrison, 2000).

The continued uplift of the Tibetan Plateau profoundly influenced Cenozoic global and Asian climate. Uplift of the Tibetan Plateau could have resulted in high rainfall on the front slopes of Himalayas as a result of the more intense monsoonal circulation and the orographic barrier (e.g., Thiede et al., 2004). The high Tibetan-Himalaya orogen would lead to greater rates of silicate weathering and erosion contributing to lowering of atmospheric CO_2 concentrations to force global cooling (e.g., Dupont-Nivet et al., 2008a; Garzione, 2008; Raymo and Ruddiman, 1992). Additionally, the high Tibetan Plateau and/or only the Himalayan mountains provided the dominant heat source for the South Asian summer monsoon or orographic insulation, driving the large-scale monsoon flow and simultaneously acting as an obstacle to southward flow of cool, dry air (Boos and Kuang, 2010; Molnar et al., 2010; Wu et al., 2012). The rising Tibetan Plateau disrupted global circulation of the westerly winds, shifting the smooth flow to the diverted flow around the high plateau (e.g., Chatterjee et al., 2013). Numerous studies show that the uplift of the Himalayan-Tibetan orogen is closely related to the onset of Asian monsoon system and Asian desertification (e.g., Chatterjee et al., 2013; Guo et al., 2002; Miao et al., 2012; Zhang et al., 2007). In this paper, we synthesize the available data to propose that there are three significant stages in the uplift of the plateau and its possible effects on climatic changes in Asia.

2. Three main phases of growth of the Tibetan Plateau and Asian drying changes during the Cenozoic

Available deformational and paleoaltimetry data indicate that there were three main phases of growth of the Tibetan Plateau since the India-Asia collision. These episodes caused regionally climatic changes as well as contributing to trends in Cenozoic global cooling. The spatial and temporal evolution of the plateau growth and effects on Asian climate are divided into three episodes: the Eocene (~55-35 Ma), the middle Oligocene-early Miocene (30-20 Ma) and the middle to late Miocene (15-8 Ma).

2.1. The significant uplift of the northern margins accompanied by Asian aridification between ~55 Ma and 35 Ma

2.1.1. Asian initial aridification during ~55-35 Ma

Recent simulations show that although the high elevation of the central Tibet has already been removed, the large-scale South Asian summer monsoon circulation was unaffected by providing the high but narrow orography of the Himalaya and adjacent mountains (Boos and Kuang, 2010). These mountains produced a strong monsoon by insulating warm, moist air over continental India from the cold and dry extratropics (Boos and Kuang, 2010). Using an atmospheric general circulation model with 1.9º longitude resolution with prescribed sea surface temperature and sea ice cover to examine the effects of the plateau uplift on climate, the results were in general agreement with Boos and Kuang (2010), suggesting that the uplift of the Himalaya would strengthen summer precipitation in southwestern margin of the Himalaya as well as central-southern India (Zhang et al., 2012). The low oxygen isotope values with strong seasonality in gastropod shells and mammal teeth from Myanmar at 40-34 Ma, and aeolian dust deposition in northwest China during the Eocene time in response to the onset of desertification and winter monsoon circulation in inner Asia show marked monsoon-like patterns in rainfall and wind south and north of Tibetan-Himalayan orogen during the late Eocene time (Licht et al., 2014) and that support the view that the Asian monsoon was probably active during the Eocene (Quan et al., 2012). The similar fossil leaf trait spectra between Eocene basins in southern China and modern Indonesia-Australia Monsoon suggest that the characteristics of the modern topographically enhanced South Asia Monsoon had to develop in Eocene time (Spicer et al., 2016). Sedimentological and numerical data shows that monsoons were not dampened by the Proto-Paratethys Sea (Bougeois et al., 2018). The strong Eocene monsoons later weakened after 34 Ma ago related to the global shift to icehouse climate (Licht et al., 2014).

The near-modern elevation of the central Tibet and further extension to the north probably forced the long-term westward sea retreat from the Tarim Basin (e.g., Bosboom et al., 2014a; Carrapa et al., 2015; Sun et al., 2016). The lithostratigraphic, biostratigraphic and magnetostratigraphic results from the southwest Tarim Basin along the Pamir and West Kunlun range show that the final sea retreat was between 47 and 40 Ma accompanied by significant aridification of the Asian interior as a result of the decrease of moisture supplied from the Paratethys Sea (Bosboom et al., 2014a, 2014b; Sun et al., 2016). Sedimentology, paleontology, sandstone petrography and zircon U-Pb ages from the Tajik depression, 400 km to the west of the Tarim basin, show that the local retreat of this part of the Paratethys Sea was at ~39 Ma, a little later than the Tarim Basin (Carrapa et al., 2015). A strong anticyclonic zone at Central Asian latitudes and an orographic effect from emerging Tibetan Plateau occurred during this period (Bougeois et al., 2018). These results are in agreement with the northward growth of the Pamir Mountains.

In the Xining basin at the northeastern of Tibetan Plateau, the palynological records show a sudden appearance of the Pinaceae family at 38 Ma in response to the cooler and drier climate, and suggest that the initiation of the continental aridification in central Asia started as early as Eocene time (Dupont-Nivet et al., 2008a). Subsequent studies of the same sedimentary sequence in Xining basin reveal second additional phases of aridification before the Eocene-Oligocene Transition (34 Ma). The first phase at~36.6 Ma was accompanied by a distinct decrease in gypsum content relative to red mudstone and the second phase was characterized by a substantial increase in clastic sedimentation rate at 34.7 Ma (Abels et al., 2011). At the Eocene-Oligocene Transition, playa lake deposits in Xining basin vanished, subsequent dominated by homogenous red mudstones with minor interstitial gypsum content, in response to a pronounced aridification of the Xining basin (Dupont-Nivet et al., 2007).

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2.1.2. Tectonic uplift of the Tibetan Plateau linked to this aridification

Previous studies indicate that the Lhasa and Qiangtang terranes underwent significant crustal thickening and surface uplift prior to the India-Asia collision (DeCelles et al., 2002; Li et al., 2015). Shortening reconstructions estimate that a ~60% crustal shortening of the Lhasa block occurred during the Cretaceous and gained 3-4 km of elevation prior to the India-Asia collision (Murphy et al., 1997). Balanced cross section restoration across the Qiangtang block suggests that ~400 km of crustal shortening occurred prior to the India-Asia collision (Li et al., 2015; van Hinsbergen et al., 2011b). The majority of intensive shortening across Central Tibet occurred before the collision based on the structural restorations, and this region has been affected by only minimal thrusting reactivation since the late Paleocene (Kapp et al., 2003, 2005). Therefore, Central Tibet (Lhasa and Qiangtang terranes) attained at least 3 km elevation prior to India-Asia collision. Since the India-Asia collision, the significant crustal thickening (~160 km) of the central Tibet only occurred within about 10 Myr. The northward subduction of Greater India slab played a major role in crustal thickening and uplifting (Li et al., 2015). The southward subduction of the Songpan-Ganzi terrane beneath the Qiangtang block also contributed to the crustal thickening of the central Tibet, as inferred from the widespread potassium-rich lavas in the northern Qiangtang (Ding et al., 2007; Li et al., 2015).

In the Qiangtang block, stable isotope results from fluvial/lacustrine carbonate cement, pedogenic carbonate and marl from the Kangtuo and Suonahu formations indicate that high elevation (> 5000 m) had been established by at least the middle Oligocene (28 Ma) (Fig 2; Xu et al., 2013). Stable isotopes revealed a paleoelevation of ~4.1-6.5 for the southern Tibet and 3.3 km for the southeast Tibet in the Eocene, respectively (Hoke et al., 2014; Ingalls et al., 2017). The low-temperature thermochronlogic results from the Qiangtang and Lhasa terranes showed a rapid to moderate exhumation between 85 and 45 Ma followed by low exhumation rates of <0.05 mm/yr, which explained the plateau formation in central Tibet by 45 Ma (Rohrmann et al., 2011). In addition, the distributions of high-K calc-alkaline andesites, dacites and rhyolites in central-western Qiangtang from 46 to 38 Ma, together with the north-south trending dikes in response to the onset of east-west extension in central Tibet between 47 and 38 Ma, suggested that the central Tibet had already attained near-modern elevation by at least 38 Ma (Wang et al., 2008, 2010). Thus, the Lhasa and Qiangtang terranes have reached near-modern elevation by at least 35 Ma.

The northern Tibetan Plateau had experienced significant uplift and exhumation between 55 and 35 Ma (Fig. 2). Low-temperature thermochronologic data shows that rocks along the major thrusts-the West Qinling thrust (Clark et al., 2010; Duvall et al., 2011), Qilian Shan (He et al., 2017), Tanggula thrust (Li et al., 2012), Fenghuoshan fold-thrust belt (Staisch et al., 2016), Kunlun fault (Jolivet et al., 2001), Altyn Tagh thrust (Jolivet et al., 2001; Yin et al., 2002) and Kashgar-Yecheng thrust (Cao et al., 2013) had undergone rapid cooling and exhumation between 55 and 40 Ma as a response to the initiation of India-Asia collision (Fig. 2; Locations have shown on the circles and detail information can be seen at table 1). Seismic reflection profiles and

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balanced cross section restoration show that the compression of the northern Qaidam basin began at 65-50 Ma, which was consistent with high accumulation rates of the foreland basin (Ji et al., 2017; Wei et al., 2013; Yin et al., 2008a) (Fig. 2).

The strong uplift of the mountains in the plateau margins during this interval would offer a large amount for clastic sediments to the adjacent basins, with peaks of influxes into the Lanzhou basin at ~58 Ma (Wang et al., 2016b), Xining basin at ~52 Ma (Dai et al., 2006), and Hoh Xil basin at ~52 Ma (Zhang et al., 2010). In the Tethyan Himalaya, emplacement of a series of undeformed granitoid bodies before 44.1±1.2 Ma indicates that significant crustal thickening had occurred within 10 to 20 Myr of the initial India-Asia collision (Aikman et al., 2008). The low-temperature thermochronologic data from the Deosai plateau in the northwest Himalaya coupled with the thermal history modeling shows that the Deosai plateau underwent continuous slow exhumation rates for the past 35 Ma, thus suggesting that the high elevation had been achieved by at least 35 Ma (Fig 2; van der Beek et al., 2009). Therefore, the plateau margins have undergone significant growth shortly after the initiation of India-Asia collision, but the altitude is still disputed.

Although the Eocene global cooling that would reduce the amount of water vapor held in the atmosphere was revealed by deep-sea stable oxygen isotope (Zachos et al., 2001), we consider that the Tibetan Plateau uplift at this period played an important role in Asian aridification. First, climate models suggest that surface uplifts of the northern Tibetan Plateau had a greater contribution to the decreased annual precipitation over inland Asia mainly due to the enhanced rain shadow effect of the mountains and changes in the regional circulations (Liu et al., 2015a; Zhang et al., 2017). Second, the outward-growth of the Tibetan Plateau would force westward sea retreat of Paratethys Sea, resulting in decrease of moisture supplied into inland Asia.

2.2 The further uplift of the plateau margins and strengthened aridification in Asia between 30 and 20 Ma

2.2.1. East Asian monsoon and strengthened aridification during 30-20 Ma

The Oligocene-Miocene transition is a significant Cenozoic cooling event referred to Mi-1 with a series of paleoenvironmental changes. Benthic foraminiferal oxygen isotope from the ODP site 1218 in Pacific shows a transient ~1‰ positive excursion as a response to the expansion of Antarctic ice sheets (Zachos et al., 2001; Pälike et al., 2006), and an apparent positive excursion of benthic foraminiferal carbon isotope (Pälike et al., 2006) (Fig 3C and 3D). Sea level estimates from coastal plain coreholes in New Jersey and Delaware show an about 50 m fall of sea level between 22.3 and 23.3 Ma (Kominz et al., 2008) (Fig 3E). The $CaCO_3$ contents and the proportion of > 150 μm (wt%) from ODP site 1264 and 1265 in the subtropical southeastern Atlantic Ocean show significant increases between 22.2 and 23.2 Ma as a feedback to the transient Oligocene-Miocene transition glaciations (Liebrand et al., 2016) (Fig 3F and 3G). The benthic foraminiferal accumulation rates (BFAR) at the southern Atlantic site 1090 significantly increased during

Oligocene-Miocene transition period, imply an enhanced paleoproductivity (Diester-Haass et al., 2011) (Fig 3H). Benthic foraminiferal Mg/Ca, Li/Ca and U/Ca records from ODP 926 and 929 in the equatorial Atlantic across the Oligocene-Miocene boundary reveal an enhanced organic carbon burial (Mawbey and Lear, 2013). However, the driving mechanism of this fundamental transition is still ambiguous. The relatively stable atmospheric CO_2 content may not be the reason for this climatic change (Fig 3B), and a minimum in eccentricity that results in low seasonality orbits favorable to ice-sheet expansion on Antarctica may be a dominant factor (Zachos et al., 2001) (Fig 3A).

Significantly, there were also obvious changes in Asian paleoenvironments during this interval. Based on a compilation of paleobotanical and lithological data from 125 cites over China, Sun and Wang (2005) argued that a reorganization of climate system, from latitudinal zonal pattern during the Paleogene to a Neogene pattern with arid zones restricted to northwest China, occurred around the Oligocene-Miocene boundary. This implies that the onset of the East Asia summer monsoon began around ~23 Ma. The continuous aeolian deposits during 22 to 6.2 Ma in Qin'an county (Gansu province) support the conclusion that modern East Asian monsoon already existed in the early Miocene (Fig 4; Guo et al., 2002). Subsequent studies from the Zhuanglang site at the western Chinese Loess Plateau confirmed that the loess deposits in the Loess Plateau began as early as 25 Ma and inland Asian desertification initiated or enhanced at least by the late Oligocene (Fig 4; Qiang et al., 2011). A 30 Ma stable isotope record of marine-deposited black carbon from the northern South China Sea reveals that C_4 plants gradually appeared since the early Miocene as a component of land vegetation in East Asia; and this shift in vegetation types might be related to the evolution of East Asian monsoon (Jia et al., 2003). The sporomorphs results from the Lanzhou basin during the latest Early Oligocene indicate a dominance of arboreal plants that represent a wetter environment characterized by relatively high precipitation and a warm climate, which suggests that East Asia summer monsoon has already supplied abundant rainfall to Lanzhou basin (Miao et al., 2013). Monsoonal circulation existed by the early Miocene was also supported by the presence of persistently lower pedogenic carbonate $\delta^{13}C$ and higher soil respiration fluxes on the Loess Plateau and in the Himalayan foreland (Caves et al., 2016). Weathering records from the ODP 1148 in South China Sea and ODP 718 in Bay of Bengal reveal an increased intensity of chemical weathering related to onset of East Asian summer monsoon (Clift et al., 2008, 2014). The intensification of the South Asian monsoon at ~24 Ma was probably a major trigger of the stronger erosion on Greater Himalayan with removal of ~1.5 km rocks leading to a major unconformity in the Himalayan foreland basin (Clift and VanLaningham, 2010).

The aridification of Asian interior further intensified during the late Oligocene-early Miocene. In Jungger basin, the earliest eolian deposition started at 24 Ma and lasted until 8 Ma, indicating that extensive arid to semiarid regions existed in the Asian interior by 24 Ma (Sun et al., 2010b). According to the radioisotopic methods (^{40}Ar-^{39}Ar and U-Pb ages) to precisely date a volcanic tuff preserved in the stratigraphy from the Aertashi and Kekeya sections in the Tarim basin, in

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combination with the magnetostratigraphy and lithostratigraphy, Zheng et al. (2015) concluded that the initial desertification of the Taklimakan desert was between ~26.7 Ma and 22.6 Ma as a response to a combination of widespread regional aridification and increased erosion in the surrounding mountain fronts, both of which were closely linked to the tectonic uplift of the Tibetan-Pamir Plateau and Tian Shan. A palynological record from the fluviolacustrine Jingou River section collected from the northern Tian Shan indicates a shift from a late Oligocene wet condition in central Asia to dry conditions at 23.8-23.3 Ma (Tang et al., 2011). A significant increase in aeolian sediments in Lanzhou basin occurred at ~26 Ma, which reveals that a large scale arid environment formed in the Asian interior since the late Oligocene (Zhang et al., 2014). In central Tibet, stable isotope analyses of modern and accurately dated ancient paleosol carbonate in the Nima basin reveal an arid climate and high paleoelevation (4.5-5 km) by 26 Ma (DeCelles et al., 2007). Major and trace element concentrations from the central Pacific show that the delivery of Asian dust materials significantly increased since 20 Ma in the ODP Site 1215 (Ziegler et al., 2007), which was compatible with the remarkable aridification of inland Asia.

2.2.2. Tectonic uplifts of the Tibet and surrounding mountains linked to this drying

This stage is characterized by relatively little tectonic active in the central Tibet and by further uplift of the plateau margins (Fig. 4; Locations that mentioned the uplift and deformation at this part have been shown on the circles and detail information can be seen table 2).

In northeastern Tibet, low-temperature thermochronologic results show that the Laji Shan (Lease et al., 2011), Ela Shan (Lu et al., 2012) and northeastern Qilian (Pan et al., 2013) underwent significant rapid cooling and exhumation between 25 and 20 Ma (Fig. 4). The unstable accumulations in the Xining basin during 25-20 Ma (Xiao et al., 2012), high accumulation rates in the Xunhua basin around 24-21 Ma (Lease et al., 2012) and sedimentary discontinuity in the Guide basin at~21 Ma (Liu et al., 2013) have been interpreted to reflect the uplift of adjacent mountains during this period. Changes in paleocurrent and detrital zircon provenance at ~30 Ma in the Lanzhou basin at the northeast margin of the Tibetan Plateau reflect the pulsed growth of the West Qinling (Wang et al., 2016b). In the northwest Tibet, the initiation of thrusting in the West Kunlun Range began in the early Miocene (~23 Ma) (Jiang et al., 2013). The apatite fission track results indicate that the Altyn Tagh fault (Jolivet et al., 2001), the Main Pamir thrust (Sobel and Dumitru, 1997), the Southwest Tian Shan (Sobel et al., 2006), and the Northern Tian Shan (Hendrix et al., 1994) underwent rapid cooling and exhumation between 30 and 20 Ma. All of these indicate the initial activity of the thrust faults and a significant tectonic deformation of the Tibet margins during the middle Oligocene-early Miocene time (Fig. 4).

In the Himalayas, low-temperature thermochronologic results in combination with the leucogranite U-Pb and K-Ar muscovite ages show the formation of the Silving Rift as early as 23-21 Ma (Searle et al., 1999). The initial thrusting of the Main Central Thrusts occurred at approximately 23-21 Ma based on the geochronology from the dating of $^{40}Ar/^{39}Ar$ from the

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Greater Himalayan paragneiss in hanging wall of the Main Central thrust (Robinson et al., 2006) and was synchronous with the South Tibetan detachment system motion (Li et al., 2015; Robinson et al., 2006). In eastern Tibet, low-temperature thermochronologic data reveals that the Longmen Shan underwent significantly cooling during 30-25 Ma (Wang et al., 2012b). Therefore, we can conclude that the plateau margins experienced intense growth between 30 and 20 Ma (Fig. 4).

The Paratethys Sea has retreated since late Eocene (Bosboom et al., 2014a), which is not the main cause of this Asian aridification. Global cooling trends and changes in CO_2 level are unlikely to account for this strengthened aridification because late Oligocene warming, as documented by the marine $\delta^{18}O$ records (Zachos et al., 2001), are not correlative with this drying changes in Asia. Therefore, we consider that the surface uplifts of the plateau margins are the dominant factor. The continuing uplift and expansion of the plateau margins would alter significantly the thermally forced circulation and enhance continental-scale winter monsoon and central Asian aridity (An et al., 2001). Climate models reveal that uplift of the northern Tibet margins have significant effects on the intensified drought in inland Asia (Liu et al., 2015a; Zhang et al., 2012). Another important factor is the Tian Shan Mountains and surrounding mountains uplift, which would reduce westerly moisture transport (Bougeois et al., 2018) and thus strengthen drying in central Asia.

2.3 The rapid uplift and erosion of the plateau margins again and Asian aridification between 15 and 8 Ma

2.3.1. Strengthened Asian winter monsoon and extensive aridification during 15-8 Ma

The middle-late Miocene time was a fundamental change in earth's climate system. A significant ~1‰ positive excursion of benthic foraminiferal $\delta^{18}O$ reflected a major expansion and permanent establishment of the East Antarctic ice sheets, and an apparent positive excursion of benthic foraminiferal $\delta^{13}C$ (Westerhold et al., 2005) (Fig 5C and 5D). Bottom waters have cooled by ~2°C and sea surface waters cooled by 6-7°C in the Southern Ocean (Holbourn et al., 2007; Shevenell et al., 2004), and cooled ~ 2°C of sea surface waters in the Eastern Equatorial Pacific (Rousselle et al., 2013) (Fig 5F). A 59 ±6 m of sea level fall in northeastern Australia at ~13.9 Ma occurred due to ice growth on Antarctica (John et al., 2011). Sea level estimates from coastal plain coreholes in New Jersey and Delaware show an about 40 m fall of sea level between 14 and 11 Ma (Kominz et al., 2008) (Fig 5E). Increases in opal accumulation from 14 to 13.8 Ma from ODP U1338 in eastern equatorial Pacific indicated an enhanced siliceous productivity (Holbourn et al., 2014). During this period, the onset of a perennial sea ice cover in the Arctic Ocean probably occurred at ~13 Ma (Krylov et al., 2008), and the extinction of tundra in continental Antarctica has taken place at ~14 Ma (Lewis et al., 2008), and decrease of mass accumulation rates of silicate sediments occurred at ~15.5 Ma in South China Sea (Wan et al., 2009) (Fig 5G). Some hypotheses were tried to interpret these paleoclimatic changes, including atmospheric CO_2 drawdown (Holbourn et al., 2005; Shevenell et al., 2008) and orbitally-paced climate changes (Holbourn et al., 2007). But, the atmospheric CO_2 reconstructions still remain unclear (Fig 5B). The eccentricity may be a pacemaker of middle Miocene climate evolution through the modulation of long-term carbon budgets (Holbourn et al., 2007) (Fig 5A).

Asian paleoclimate underwent major changes during the middle to late Miocene from relatively wet interval during ca. 17 to 15 Ma to a more arid one that continued to the present (Hui et al., 2011; Song et al., 2014). A notable high magnetic susceptibility value interval between 16 and 14 Ma from Zhuanglang site at western Chinese Loess Plateau was interpreted to reflect the Miocene climatic optimum (Qiang et al., 2011). Sporopollen data from the Tianshui basin at the NE Tibetan Plateau indicates a dominated temperate, warm-temperate broad-leaved forest between 17.1 and 14.7 Ma in response to the wet conditions (Hui et al., 2011).

But After ca.15 Ma, dry conditions have prevailed in the inland Asia. Palynological records from the Tianshui basin (Hui et al., 2011; Liu et al., 2016), Wushan Basin in the Northeastern Tibetan Plateau (Hui et al., 2017), Guyuan at the Ningxia province (Jiang and Ding, 2008), western Qaidam basin (Miao et al., 2011), and northern Tian Shan (Tang et al., 2011) show that the *Artemisia*, *Chenopodiaceae* (Fig 6A), *Ephedra* and *Poaceae* significantly increased and remained the dominant taxa in the pollen assemblages, indicating a persistent drier condition in central Asia after the middle Miocene climatic optimum. A rapid decrease of magnetic susceptibility within the Neogene eolian sequences from the eastern Xorhol basin at the northeastern Tibetan Plateau indicate that the aridity of Asian interior intensified after 11.5-10.3 Ma period (Li et al., 2014). Carbonate content from the western Qaidam basin reveal a sharp decrease since 11 Ma in response to the increase of regional aridity (Song et al., 2014) (Fig 6D). Isotopic data from pedogenic and lacustrine carbonates in the northeastern Qaidam basin and Xunhua basin in the northeastern Tibetan Plateau displays a positive shift of ~2.5‰ and ~1.5‰ in $\delta^{18}O$ values during this period, respectively (Fig 6B), indicating that intensified aridity in central Asia occurred at~12 Ma (Zhuang et al., 2011; Hough et al., 2014). A similar study from the southwestern Qaidam basin has shown that a~1.5‰ positive shift in the most negative $\delta^{18}O$ values of carbonate cements and pedogenic carbonates occurred at 13-12 Ma (Li et al., 2016). Another similar study from the Qaidam basin show that suddenly decrease of the ostracod species diversity, abrupt positive shifts of about 3.75‰ in $\delta^{18}O$ values and 5.28‰ in δ^{13} C values for ostracod valves, and markedly decrease of the chemical index of weathering (CIW) occurred since 13.3 Ma ago (Song et al., 2017). Multiproxies of the Sikouzi section in the Ningxia province in China changed substantially after 12-11 Ma, with an increase of magnetic susceptibility, lightness and total inorganic carbon and a decrease of the pollen humidity index, total organic carbon and redness; these imply that the paleoclimate in central Asia became cooler and drier since 12 Ma (Jiang et al., 2008). The expansion of the dry areas in western China after ca 15 Ma would supply a larger amount of the dust to the Lanzhou basin (Zhang et al., 2014) and Chinese Loess Plateau forming the Red Clay sediments (Xu et al., 2009). The long-term drying of inland Asia after ca 15 Ma led to the disappearance of late Miocene episodic lakes in the Tarim basin and shifted to the currently prevailing desert environments (Liu et al., 2014). In addition, increased frequencies of

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fire in the dry Inner Asia may be related to a continuous aridification in Asia (Miao et al., 2016).

The Asian monsoon apparently changed during 14-8 Ma. Gradually increase percentages of xerophytic taxa in the Qaidam basin suggest gradual strengthening of East Asian winter monsoon and weakening of East Asian summer monsoon (Miao et al., 2011). Pollen and grain-size studies from the Sikouzi area on the east side of the Liupan Mountains also reveal a weak intensity of East Asian summer monsoon since 12 Ma ago (Jiang and Ding, 2008, 2009). Late Miocene winter monsoon intensification is evidenced in the decreased magnetic susceptibility variability of Zhuanglang Red Clay deposits (Qiang et al., 2011) (Fig 6F); which was consistent with the relatively low calcite/quartz ratios during 9.5-7.5 Ma in response to the strong East Asian winter monsoon intensity (Sun et al., 2015). Lacustrine micrite and pedogenic carbonate from the Xunhua basins at the northeastern Tibetan Plateau (Hough et al., 2011, 2014), and from the northeastern Qaidam basin (Zhuang et al., 2011) show a positive shift of ~1.5‰ and ~2.5‰ in $\delta^{18}O$ values during this period, respectively, imply an increased regional aridification and related to enhanced East Asian winter monsoon. Increased mineralogical ratios (chlorite/quartz, illite/quartz, calcite/quartz and protodolomite/quartz) from the Zhuanglang section in the western Chinese Loess Plateau indicated weak East Asian summer monsoon intensity during 18.5-9.5 Ma (Sun et al., 2015). The ratios of (illite+chlorite)/smectite and (quartz+feldspar)% from ODP site 1146 in South China Sea reveal a significant increase at~15 Ma as a result of enhanced winter monsoon (Wan et al., 2007). The CIA ($100\times Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)$) from the same site 1146 show a significant decrease at about 15 Ma related to decreased summer monsoon intensity (Wan et al., 2009) (Fig 6E). The illite/smectite ratios from IODP U1430 in Japan Sea show a rapid increase at~11.8 Ma as suggestive of increased eolian input related to enhanced winter monsoon (Shen et al., 2017) (Fig 6C). A comprehensive review of numerous proxies from the South China Sea sediments reveals a strong summer monsoon during ~21-18.5 Ma, followed by an extended period of summer monsoon maximum from 18.5 to 10 Ma, then weakening (Clift et al., 2014).

The South Asian summer monsoon may begin and/or strengthen during this period. The D/H ratios of pedogenic clay and the $^{18}O/^{16}O$ ratio of carbonate nodules from Siwalik sediments in India reveal a substantially strengthened Indian monsoon at ~11 Ma (Sanyal et al., 2010). But, the geophysical and geochemical data from the IODP Expediton 359 in Indian Ocean reveal an abrupt modern South Asian Monsoon onset at ~12.9 Ma (Betzler et al., 2016), with an apparent decrease content of Mn/Ca ratios (Fig 6G). This age was also reported by Gupta et al.(2015) based on the stable isotope analysis of planktonic foraminifera in the Arabian Sea and significant increase of TOC contents (Fig 6H). Recent research from ODP site 722B and 730A in the western Arabian Sea revealed a major drop in sea-surface temperature in the period of 11-10 Ma related to the establishment of monsoonal upwelling (Zhuang et al., 2017).

2.3.2. Uplifts of the plateau margins linked to this Asian drying

During this period, the plateau margins underwent rapid uplift again and there was the onset of S-N rifting in central Tibet (Fig. 7; Locations that mentioned the uplift and deformation at this part have been shown on the circles and detail information can be seen table 3).

In northeastern Tibet, low-temperature thermochronological and detrital zircon analyses indicate that the North Qilian Shan (Zheng et al., 2010; Pan et al., 2013; Wang et al., 2016a), Jishi Shan (Lease et al., 2011), Liupan Shan (Wang et al., 2017), and Haiyuan fault (Duvall et al., 2013) had undergone accelerated exhumation between 14 and 10 Ma. The rapid deformation and exhumation of these mountains would lead to hydrologic separation in the adjacent basins, such as Xunhua and Linxia basins (Hough et al., 2011), and to a high sedimentation rate for foreland basins and new detrital zircon components (Lease et al., 2012; Liu et al., 2013; Saylor et al., 2017). A combination of magnetostratigraphy and cosmogenic burial ages from the fluvial deposits in Gonghe basin, together with lithostratigraphic patterns and paleocurrent records, indicates that the rise of the Gonghe Nan Shan became significant at ~10 Ma (Craddock et al., 2011). A clockwise rotation of 25.1±4.6º of the Guide basin took place between 17 and 11 Ma (Yan et al., 2006). A magnetostratigraphic study of the Dahonggou section in the northern Qaidam basin coupled with the variations in lithofacies, sedimentation rate and magnetic susceptibility reveal that the Qilian Shan and the Altyn Tagh fault were synchronously tectonically active at ~12 Ma (Lu and Xiong, 2009). This time was consistent with the onset of molasse deposits along the Altyn Tagh fault at about 13 Ma (Sun et al., 2005). In the northwestern Tibet, apatite fission track results reveal that the West Kunlun range experienced rapid cooling and exhumation during 12-8 Ma, which was consistent with sharply increased sedimentation rates at the southern margin of the Tarim basin (Wang et al., 2003). The uplift and erosion of the Tian Shan accelerated at ~11 Ma, as constrained by a two-fold increase in sedimentation rate as well as marked changes in rock magnetic characteristics at this time in the Yaha section on the southern flank of the central Tian Shan (Charreau et al., 2006).

In Himalayas, the extrusion rate of the Higher Himalayan Crystalline thrust sheet onto the Lesser Himalaya sequence slowed in the middle Miocene and ceased by ca. 12 Ma (Godin et al., 2006). The activity of the Main Central thrust and the South Tibetan Detachment System had ceased by 13-12 Ma based on U-Pb ages of deformed pegmatites, $^{40}Ar/^{39}Ar$ hornblende ages and Rb-Sr cooling ages of muscovite and biotite (Catlos et al., 2002; Daniel et al., 2003; Tobgay et al., 2012). The Main Boundary thrust began active during 12-9.5 Ma inferred from the regional increasing erosion in the Lesser Himalaya and rates of the foreland-basin fill (Huyghe et al., 2001; Meigs et al., 1995). Thiede et al. (2009) integrated 255 apatite and zircon fission track and white mica $^{40}Ar/^{39}Ar$ ages from the northwest Himalaya, and suggested that a high exhumation rate of 1-2 mm/a existed since 11 Ma along the southern High Himalayan slopes. In the Tethyan Himalaya, the rapid exhumation range was from 17 to 5.7 Ma in the central Himalaya and from 15 to 3 Ma in the southwestern Himalaya (Liu et al., 2005; Thiede et al., 2005). A series of N-S striking rifts and high-angle normal faults were documented in the Himalaya, such as the Kung Co, Thakkola, Yadong-Gulu. Based on magnetostratigraphy of the Tetang Formation, the initiation of Thakkola

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rift extension was constrained between 11 and 10 Ma (Garzione et al., 2000, 2003). The zircon and apatite (U-Th)/He ages from the footwall of the early Miocene Kung Co granite in southern Tibet suggest that initiation of normal fault slip was at ~13-12 Ma and that rapid exhumation of the footwall was between ~13 Ma and 10 Ma (Lee et al., 2011). In eastern Tibet, low-temperature thermochronological results show that southwestern Longmen Shan experienced rapid cooling at 15 Ma (Cook et al., 2013), the central Longmen Shan was initially active at ~11 Ma (Kirby et al., 2002), and the northeastern part of Min Shan was at 7-4 Ma (Kirby et al., 2002). Moreover, the thermochronlogic analyses from the central and southern Longmen Shan Thrust-Nappe belt reveal differential cooling across the Erwangmiao and Yingxiu-Beichuan faults during Miocene (Arne et al., 1997).

We cannot rule out the effects of global cooling during this period, which would reduce the amount of water vapor held in the atmosphere and thereby can cause terrestrial drying. But, the further outward-growth of the plateau margins played an important role for Asian drying. First, Miao et al.(2012) examined the evolution of Miocene climate for five separate regions in Eurasia, including Europe, High-latitude Asia, the East Asian Monsoon region, the South Asian Monsoon region, and Central Asia. The results show that the moisture evolution in Central Asia shows less similarity with other four regions, and thereby the uplift of the plateau margins could provide a possible explanation for these differences. Second, climatic proxies from the Central Asia, Japan Sea and South China Sea (Fig.6) do not show synchronously changes in response to global cooling. If we do not consider the age reliable, this may imply that regional factors, especially differential uplift of the marginal mountains on the edge of the Tibetan Plateau, played an important role for proxy changes in the context of Middle-Late Miocene global cooling.

3. Discussion

At least four hypotheses are proposed to interpret the Asian aridification changes: (1) the uplift of the Tibetan Plateau (e.g., Miao et al., 2012; Zheng et al., 2015); (2) the retreat of the Tethys Sea in Asia (e.g., Bosboom et al., 2014a; Ramstein et al., 1997); (3) the global cooling during the Cenozoic (e.g., Dupont-Nivet et al., 2007; Lu and Guo, 2013); and (4) the decreasing concentration of atmospheric CO_2 (e.g., Lu and Guo, 2013). Previous studies show that the retreat of the Tethys Sea occurred around 47-40 Ma. This regression was coeval with the initial aridification of the central Asia, the regional disappearance of a relatively wet perennial saline lake system, and a prominent shift to relatively more arid flora around ~41 Ma recorded in the Xining basin (Bosboom et al., 2014a; Sun et al., 2016). Therefore, some scholars suggested that the sea retreat in central Asia played an important role in the deterioration of the Asian paleoenvironment (Bosboom et al., 2014b; Ramstein et al., 1997). The global cooling is another factor for Asian desertification. The cooling would not only cause ice-sheet expansion and an increase in meridional temperature gradients leading to the southward retreat of summer monsoon, but also would reduce the amount of water vapor held in the atmosphere leading to both additional cooling and further weakening of the East-Asian summer monsoon (e.g., Dupont-Nivet et al., 2007; Jiang and Ding, 2008; Lu and Guo, 2013). The decrease in average atmospheric CO_2 concentration would not only cause global cooling but also would shift the inter-tropical convergence zone southward, thereby reducing the monsoon precipitation accompanied by the intensification of Asian desertification (e.g., Anagnostou et al., 2016; Lu and Guo, 2013).

Although numerous elements influence evolution of East Asian climate, we consider that the three main phases of uplift of the Tibetan Plateau region played an important role in drying in Asia.

During the first pulse, the central Tibet reached the near-modern elevation and probably the Himalayas had already obtained the present-day elevation by at least 35 Ma. The high elevation in central Tibet would increase silicate weathering and erosion contributing to lowering of atmospheric CO_2, which was a major cause of global cooling (e.g., Dupont-Nivet et al., 2008a; Garzione, 2008). Global deep-sea oxygen records show a significantly positive shift in response to rapid global cooling during 50-35 Ma (Fig. 8). Reconstructions of atmospheric CO_2 concentrations based on the boron isotope composition of well preserved planktonic foraminifera show a relative decline in CO_2 concentrations through the Eocene of about 50 ppm that would be sufficient to drive the high-and low-latitude cooling during late Eocene (e.g., Anagnostou et al., 2016). The continuing uplift of the plateau, combined with a decrease of seafloor spreading rates, would result in declining atmospheric CO_2 concentrations below ~760 ppm allowed for a critical expansion of ice sheets on Antarctica (Dupont-Nivet et al., 2008a; Pearson et al., 2009). In addition, the continuing northward injection of the Pamir related to the Tibet uplift forced the long-term westward sea retreat from the Tarim basin (Carrapa et al., 2015; Sun et al., 2016). This resulted in the regional initiation of the Asian aridification induced by the decrease of moisture supplied from the Paratethys Sea (Bosboom et al., 2014b). More notably, the high Himalayas and south Tibet would lead to the formation of the south Asian monsoon by orographic insulation (Boos and Kuang, 2010) or thermal forcing (e.g., Wu et al., 2012). However, the warm and moist air from the Indian Ocean could not easily flow toward the central and northern Tibet due to the topographic barrier of the high Himalayas. Additionally, the significant uplift of the northern Tibet during this interval probably caused a relatively weak monsoon-like climate during the Eocene time, which was consistent with recent climate model simulations that the uplift of northern Tibet was critical for intensification of East Asian monsoon (Liu and Dong, 2013; Liu et al., 2015a; Tang et al., 2013).

The second pulse between 30 and 20 Ma is characterized by a further uplift of the plateau margins. However, the intense uplift of the plateau margins during this period cannot interpret the rapid warming of global climate during the Late Oligocene, which suggests that the process of silicate weathering of these elevated mountain belts and the subsequent sequestration of carbon was not sufficient in itself to counter the recorded relative rise in atmospheric CO_2 concentration (Fig. 8). Instead, this late-Oligocene climatic warming may have been partly a side-effect of a

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decrease of organic carbon burial and a net addition of CO_2 to the atmosphere (e.g., Raymo and Ruddiman, 1992). Nevertheless, the uplift of the plateau margins during this interval had major regional impacts on the climate of central Asia. Climatic simulations reveal that the uplift of the northern Tibet would cause an initial formation of the East Asian monsoon as well as the desertification in central Asia (e.g., Liu and Dong, 2013; Liu et al., 2015a, 2017; Zhang et al., 2012, 2017). Moreover, the intense uplift of the northern margins would strongly strengthen the land-sea thermal contrast, thereby leading to intensification of the East Asian winter monsoon and reducing precipitation in inland Asia (Wu et al., 2012). The synchronous occurrence of the plateau uplift and intensification of the East Asian monsoon suggests that the uplift of the plateau margins was the primary mechanism for the climatic variations in central Asia during this period.

The third uplift of the plateau from 15 to 8 Ma was dominated by the uplift of the plateau margins. Although Willenbring and von Blanckenburg (2010) suggested that pulses in mountain uplift over the past 10 Ma might have been neither a direct cause nor an inevitable consequence of climate change, we consider that the Asian drying changes during this interval are primarily attributed to the rapid uplift of the Tibetan Plateau coupled with the global cooling (Fig. 8). Temperature and moisture proxy data from the five regions (Europe, high-latitude Asia, East Asian monsoon region, South Asian monsoon region, and Central Asia) suggests that the moisture evolution of central Asia was largely decoupled from adjacent regional trends during the mid-late Miocene, implying that the uplift of the Tibetan Plateau played an important role in the strengthening of aridification in central Asia (Miao et al., 2012). Climatic simulations show that the uplift of the northern Tibet would enhance the desertification of inland Asia and simultaneously strengthen the East Asian winter monsoon (Liu et al., 2015a; Tang et al., 2013). There is some evidence of a significant weaken of the East Asian summer monsoon from 14 to 11 Ma. But Chemical weathering data from ODP site 1146 and 1148 in South China Sea suggests that the summer monsoon was relatively constant and wet during 14-10 Ma (Clift et al., 2008, 2014). After 11 Ma, the further strengthening of East Asian winter monsoon was attributed to the Himalaya-Tibetan Plateau uplift and global cooling (e.g., An et al., 2001).

Although we try to establish the linkages between the uplift of the Tibetan Plateau and Asian climatic evolution, the effects between global cooling and the Tibetan Plateau uplift can still not be differentiated. Climate models did not take into account the detailed topography and other boundary conditions at each stage of the uplift (Tada et al., 2016). Additionally, there are still widely debates on paleoaltimetry of the Tibetan Plateau (Deng and Ding, 2015). Thus, more accurate evolution of the Tibetan Plateau uplift and the paleoclimatic variations in Asia should be reestablished in future.

4. Conclusion

The growth stages of the Tibetan Plateau and its margins during the Cenozoic had a series of potential effects on Asian climate. During the first stage (~55-35 Ma; Eocene), the central Tibet

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has obtained near-modern elevation accompanied by the significant uplift of the northern margins. The high elevation of south Tibet would increase rates of silicate weathering, thereby leading to the drawdown of atmospheric CO_2 and contributing to global cooling. Meanwhile, the progressive northward trend in uplift of the plateau probably forced the long-term westward withdrawal of the Paratethys Sea, which contributed to the onset of regional Asian desertification by decreasing moisture supply. The global cooling and sea retreat, coupled with the topographic barrier effect of the Tibetan Plateau, were major factors in the initial aridification of central Asia.

The second uplift stage during late Oligocene and early Miocene is characterized by relatively little tectonic activity in central Tibet, but by a further uplift of the plateau margins. The uplift of northern margin of Tibet during this interval led to the onset of East Asian winter monsoon as well as the intensive desertification of inland Asia. During the third stage, from 15 to 8 Ma, the plateau margins again underwent major uplift, thereby further strengthening the Asian winter monsoon and the desertification of the inland Asia.

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Figure captions

Fig 1. Major tectonic units of the Himalayan-Tibetan orogen and its movements constrained by global positioning system measurements. The global positioning system velocities in and around the Tibetan Plateau with respect to stable Eurasia are from Zhang et al. (2004). Abbreviations: IYS-Indus-Yarlung suture; JF: Jiali fault; BNS: Bangong-Nujiang suture; JS: Jinsha suture; XF:Xianshuihe fault; KLF: Karakomrum fault; KS: Karakash fault; KF: Kunlun fault; ALT: Altyn Tagh fault.

Fig 2. Topographic map of the Tibetan Plateau showing evidence of rejuvenation or initiation of tectonic activities at~65-35 Ma. The black circles represent some geographic locations mentioned in the article. The detailed information of tectonic activities at ~65-35 Ma is shown in table 1.

Fig 3. Temporal evolution of paleoclimatic proxies over the time period 26-20 Ma. (A) long-term variations of eccentricity (Laskar et al., 2004); (B) the reconstruction atmospheric CO_2 based on di-unsaturated alkenones (Pagani et al., 1999a, 1999b, 2005); (C) Benthic foraminiferal carbon isotope from ODP site 1218 in Pacific (Pälike et al., 2006); (D) Benthic foraminiferal oxygen isotope from ODP site 1218; (E) Sea-level estimates from the New Jersey and Delaware coastal plain coreholes (Kominz et al., 2008), with best estimates (black circles) and best with imaginary lowstands (green circles); (F) Carbonate content estimated by In (Ca/Fe) from ODP 1264 (black line) and 1265 (red line) in the subtropical southeastern Atlantic Ocean (Liebrand et al., 2016); (G) Weight percent (wt%) records of >150 μm size fractions from ODP 1264 in the subtropical southeastern Atlantic Ocean (Liebrand et al., 2016); (H) Benthic foraminiferal accumulation rates (blue curve) and benthic foraminiferal tests per gram sediment (pink curve) from ODP site 1090 in the southern Atlantic Ocean (Diester-Haass et al., 2011).

Fig 4. Topographic map of the Tibetan Plateau showing evidence of rejuvenation or initiation of tectonic activities at 30-20 Ma. The black circles represent some geographic locations mentioned in the article The detailed information of tectonic activities at 30-20 Ma is shown in table.2.

Fig 5. Temporal evolution of paleoclimatic proxies over the time period 16-8 Ma. (A) long-term variations of eccentricity (Laskar et al., 2004); (B) reconstruction of atmospheric CO_2 from di-unsaturated alkenones with uncertainty band (Pagani et al., 1999a, 1999b, 2005) (yellow circles) and boron isotope data with uncertainty band (Foster et al.,2012) (blue circles), and from B/Ca (Tripati et al., 2009); (C) and (D) Benthic foraminiferal oxygen and carbon isotope from ODP Site 1146 in South China Sea (Holbourn et al., 2007, 2013); (E) Sea-level estimates from the New Jersey and Delaware coastal plain coreholes (Kominz et al., 2008), with best estimates (red circles) and best with imaginary lowstands (blue circles); (F) Sea Surface Temperature (SST) estimated by Rousselle et al.(2013) from IODP site U1338 in the Eastern Equatorial Pacific; (G) Mass accumulation rates (MAR) of silicate sediments at ODP site 1146 (red boxes) (Wan et al., 2009) and ODP site 1148 (black circles) (Clift, 2006).

Fig 6. Temporal evolution of paleoclimatic proxies over the time period 16-8 Ma in Asia. (A) pollen grains of *Chenopodiaceae* from Sikouzi section in the east side of the Liupan Mountains (green) (Jiang and Ding, 2008) and from western Qaidam basin (pink) (Miao et al., 2013); (B) Pedogenic and lacustrine carbonates $\delta^{18}O$ from northeastern Qaidam basin (black circles) (Zhuang et al., 2011) and Xunhua basin in the northeastern Tibetan Plateau (red circles) (Hough et al., 2011); (C) illite/smectite ratios from IODP U1430 in Japan Sea (Shen et al., 2017); (D) carbonate contents from Qaidam basin (Song et al., 2014); (E) the CIA ($100\times Al_2O_3/(Al_2O_3+CaO+Na_2O+K2O)$) from ODP 1146 in the South China Sea (Wan et al., 2009); (F) Magnetic susceptibility from the Zhuanglang section in the western Loess Plateau (Qiang et al., 2011); (G) Mn/Ca ratios of a 3 point running average from IODP site U1466, U1468 and U1471 in Indian Ocean (Betzler et al., 2016); (F) total organic carbon (TOC wt%) values from ODP site 731A and 722B in the western Arabian Sea (Gupta et al., 2015).

Fig. 7. Topographic map of the Tibetan Plateau showing evidence of rejuvenation or initiation of tectonic activities during 15-8 Ma. The black circles represent some geographic locations mentioned in the article.The detailed information of tectonic activities during 15-8 Ma is shown in table.3.

Fig 8. Evolution of Asian climate and the Tibetan Plateau, and their relation with global changes during the Cenozoic. The data of benthic foraminiferal $\delta^{18}O$ and atmospheric CO_2 content is modified from Zachos et al. (2001) and Zachos et al. (2008), respectively.

Figure 1

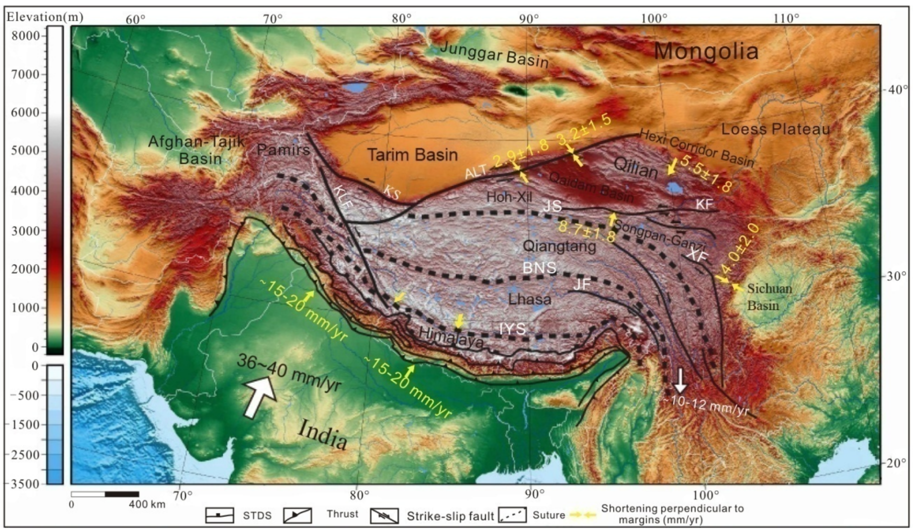

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Figure 2

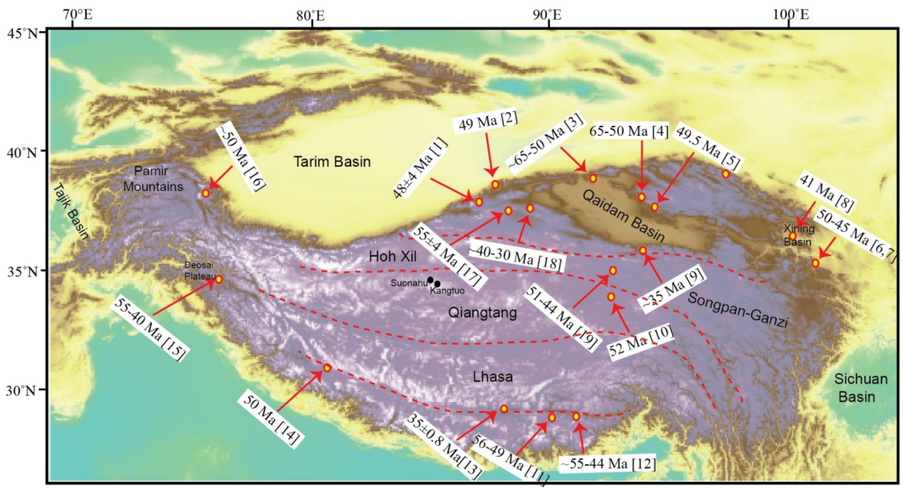

Figure 3

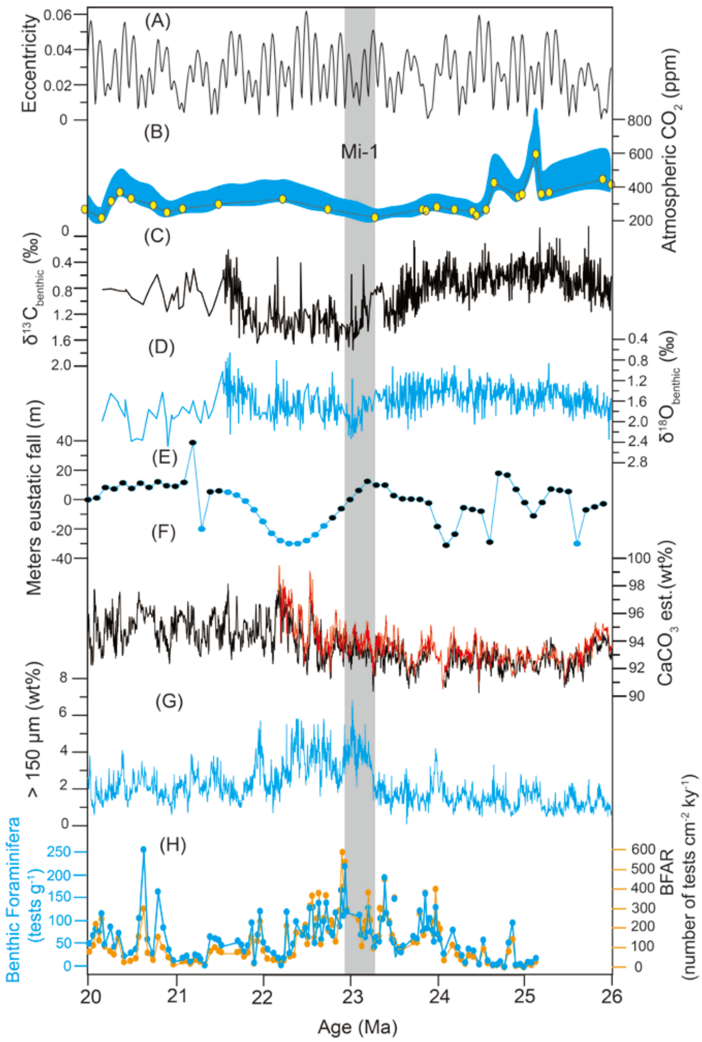
(A)
Eccentricity
0.06
0.04
0.02
0
(B)
Mi-1
Atmospheric CO2 (ppm)
800
600
400
200
(C)
δ13Cbenthic (‰)
0
0.4
0.8
1.2
1.6
2.0
(D)
δ18Obenthic (‰)
0.4
0.8
1.2
1.6
2.0
2.4
2.8
Meters eustatic fall (m)
40
20
0
-20
-40
(E)
(F)
CaCO3 est.(wt%)
100
98
96
94
92
90
(G)
> 150 µm (wt%)
8
6
4
2
0
(H)
Benthic Foraminifera (tests g-1)
250
200
150
100
50
0
BFAR (number of tests cm-2 ky-1)
600
500
400
300
200
100
0
20
21
22
23
24
25
26
Age (Ma)

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Figure 4

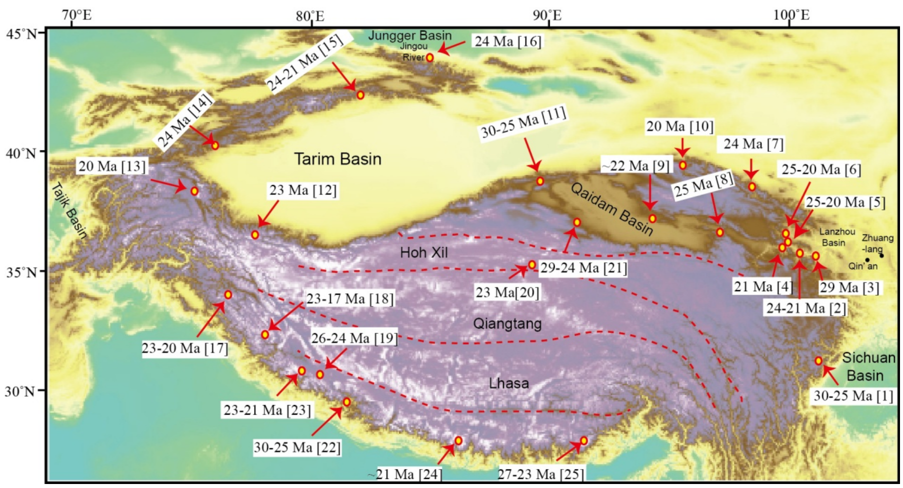

Figure 5

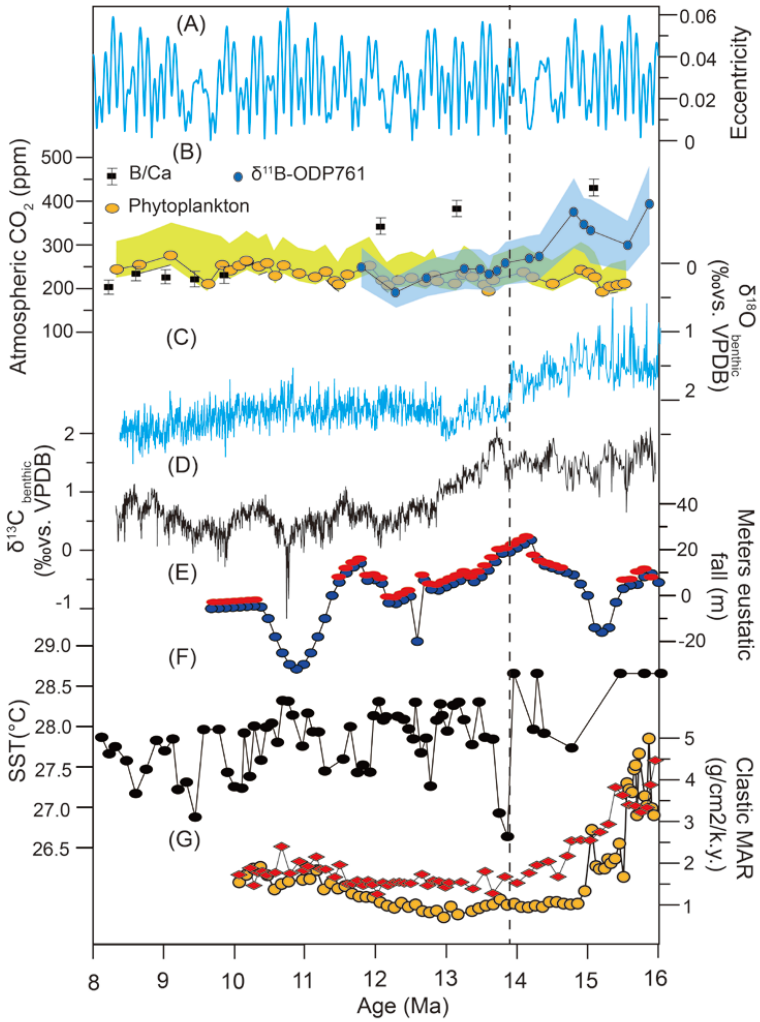
(A)
(B)
(C)
(D)
(E)
(F)
(G)
Eccentricity
0.06
0.04
0.02
0
B/Ca
δ11B-ODP761
Phytoplankton
Atmospheric CO2 (ppm)
500
400
300
200
100
δ18Obenthic (‰vs. VPDB)
0
1
2
δ13Cbenthic (‰vs. VPDB)
2
1
0
-1
Meters eustatic fall (m)
40
20
0
-20
SST(°C)
29.0
28.5
28.0
27.5
27.0
26.5
Clastic MAR (g/cm2/k.y.)
5
4
3
2
1
Age (Ma)
8
9
10
11
12
13
14
15
16

Figure 6

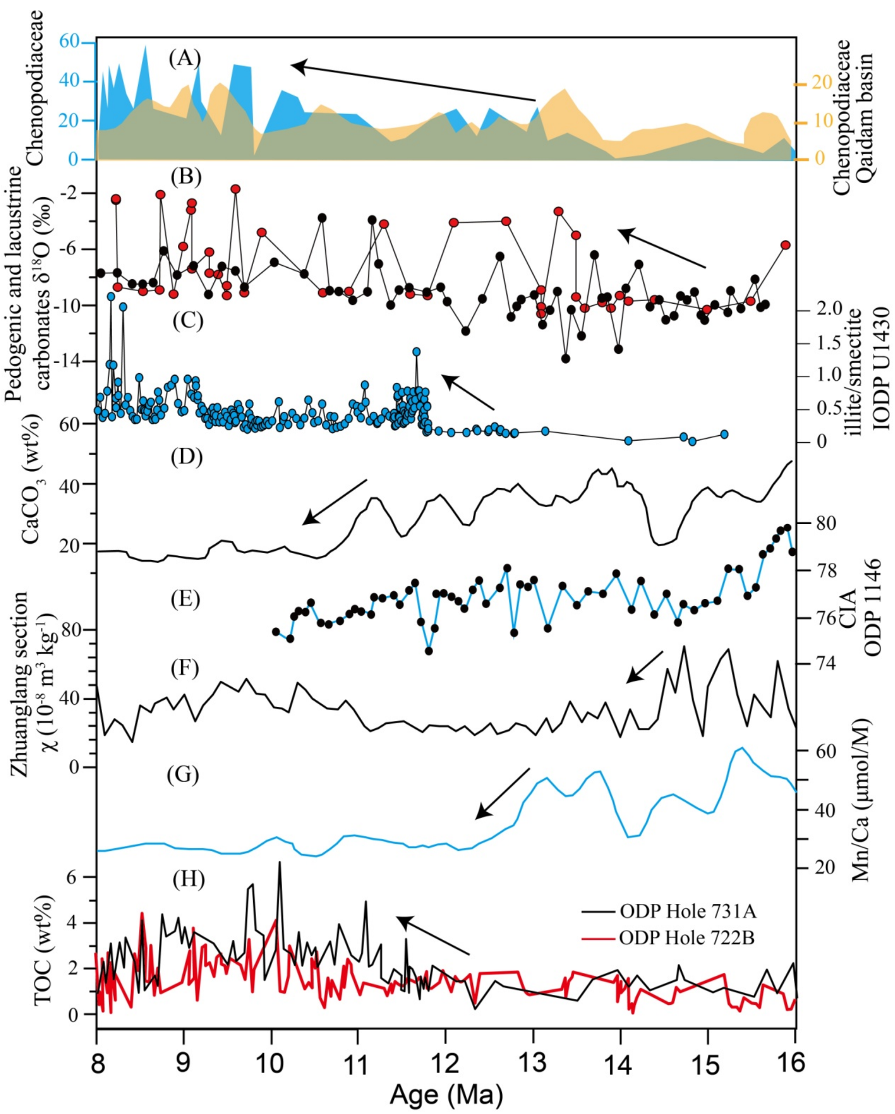
(A)
(B)
(C)
(D)
(E)
(F)
(G)
(H)
Chenopodiaceae
Chenopodiaceae Qaidam basin
Pedogenic and lacustrine carbonates δ18O (‰)
illite/smectite IODP U1430
CaCO3 (wt%)
CIA ODP 1146
Zhuanglang section χ (10-8 m3 kg-1)
Mn/Ca (μmol/M)
TOC (wt%)
ODP Hole 731A
ODP Hole 722B
Age (Ma)

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Figure 7

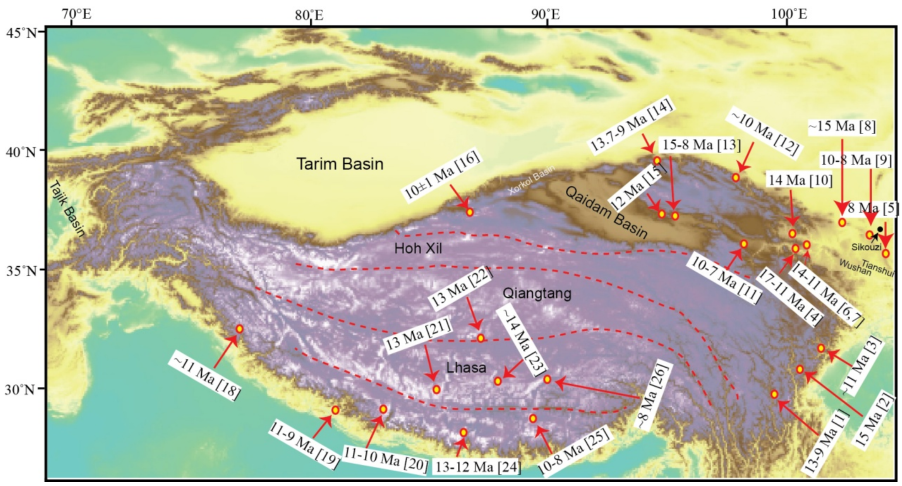

Figure 8

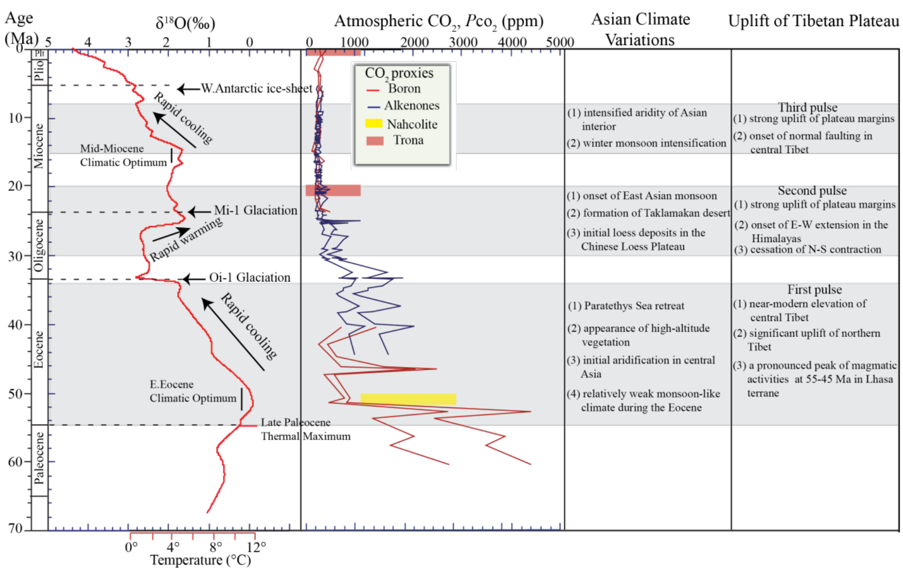

Table captions

Table 1. Detailed information of rejuvenation or initiation of tectonic activities at ~65-35 Ma in the Tibetan Plateau.

Table 2. Detailed information of rejuvenation or initiation of tectonic activities at 30-20 Ma in the Tibetan Plateau.

Table 3. Detailed information of rejuvenation or initiation of tectonic activities at 15-8 Ma in the Tibetan Plateau.

Table 1

Region/thrusts	Events and Ages	Methods	References	Marks
Altyn Tagh fault	Initial active (~49 Ma)	Apatite fission track (AFT)	Jolivet et al. (2001),Yin et al. (2002)	[1,2]
Altyn Tagh	Rapid uplift (65-50 Ma)	Zircon fission track and sedimentary	Wang et al. (2015)	[3]
Northern Qaidam basin	Initial contraction (65-50 Ma)	Seismic reflection and balanced cross section	Yin et al. (2008a)	[4]
Northern Qaidam basin	High accumulation rate (~49.5 Ma)	Sediments	Wei et al. (2013)	[5]
West Qinling thrust	Rapid cooling (50-45 Ma)	Apatite (U-Th)/He	Clark et al. (2010)	[6]
West Qinling thrust	Initial active (~50 Ma)	^{40}Ar-^{39}Ar	Duvall et al. (2011)	[7]
Xining basin	25ºof clockwise rotation (41 Ma)	Paleomagnetic data	Dupont-Nivet et al. (2008b)	[8]
Eastern Kunlun	Rapid cooling (~35 Ma)	Apatite (U-Th)/He	Clark et al. (2010)	[9]
Tanggula thrust	Initial active (~52 Ma)	Sediments and angular unconformities	Li et al. (2012)	[10]
Tethyan Himalaya thrust	Initial active (56-49 Ma)	^{40}Ar-^{39}Ar	Wiesmayr and Grasemann (2002)	[11]
Tethyan Himalayan	Significant crustal thickening(~55-44 Ma)	U-Pb, K-Ar and ^{40}Ar-^{39}Ar	Aikman et al. (2008)	[12]
Mabja Dome	Onset of mid-crustal extension (35±0.8 Ma)	U-Pb	Lee and Whitehouse (2007)	[13]
Northwestern Himalaya	Large-scale granite intrusion (~50 Ma)	U-Pb	Wang et al. (2012a)	[14]
Deosai plateau	Rapid cooling (55-40 Ma)	AFT, apatite and zircon (U-Th)/He	van der Beek et al. (2009)	[15]
Kashgar-Yecheng thrust	Initial motion (~50 Ma)	zircon and apatite fission track	Cao et al. (2013)	[16]
Kunlun fault	Rapid cooling (55±4 Ma)	AFT	Jolivet et al. (2001)	[17]
Qimen Tagh mountains	Initial uplift (~40-30 Ma)	AFT	Liu et al. (2015b)	[18]
Fenghuoshan fold-thrust belt	Initial deformation (51-44 Ma)	AFT, apatite (U-Th)/He, ^{40}Ar-^{39}Ar	Staisch et al. (2016)	[19]

Table 2

Region/thrust	Events and Ages	Method	Reference	Marks
Longmen Shan	Initial uplift (30-25 Ma)	AFT, apatite and zircon (U-Th)/He	Wang et al. (2012b)	[1]
Xunhua basin	High accumulation rates (24-21 Ma)	Magnetostratigraphy	Lease et al. (2012)	[2]
Linxia Basin	Rapid subsidence (29 Ma)	Magnetostratigraphy	Fang et al. (2003)	[3]
Guide Basin	Sedimentary discontinuity (21 Ma)	Structural geology and sedimentary	Liu et al. (2013)	[4]
Laji Shan	Rapid uplift (25-20 Ma)	Magnetostratigraphy and U-Pb	Lease et al. (2012)	[5]
Xining basin	Unstable accumulations (25-20 Ma)	Magnetostratigraphy	Xiao et al. (2012)	[6]
Northeast Qilian	Rapid cooling (24 Ma)	AFT	Pan et al. (2013)	[7]
Elashan	Rapid uplift (25 Ma)	Magnetostratigraphy and AFT	Lu et al. (2012)	[8]
North Qaidam basin	Fault reactivation(~22 Ma)	Constrained by the sedimentary	Lu and Xiong (2009)	[9]
North Qilian	Rapid exhumation (20 Ma)	AFT, vitrinite-reflectance analysis	George et al. (2001)	[10]
Altyn Tagh fault	Rapid exhumation (30-25 Ma)	AFT and sediments	Jolivet et al. (2001)	[11]
West Kunlun Shan	Rapid uplift (23 Ma)	Seismic reflection and drill-well data	Jiang et al. (2013)	[12]
Main Pamir thrust	Rapid cooling (20 Ma)	AFT	Sobel and Dumitru (1997)	[13]
Southwest Tian Shan	Rapid exhumation (24 Ma)	AFT	Sobel et al. (2006)	[14]
Southern Tian Shan	Initial uplift (24-21 Ma)	Sedimentary record and Magnetostratigraphy	Yin et al. (1998)	[15]
Northern Tian Shan	Initial unroofing (~24 Ma)	AFT	Hendrix et al. (1994)	[16]
Zanskar Shear Zone	Cooling ages of muscovites (23-20 Ma)	^{40}Ar-^{39}Ar	Walker et al. (1999)	[17]
Sutlej Rift	Exhumation of deep crustal rocks (23-17 Ma)	^{40}Ar-^{39}Ar	Vannay et al. (2004)	[18]
Kailas basin	Initial deposition (26-24 Ma)	Igneous zircon U-Pb age	DeCelles et al. (2011)	[19]
Hoh Xil basin	Sedimentary discontinuity (23 Ma)	Constrained by sedimentation	Wang et al. (2002)	[20]
Eastern Kunlun	Initial uplift (29-24 Ma)	Constrained by sedimentary of foreland basin	Yin et al. (2008b)	[21]
Ama Drime range	Partial melting (30-25 Ma)	(U-Th)/He, ^{40}Ar-^{39}Ar and U-Th/Pb	Kali et al. (2010)	[22]
Silving leucogranite	Rapid cooling (23-21 Ma)	U-Pb, AFT and ^{40}Ar-^{39}Ar	Searle et al. (1999)	[23]
Everest	Initial movement of MCT (~21 Ma)	U-Pb and ^{40}Ar-^{39}Ar	Viskupic et al. (2005)	[24]
Gangdese thrust	Initial motion (27-23 Ma)	^{40}Ar-^{39}Ar	Yin et al. (1994)	[25]

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Table 3

Region/thrust	Events and Ages	Method	Method	Marks
Southeastern Tibet	Rapid cooling (13-9 Ma)	AFT and apatite (U-Th)/He	Clark et al. (2005b)	[1]
Southwestern Longmen	Rapid exhumation (15 Ma)	AFT, apatite and zircon (U-Th)/He	Cook et al. (2013)	[2]
Central Longmen Shan	Rapid exhumation (~11 Ma)	^{40}Ar-^{39}Ar, apatite and zircon (U-Th)/He	Kirby et al. (2002)	[3]
Guide basin	Clockwise rotation (17-11 Ma)	Paleomagnetic data	Yan et al. (2006)	[4]
Liupan Shan	Rapid exhumation (~8 Ma)	AFT	Zheng et al. (2006)	[5]
Jishi Shan	Rapid uplift (14-11 Ma)	AFT, apatite (U-Th)/He and U-Pb	Lease et al. (2011,2012)	[6,7]
Central Haiyuan fault	Initial motion (~15 Ma)	AFT, apatite and zircon (U-Th)/He	Duvall et al. (2013)	[8]
Eastern Haiyuan fault	Initial motion (10-8 Ma)	AFT, apatite and zircon (U-Th)/He	Duvall et al. (2013)	[9]
Xining basin	Significant uplift (14 Ma)	Paleomagnetic age of river terraces	Lu et al. (2004)	[10]
Gonghe Nan Shan	Initial active (10-7 Ma)	Constrained by sediments of foreland basin	Craddock et al. (2011)	[11]
North Qilian Shan	Rapid cooling (~10 Ma)	Apatite (U-Th)/He	Zheng et al. (2010)	[12]
Eastern Qaidam basin	High accumulation rates (15-8 Ma)	Inferred from magnetostratigaphy	Fang et al. (2007)	[13]
Altyn Tagh	Rapid uplift (13.7-9 Ma)	Paleomagnetic age of molasse deposits	Sun et al. (2005)	[14]
Southern Qilian Shan	Rapid uplift (12 Ma)	Magnetostratigraphy	Lu and Xiong (2009)	[15]
Altyn Tagh fault	Rapid cooling (10±1 Ma)	AFT	Jolivet et al. (2001)	[16]
West Kunlun	Rapid uplift (12-8 Ma)	AFT	Wang et al. (2003)	[17]
Sutlej Valley	Peak metamorphism (~11 Ma)	U-Pb ages	Caddick et al. (2007)	[18]
Main Boundary thrust	Initial motion (11-9 Ma)	Inferred from sediments in Siwalik Group	Meigs et al. (1995)	[19]
Thakkola rift	Initial extension (11-10 Ma)	Magnetostratigraphy	Garzione et al. (2000)	[20]
Tangra Yumco rift	Initial extension (13-12 Ma)	Zircon and apatite (U-Th)/He	Dewane et al. (2006)	[21]
Shuanghu rift	Initial extension (13 Ma)	^{40}Ar-^{39}Ar	Blisniuk et al. (2001)	[22]
Xainza rift	Initial extension (~14 Ma)	U-Pb and apatite (U-Th)/He	Hager et al. (2009)	[23]
Kung Co rift	Initial extension (13-12 Ma)	Zircon and apatite (U-Th)/He	Lee et al. (2011)	[24]
Yadong-Gulu rift	Initial extension (10-8 Ma)	Constrained by monazite Th-Pb ages	Edwards and Harrison (1997)	[25]
Nyainqentanglha rift	Initial extension (~8 Ma)	^{40}Ar-^{39}Ar	Harrison et al. (1995)	[26]