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Neogene tectonics and climate forcing of carnivora dispersals between Asia and North America

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Abstract

Exchange records of terrestrial mammals can be combined with available tectonic and climatic documents to evaluate major biological and environmental events. Previous studies identified four carnivoran dispersals between Eurasia and North America in the Neogene, namely, at ~ 20, 13–11, 8–7, and ~ 4 Ma. In order to evaluate driving mechanism of these biological events, we collected, compared and analyzed a large number of published records. The results indicate that the carnivoran dispersal from Eurasia to North America at ~ 20 Ma was probably caused by intense tectonic movements in Asia. During 13–11 Ma, global cooling possibly drove the mammal exchanges between Eurasia and North America. By comparison, the carnivoran dispersal from Eurasia to North America at 8–7 Ma was probably caused by the combination of global cooling and tectonic movements of the Tibetan Plateau. Similar to during 13–11 Ma, the carnivoran exchanges between Eurasia and North America at ~ 4 Ma were possibly driven by global cooling.

1 Introduction

Widely distributed terrestrial mammals were highly mobile during the Cenozoic Era. They exchanged frequently between the mainland commonly corresponding to global and regional environmental changes, such as significant climate changes, major block reorganizations, and relevant biogeographic changes. Thus exchange records of terrestrial mammals can be combined with available tectonic and climatic documents to evaluate major biological and environmental events, especially about occurrence time and driving mechanism (e.g. Flynn and Swisher III, 1995; Eronen and Rook, 2004; Kohn and Fremd, 2008; Eronen et al., 2012). However, such study is usually limited by research advances of both aspects: major exchange events of mammals and remarkable environmental events.

SED
7, 2445–2479, 2015

A reliable reconstruction of faunal exchange history depends heavily on solid support from both the abundant fossil records and a stable classification. As migrants from Eurasia to America, Repenning (1967) listed 9 genera (*Simocyon, Indarctos, Agriotherium, Plionarctos, Lutravus, Eomelivora, Plesiogulo, Lutra,* and *Machairodus*) from the Hemphillian mammal faunas and 7 genera (*Lynx, Trigonictis, Canimartes, Enhydra, Enhydriodon, Ursus,* and *Chasmaporthetes*) from the Blancan mammal faunas. This is an early attempt though with some degree of uncertainty. Similar endeavors were made by Korotkevitch and Topachevskii (1986) and by Kurtén (1986). Later, Tedford et al. (1987) presented 38 North American Neogene carnivorans as exotic taxa and most of them were believed to have migrated from Eurasia. This contributed greatly in our understanding of Neogene mammal faunal exchange history. Furthermore, considerable progress has been made in the carnivoran fossil records and stable classification since Tedford et al.'s fundamental contribution (Tedford et al., 2004). Based on published fossil records, Qiu (2003) identified three major carnivoran dispersal waves of filter-bridge type between Eurasia and North America in the Neogene. The first occurred at ~ 20 Ma and the carnivorans migrating from Eurasia to North America included *Cynelos, Ysengrinia, Amphicyon, Cephalogale, Phoberocyon, Ursavus, Potamotherium*, and *Proailurus*. The second wave occurred at 7–8 Ma and the carnivorans migrating from Eurasia to North America included *Indarctos, Agriotherium, Simocyon, Eomellivora, Plesiogulo,* and *Machairodus*. The last wave took place at ~ 4 Ma and the Eurasian emigrants found in North America are *Ursus, Parailurus, Lynx (?), Felis (?), Homotherium,* and *Chasmaporthetes* (Tseng et al., 2013). In the meantime, *Megantereon* and *Pannonictis* migrated from North America to Eurasia. In addition, at about 13 Ma, *Leptarctus* migrated from North America to Eurasia while *Sansanosmilus* and *Plithocyon* migrated from Eurasia to North America (Qiu, 2003; Wang et al., 2003a). Given that Asia and Western North America became connected by land across the Bering Sea in the Mid-Cretaceous and the continents remained joined by the Bering land bridge until the Pliocene (Marincovich and Gladenkov, 1999; Sanmartin

SED
7, 2445–2479, 2015

et al., 2001), these migrating events provide a chance to untangle major environmental events and palaeogeographic changes during the Late Cenozoic.

Recently, a growing body of advance has been made on uplift of the Tibetan Plateau and palaeoenvironmental evolution in East Asia during the Late Cenozoic (e.g. Jiang et al., 2007, 2010; Zhang et al., 2010; Jiang and Ding, 2010). This makes it possible for us to compare and analyze land mammal exchange events and significant tectonic and climatic events with an aim to evaluate occurrence timing and driving mechanism of major biological and environmental events during the Late Cenozoic. Accordingly, in this study, we systematically collect tectonic and climate records occurring at ∼ 20, 13–11, 8–7 and ∼ 4 Ma in East Asia, and compare with major carnivoran exchange events between Eurasia and North America. This will help us to gain insight about driving mechanism behind major land mammal exchange and tectonic and climate evolution in East Asia during the Late Cenozoic.

2 Carnivoran dispersal from Eurasia to North America at ∼ 20 Ma probably caused by tectonic movements

Evidence for significant exhumation and deformation of the Himalaya–Tibetan Plateau is widespread during the 25–20 Ma (e.g. Harrison et al., 1992a; Zhang et al., 2010; Xiao et al., 2012). The onset of exhumation and deformation is also reported at 25–20 Ma in the Tianshan, Altyn Tagh, Western and Eastern Kunlun regions (e.g. Jolivet et al., 2001; Sobel et al., 2006). In order to determine the most significant tectonic event during the Mid-Tertiary, we review and analyze a number of studies on the tectonic movements in East Asia (Fig. 2 and Table 1).

Many studies focused on dating the onset of accelerated crustal melting, uplift, and deformation of the Himalaya and the southern Tibet, commonly centering on ∼ 20 Ma (e.g. Zeitler, 1985; Maluski et al., 1988; Hubbard and Harrison, 1989; Noble and Searle, 1995; Hodges et al., 1996; Copeland et al., 1996; Arita et al., 1997; Lee et al., 2000; Najman and Garzanti, 2000; White et al., 2001; Murphy et al., 2002; Tobgay et al., 2012). Sedimentary records on the basin flanks of the Himalaya and out into the Indian Ocean generally show a similar change around 20 Ma. About 69 % of the Himalayas south of the Indus–Yarlung suture zone, or about 6.7×10^6 km^3, have been denudated since ~ 20 Ma (Einsele et al., 1996). Records of isotopic ratio changes through time provide another window to observe the significant tectonic or environmental change in Asia around 20 Ma. The steepest rise in the strontium isotopic ratio (^{87}Sr/^{86}Sr) of seawater during the Cenozoic was from 20 to 14.4 Ma (Hodell et al., 1991; Richter et al., 1992; Hodell and Woodruff, 1994). Similarly, lithium isotopes in seawater (δ^7Li$_{SW}$) increased abruptly at ~ 20 Ma, then generally decreased from 20 to 15 Ma (Misra and Froelich, 2012). Hence, the Himalaya and southern Tibet was significantly uplifted and eroded at ~ 20 Ma. This conclusion is consistent with a marked slowdown in the convergence rate between India and Eurasia by more than 40 % since 20 Ma (Molnar and Stock, 2009).

Modeling of apatite fission track data from the Songpan–Ganzi Fold Belt suggests that exhumation accelerated ~ 20 Ma in East Tibet, consistent with the mid-Tertiary timing inferred for reactivation of the Wenchuan–Maoxian Fault from zircon fission track data (Arne et al., 1997). Moreover, ages on the Anning transect suggest an early initiation of rapid cooling (ca. 20 Ma, Clark et al., 2005). Thus significant tectonic movements occurred along the eastern margin of the Tibetan Plateau at ~ 20 Ma.

Along the northeastern margin of the Plateau, several basins also record significant tectonic changes around 20 Ma, such as the transitions of sedimentary facies in the Lanzhou and Qaidam Basins (Yue et al., 2001; Qiu et al., 2001; Lu and Xiong, 2009), the onset of widespread contractional deformation in the Gonghe Basin (Craddock et al., 2011; Lu et al., 2012), the initiated deposition of Xunhua Basin (Hough et al., 2011), and the transition to alluvial facies in the Hualong Basin (Lease et al., 2012). Similarly, basins and bounding mountain ranges on the northern margin of the Plateau also experienced increased deformation around 20 Ma, such as an unroofing event in the Western Kunlun range (Mock et al., 1999; Li et al., 2007, 2008). Thrusting in the southern Tianshan range probably initiated ~ 20 Ma (Huang et al., 2006). Even farther north, deformation is also recorded in the Junggar Basin around 20 Ma (Ji et al., 2008; Tang et al., 2011, 2012).

Together, these studies suggest that the most significant tectonic activities along the northern, the southern, and the eastern margins of the Plateau are temporally synchronous, perhaps as a regional delayed response to the Indo–Eurasian collision (Sun and Zheng, 1998; Zhang et al., 2010). In contrast, no obvious climate changes in East Asia are observed at ~ 20 Ma. For example, in the Kuche Basin of Xinjiang Province (Fig. 3a and b, Li et al., 2006; Huang et al., 2006) and the Qaidam basin of Qinghai Province (Fig. 3c–f, Lu and Xiong, 2009; Lu et al., 2014), Northwest China, most sedimentary proxies do not indicate a clear climate change at ~ 20 Ma, with the exception of an SUS increase of the sediments in the Kuche Basin (Fig. 3b), probably because of provenance change caused by tectonic activities on the Tian Shan at ~ 20 Ma (Huang et al., 2006). Widespread deformation in Central to East Asia was driven by the intense uplift of the Himalaya–Tibetan Plateau at ~ 20 Ma (Fig. 2 and Table 1). With such widespread deformation recorded, there also is a large impact on the faunal changes in Asia.

3 Mammal exchanges between Eurasia and North America during 13–11 Ma possibly driven by global cooling

At about 13 Ma, *Leptarctus* migrated from North America to Asia while *Sansanosmilus* migrated from Eurasia to North America (Fig. 1, Qiu, 2003). At 11.1 Ma (Garces et al., 1997) or 11.5 Ma (Sen, 1997), *Hipparion* migrated from North America to Eurasia. In the Linxia Basin, Gansu Province, Northwest China, the average δ^{18}O values of tooth enamel of rhinos shows a large positive shift during 13–11 Ma (Wang and Deng, 2005), well correlated with the substantial δ^{18}O enrichment at 12 Ma from lacustrine carbonates in the same basin (Dettman et al., 2003). The latter was believed to reflect a shift to more arid conditions and thus a major reorganization of atmospheric circulation patterns possibly caused by a significant uplift of the Tibetan Plateau. Such inference was then supported by several studies from the Dahonggou section (changes in sedimentation facies and SUS, Lu and Xiong, 2009), the Wulan section (changes in sedimentation facies and mean declination, Lu et al., 2012), and the Huaitoutala section (changes in the δ^{18}O of lacustrine carbonates, Zhuang et al., 2011) in the Qaidam Basin. That is to say, these regions in the northeast Tibetan Plateau experienced significant tectonic movements at ~ 12 Ma.

Nevertheless, it is noteworthy that the East Antarctic Ice Sheet expanded significantly since 14 Ma and initiated the Mid-Miocene Climate Transition (MMCT), probably causing a marked cooling in East Asia during 14–11 Ma (Fig. 4a, Jiang and Ding, 2008). This aroused a wide curiosity about whether the Tibetan uplift or the global cooling has been the first-order driver controlling stepwise drying in Asia (e.g. Jiang et al., 2008; Lu et al., 2010; Zhuang et al., 2011; Miao et al., 2012; Lu and Guo, 2014). In order to explore the evolution of climate through the MMCT, Jiang et al. (2007, 2008) analyzed multiple proxies from the 2900-m-thick fluviolacustrine sediment sequence at Sikouzi, Ningxia, China, such as pollen humidity index (Fig. 4a), redness (Fig. 4b), Lightness (Fig. 4c), Susceptibility (Fig. 4e), TIC, and TOC. The results indicate that the palaeoclimate in East Asia has got cooler and drier since 12–11 Ma. This climate change also left imprints in many other regions of the world, probably linked with the marked expansion of the East Antarctic Ice Sheet and resultant positive feedbacks of vegetation change and greenhouse gas fluctuations (Jiang et al., 2008). This inference is supported by a good correlation of the thick eolian silt sequences of Asian drying from the Early Miocene to Late Pleistocene with global cooling (Lu et al., 2010). Later, Zhuang et al. (2011) attributed the isotope-constrained intensified aridity in the Qaidam Basin at 12 Ma to retreat of Paratethys from central Asia, blocking moisture-bearing air masses by the elevated south-central Tibetan Plateau, and enhanced isolation and outward growth of the northern Tibetan Plateau. In these contexts, Miao et al. (2012) reviewed the climate records from five separate regions (Europe, high-latitude Asia, East Asia, South Asia, Central Asia) of Eurasia during 17–5 Ma and compared them with the global deep-sea oxygen isotope records. The results indicated that compiled moisture proxy data from

SED
7, 2445–2479, 2015

the four regions surrounding Central Asia co-varied and correlated with each other (Miao et al., 2012), supporting the inference that global cooling provided a dominant driving factor for the drying of Eurasia (Jiang et al., 2008; Lu et al., 2010; Lu and Guo, 2014). Accordingly, global cooling is believed to have been responsible for the mammal exchanges between North America and Eurasia during 13–11 Ma.

Noticeably, both the climate and tectonic records and the observed mammal fauna are relatively few in East Asia during the MMCT. With further investigations and more climatic and tectonic records published in the future, the timing interval of mammal exchange between North America and Eurasia during the MMCT would be narrower and clearer.

4 Carnivoran dispersal from Eurasia to North America at 8–7 Ma probably caused by the combination of global cooling and tectonic movements of the Tibetan Plateau

The pollen record from Guyuan, Ningxia, China, indicates that the East-Asian summer monsoon declined significantly from 14.25–11.35 Ma and kept weak since 11.35 Ma (Fig. 4a, Jiang and Ding, 2008). This is well consistent with marked development of herbs and shrubs in the vast region north to the Yangtze River of South China during the late Middle to Late Miocene as synthesized by Jiang and Ding (2009), probably correlated with evident global cooling caused by significant expansion of the East Antarctic Ice Sheet during the MMCT (e.g. Woodruff and Savin, 1989; Flower and Kenett, 1994; Ohta et al., 2003; Shevenell et al., 2004; Zachos et al., 2001, 2008). Following the MMCT, the climate evolution in East Asia during 11–8 Ma is pivotal to understanding the fauna exchange between North America and Eurasia at 8–7 Ma.

In Ningxia Province, the redness (a*) record of the Sikouzi fluviolacustrine sediments showed a slight decrease from 11 to 8 Ma (Fig. 4b), possibly reflecting a declining oxidation caused by global cooling (Jiang et al., 2007, 2008). Such a declining oxidation increased magnetic minerals in the sediments, which is mirrored as a continuous increase of SUS values from 11 to 8 Ma (Fig. 4e, Jiang et al., 2008). The Sikouzi lightness (L*) record during 11–8 Ma maintained higher values than previously (Fig. 4c), implying high contents of carbonate in sediments and thus a more arid environment (Jiang et al., 2008). Its slight decreasing trend from 11 to 8 Ma is possibly related to the evident increase in sedimentation rate during this period, especially during the late period (Jiang and Ding, 2008). Such inference is confirmed by an evident increase of SUS during this period (Fig. 4e). Furthermore, the pollen record from the Linxia Basin on the northeastern margin of the Tibetan Plateau indicates that, during 11–8 Ma, the conifers showed a steep decline while the herbs and shrubs increased significantly (Ma et al., 1998), implying a rapid drying environment. Similarly, the coniferous pollen in the Qaidam Basin decreased while the xerophytes increased during 11–8 Ma (Miao et al., 2011), indicating that drying in the Qaidam intensified during this period.

Therefore, it is clear that the climate evolution in East Asia during 11–8 Ma is characterized by slow cooling and gradual drying. This is well correlated with further enrichment of the integrated δ^{18}O of marine benthic foraminifera (Fig. 5a, Zachos et al., 2008) and the significant sea-level fall during this period (Fig. 5b, Haq et al., 1987). Such a global declining climate during 11–8 Ma probably resulted in stepwise enhancement of the East Asian winter monsoon (transporting relatively coarse dust particles) and of the westerlies (transporting relatively fine dust particles), providing important transporting agents and arid geographic locations for widespread dust accumulation in North China and even the western Pacific since ~ 8 Ma.

Previous studies indicate that the Tibetan Plateau experienced significant tectonic movements at ~ 8 Ma (e.g. Pan and Kidd, 1992; Harrison et al., 1995; Kirby et al., 2002; Fang et al., 2005; Zheng et al., 2006; Lease et al., 2011; Duvall et al., 2012). As shown in Table 2 and Fig. 6, we collected 18 records revealing that tectonic movements occurred at 17 sites in and around the Plateau from 8.5 to 7.5 Ma. They are mainly distributed in the eastern and northeastern Tibetan Plateau, reaching up to 11 sites. By comparison, only 4 sites of tectonic movements were observed in the Himalaya and southern Tibet. One location in the northern Plateau documented tectonic movement at this time. Accordingly, it is speculated that tectonic activities in the eastern and northeastern Plateau generated large quantities of dust materials since 8.5–7.5 Ma and provided adequate material sources for widespread dust accumulation in North China and even the western Pacific. This is probably responsible for the significant increase of eolian deposit from 4 sites during 14–7.5 Ma to 14 sites during 7.5–3.6 Ma in North China (Lu et al., 2010). Furthermore, at some sites, red clay overlies much older rock of a different type, such as Lingtai (7.05 Ma, Ding et al., 1998a, 1999), Xifeng (7.2 Ma, Sun et al., 1998), Jiaxian (8.35 Ma, Qiang et al., 2001), and Chaona (8.1 Ma, Song et al., 2007). Almost at the same time, both sedimentation rate and mean grain-size of sediments increased clearly in North China (e.g. Lu et al., 2004, 2007; Guo et al., 2002; Qiao et al., 2006).

Therefore, significant environmental events characterized by widespread dust accumulation occurred at 7–8 Ma in North China and the western Pacific (e.g. Ding et al., 1998b; Rea et al., 1998; Sun et al., 1998; Pettke et al., 2000; Guo et al., 2001; Qiang et al., 2001). Such events are responsible for the carnivoran dispersal from Eurasia to North America at 8–7 Ma, probably driven by a combination of continuous global cooling and tectonic movements of the eastern and northeastern Tibetan Plateau.

5 Carnivoran exchanges between Eurasia and North America at ~ 4 Ma possibly driven by global cooling

Previous studies indicate that climate was relatively warm and wet during the Early Pliocene and declined during the Late Pliocene, especially in East China (e.g. Yu and Huang, 1993; Ding et al., 2001; Guo et al., 2004; Wu et al., 2006; Jiang and Ding, 2009; Xiong et al., 2010). This arouses a wide interest in the beginning of climate recession during the Late Pliocene. The grain-size record of the Sikouzi section at Guyuan, Ningxia, China suggests that Md (median grain size) ranged from 1.6 to 47.1 µm with a low mean value of 10.9 µm during 7.0–4.2 Ma but oscillated with large amplitudes from 2.2 to 401.2 µm (average 31.0 µm) during 4.2–0.07 Ma (Fig. 4d, Jiang and Ding, 2010). Similarly, the Sikouzi SUS curve oscillated slightly (2.6–22.4, mean 12.7) during 7.0–4.2 Ma. Since 4.2 Ma, the amplitudes increased abruptly (1.0–31.6, mean 14.0) with a distinct increase from 4.2 to 3.0 Ma, probably reflecting enhancement of magnetite concentration in sediments influenced by temperature decline and aridity increase (Fig. 4e, Jiang et al., 2008). The Sikouzi L* value was generally less than 61.6 (52.8–65.7, mean 59.8) during 7.0–4.2 Ma and higher than 61.6 (56.7–67.6, mean 62.4) during 4.2–0.07 Ma, possibly indicating an increase in carbonate content and thus growing aridity of the sedimentation environment (Fig. 4c, Jiang et al., 2008). The Sikouzi redness (a*) was generally high (8.1–12.9, mean 10.5) during 7.0–4.2 Ma and decreased distinctly (8.0–13.2, mean 10.1) during 4.2–0.07 Ma, possibly implying a stepwise decrease in temperature influencing the oxidation of iron-bearing minerals in arid to semi-arid regions (Fig. 4b, Jiang et al., 2007, 2008). These records and their inferred climate changes have similar responses for the Lingtai section (Ding et al., 1998a, 2001; Sun et al., 1998), the Xifeng section (Guo et al., 2001, 2004; Wu et al., 2006), the Chaona section (Bai et al., 2009), and the Baishui section (Xiong et al., 2002, 2003, 2010) in the Chinese Loess Plateau (CLP).

What's more, the climate change at ~ 4 Ma also left imprints in the low-latitude South China Sea (SCS) and the high-latitude Lake Baikal. The L* of sediments at ODP Site 1148 in the northern SCS was high (41.2–58.0, mean 50.3) during 7.0–4.0 Ma and declined distinctly (54.8–35.2, mean 44.5) since 4.0 Ma, suggesting a decrease in carbonate content, increase in terrigenous sediments and a lowering of sea level controlled by global cooling (Hay et al., 1988; Tian et al., 2008). This inference is supported by the benthic $\delta^{18}O$ record of the same core (Tian et al., 2008) and the grain-size record at ODP Site 1146 (Wan et al., 2007). Similarly, oscillating amplitude of the grain-size record of core BDP98 (600 m) from Academician ridge (53°44′40″ N, 108°24′30″ E) in central Lake Baikal was much smaller during 7.0–4.0 Ma and increased afterwards, especially after 2.75 Ma (Kashiwaya et al., 2001, 2003). This climate recession since ~ 4 Ma in the Northern Hemisphere agrees well with the stepwise enrichment of the integrated global $\delta^{18}O$ record of marine benthic foraminifera since ~ 4 Ma (Fig. 5a,

SED
7, 2445–2479, 2015

Lisiecki and Raymo, 2005; Zachos et al., 2008), and is also correlated with strengthened periodicity of sea-level fluctuations since ~ 4 Ma (Fig. 5b, Haq et al., 1987).

In general, the above data suggest that Late Cenozoic global climate probably entered a new state at ~ 4 Ma. The factor responsible for this significant climate change deserves further investigation. The change in depositional facies and increase in sedimentation rate of the Yecheng section in the western Kunlun Mountains reflects the main uplift of the northwestern Tibetan Plateau ca. 4.5–3.5 Ma (Zheng et al., 2000, 2006). Nevertheless, more studies indicate that the Tibetan uplift subsequent to ca. 3.6 Ma was intense, such as the upper reaches of the Yellow River (Li et al., 1996, 1997), the Linxia Basin (Fang et al., 2005), the Guide Basin (Pares et al., 2003), the Guyuan Basin (Jiang et al., 2007; Jiang and Ding, 2010), and the Sanmenxia Basin (Wang et al., 2002). Regional unconformities at ~ 4 Ma are observed in the Great Plains and western United States (Hanneman et al., 2003; Hanneman and Wideman, 2006). However, all of these apparently could not explain the increases in sedimentation rates as well as in grain sizes of sediments at 4–2 Ma in a variety of settings around the globe (Zhang et al., 2001). Increase in erosion rates caused by global cooling is a major feature of environmental changes in various regions around the globe at ~ 4 Ma (Zhang et al., 2001; Jiang et al., 2010). Recent climate modeling results suggest that the progressive closure of the Central American Seaway (CAS) initiated strengthening of Atlantic meridional overturning circulation (AMOC) between 4.8 and 4.0 Ma, leading to both warming of the Northern Hemisphere (NH) and cooling of the Southern Hemisphere (SH) (Steph et al., 2010). Cooling of the SH would induce a marked development of the Antarctic Ice Sheets at ~ 4 Ma, pushing the Intertropical Convergence Zone northward. This was superimposed on warming of the NH and brought more precipitation to the middle latitudes of the NH, resulting in increases in coarse-grained sediments in the Guyuan Basin since 4.2 Ma. On the other hand, development of the Antarctic Ice Sheets would induce global cooling and enhancement of physical weathering, initiating increases in sedimentation rates as well as increases in grain size from Lake Bikal to the CLP to the SCS (Jiang et al., 2010). Therefore, the closure of the CAS

SED
7, 2445–2479, 2015

during 4.8–4.0 Ma and its influence on ocean circulation was possibly the major forcing factor for global cooling since ∼ 4 Ma, which should be responsible for carnivoran exchanges between Eurasia and North America at ∼ 4 Ma.

6 Conclusions

Previous studies identified four carnivoran dispersals between Eurasia and North America in the Neogene, namely, at ∼ 20, 13–11, 8–7, and ∼ 4 Ma. In order to evaluate driving mechanism of these biological events, we collected, compared and analyzed a large number of published records. The results indicate that the carnivoran dispersal from Eurasia to North America at ∼ 20 Ma was probably caused by intense tectonic movements in Asia. During 13–11 Ma, global cooling possibly drove the mammal exchanges between Eurasia and North America. By comparison, the carnivoran dispersal from Eurasia to North America at 8–7 Ma was probably caused by the combination of global cooling and tectonic movements of the Tibetan Plateau. Similar to during 13–11 Ma, the carnivoran exchanges between Eurasia and North America at ∼ 4 Ma were possibly driven by global cooling.

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Carnivora dispersals between Asia and North America

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Table 1. Locations of 20 sites with significant tectonic and/or environmental events around ~ 20 Ma.

No.	Site	Location	Elevation (m)	Duration (Ma)	Inferred environment change or tectonic movement	Evidence
1	Zanskar, India, western Himalaya (Noble and Searle, 1995)	33°25′ N,76°35′ E (Zanskar); 34°05′ N,76°15′ E (Shafat)		21–19.5	Crustal melting occurred at 21–19.5 Ma and anatexis occurred along the Himalaya at least from Kashmir–Zanskar to eastern Nepal at 24–19.5 Ma.	U-Pb age data
2	Ailao Shan/Red River metamorphic belt (Harrison et al., 1992b)	25°20′–23°20′ N, 100°30′–102° E		~ 20	Left-lateral, strike-slip ductile deformationhad ceased by ~ 20 Ma	40Ar/39Ar age spectrum analyses
3	Red River Fault (Harrison et al., 1992a)	22°40′–26°40′ N, 99°30′–103° E		25–20	Left-lateral, strike-slip ductile deformation appears to have ceased by ~ 20 Ma	$^{40}Ar/^{39}Ar$, K-Ar
4	Xianshuihe fault (Xu et al., 1992, 2007)	30°0′–30°24′ N, 100°40.8′–101°58′ E	2500–3169	Mio-Pleistocene	Onset of displacement at ~ 20 Ma	Nearly synchronous early Miocene initiation of cooling/denudation phase evidenced by zircon and apatite fission track ages
5	Anning River fault (Clark et al., 2005)	29°16.6′–27°53.9′ N, 102°17′–102°13.3′ E	1600–3000	~ 20	an early initiation of rapid cooling	thermochronological analysis from deep river gorges that are cut into the relict landscape
6	Songpan–Ganzi Fold Belt (Arne et al., 1997)	31°37′–32°38′ N, 100–103°36′ E		~ 20	Exhumation accelerated	apatite fission track data
7	Linxia Basin (Ma et al., 1998; Fang et al., 2003; Dettman et al., 2003; Garzione et al., 2004)	35°10′–35°51′ N, 102°30′–104° E	2000–2400	30.6–5.0	cooling and onset of variation between open and closed lake conditions at ~ 20 Ma	significant increase in coniferous pollen and high frequency alternation between negative and positive values of $\delta^{18}O$ and $\delta^{13}C$ since ~ 20 Ma
8	Zhuanglang section, Gansu Province (Zhang et al., 2011)	35°13.56′ N, 106°4.18′ E	1405–2857	20–0	The sizable deserts must have existed in the interior of Asia by ~ 20 Ma and maintained from that time to present.	tracing of C4 ecosystem back to as early as ~ 20 Ma
9	Qin'an-III (Hao and Guo, 2007)	35°01′ N, 105°48′ E	~ 1880	21.4–11.4	Onset of loess accumulation at ~ 19.6 Ma	the portion older than 19.6 Ma being partially water-reworked
10	Yongdeng section, Lanzhou Basin (Yue et al., 2001; Qiu et al., 2001)	36°23′ N, 103°30′ E	~ 1800	51.0–16.5	Influenced by the uplift of the Tibetan Plateau at ~ 20 Ma	Onset of white thick sandstone deposition since ~ 20 Ma
11	Sikouzi, Ningxia (Jiang et al., 2007, 2008; Jiang and Ding, 2010)	36°16′ N, 105°59′ E	1550	20–0	Initial sedimentation at ca. 20 Ma	parallel unconformity; from brick-red fluvial sandstones to dark brownish fluvio-lacustrine fine sediments
12	Dahonggou section, Qaidam basin (Lu and Xiong, 2009)	37°24.38′ N, 95°13.82′ E	3140	34–8.5	Rejuvenation of nearby fold and thrust belts at 21–20 Ma	Conglomerate deposits; from lacustrine to alternations of lake, overbank and alluvial fan deposits at 21–20 Ma
13	Gonghe Basin, north-eastern TP (Craddock et al., 2011; Lu et al., 2012)	35.69–35.77° N, 100.23–100.43° E	2839–3130	20.0–8.0	Initial sedimentation at ca. 20 Ma as a significant depocenter	angular unconformity; from fluvio-lacustrine to fluvial-floodplain
14	Xunhua Basin in Qinghai Province (Hough et al., 2011)	35°50.4′ N, 102°27.6′ E	~ 2300	20.3–3.5	Significant tectonic movement at ~ 20.3 Ma	The deposition of the Xunhua Basin initiated at ~ 20.3 Ma with a set of dark red coarse-grained sandstones lying unconformably over Cretaceous sandstones and conglomerates in the east and on Proterozoic granodiorites in the west.

Table 1. Continued.

No.	Site	Location	Elevation (m)	Duration (Ma)	Inferred environment change or tectonic movement	Evidence
15	Hualong Basin in the Qinghai Province (Lease et al., 2012)	36°6.6′ N, 102°18′ E	~ 2850	30–9.3	Significant tectonic movement at ~ 20 Ma	a transition to alluvial facies at 20 Ma that was coincident with intensified erosion of basement source terranes in the Laji–Jishi Shan by 19 Ma
16	Xiejia Formation in the eastern Qinghai Province (Wang and Deng, 2009)	36°31.73′ N, 101°50.98′ E	2388	23.03–20.43	a cooling climate	the gymnospermous pollen, especially Picea, increased significantly upwards
17	Tashan, Xiejia and Shuiwan sections in the Xining Basin (Xiao et al., 2012)	36.5–36.65° N, 101.8–101.9° E	~ 2400	19.7–25.3	a significant change in provenance during this peculiar period	unstable accumulation and a marked permanent increase in magnetite content of the sediments
18	Xishuigou section, Danghe area, Subei (Gilder et al., 2001; Wang et al., 2003b)	39°27′–30′ N, 94°37′–46′ E	2500–3000	20–9.3	Onset of fine sediments at 20 Ma	angular unconformity; cut off by the ramp fault F0
19	Kuche Depression of the Tarim Basin (Huang et al., 2006)	42°0′–10′ N, 83°5′–20′ E	1500–3000	31–5.5	Initiation of thrusting in the south of the Tianshan at ~ 20 Ma	Marked increase of Km at ~ 20 Ma suggesting influx of magnetite-rich detritus.
20	Jingouhe section, Xinjiang (Ji et al., 2008; Tang et al., 2012)	44°10.94′ N, 85°27.18′ E	1000–1500	30.5–4.6	Significant uplift of the Tianshan at 23.3–20.0 Ma	Increased strain evidenced by more tightly grouped Kmax directions and Kmin largely distributed within a clear N–S girdle.

SED
7, 2445–2479, 2015
Carnivora dispersals between Asia and North America
H. Jiang et al.

SED
7, 2445–2479, 2015

Carnivora dispersals between Asia and North America

H. Jiang et al.

Table 2. Locations of 18 sites with significant tectonic and/or environmental events at 8.5–7.5 Ma.

No.	Sites	Lat.	Long.	Age (Ma)	Age control	Evidence	References
1	Altun shan	39	89	~ 15–0	NAFT, (U-Th)/He	coarse conglomerate, mean surface uplift rate of nearly 100 m/Ma	Ritts et al. (2008)
2	Eastern Tibet	32	97	11–4	(U-Th)/He	erosion rates increase by an order of magnitude	Duvall et al. (2012)
3	Qilian Shan	39	99.5	~ 10–0	(U-Th)/He	vertical and horizontal fault slip rates of ~ 0.5 mm yr^{-1} and ~ 1 mm/yr	Zheng et al. (2010)
4	Chaka	38.6	101	11–3.8	Mag.	paleocurrent, conglomerate provenance, lithostratigraphic character of the basin fill	Zhang et al. (2012)
5	Guide	36.1	102	8–1.8	Mag.	increases in accumulation rates, gravel content and sizes of its components, changes of bedding dips and source rock types, and marginal growth faults	Fang et al. (2005)
6	Laji Shan	36.3	103	8	U/Pb Zircon	differential rock uplift and progressive erosion that began ca. 8 Ma in the Laji Shan	Lease et al. (2007)
7	Linxia	34.5	103	8–5.4	AFT	granite conglomerate, the dip angle decreases progressively since 7 Ma	Zheng et al. (2003)
8	Jishi Shan	32	103	13–0	AFT, (U-Th)/He	AFT data are clustered and yield intervals of accelerated cooling, and significant change in thrust-fault orientation	Lease et al. (2011)
9	Longmen Shan	31.5	104	11–5, 5–3	^{40}Ar-^{39}Ar, (U-Th)/He	the erosional response reflected by rapid cooling to the deformation of the Tibetan Plateau margin	Kirby et al. (2002)
10	Longmen Shan	31.3	104	10–0	FT, (U-Th)/He	rapid exhumation estimated from composite age-elevation transect	Wang et al. (2012)
11	Longmen Shan	31.3	104	11–8	(U-Th)/He	high exhumation inferred from modelings	Godard et al. (2009)
12	Sikouzi	36.2	106	10.5–8, 3.4–0.07	Mag.	increase in sedimentation rate and coarse conglomerate sedimentation	Jiang et al. (2007), Jiang and Ding (2008)
13	Liupan Shan	35.7	106	7.3–8.2	AFT	a rapid cooling event revealed by AFT ages	Zheng et al. (2006)
14	Sutlej	31.5	78	10–6	$^{206}Pb^*/^{238}U$	phase-equilibria constraints, mineral structures and compositions, and in-situ monazite geochronology	Caddick et al. (2007)
15	Langtang	28	85.5	10–7	^{40}Ar-^{39}Ar	accelerating cooling and enhanced exhumation rates revealed by a new ^{40}Ar-^{39}Ar age-elevation transect	Wobus et al. (2008)
16	Yarlung Zangbo	29.3	89	~ 11–8	(U-Th)/He	Rapid exhumation revealed by age–elevation relationships and multisystem thermochronometers, was probably caused by Yarlung Zangbo rapid incision, north–south normal faulting, or both.	Dai et al. (2013)
17	Nyainqentanghla	30	90.5	11–5	^{40}Ar-^{39}Ar	metamorphosed granitic rocks involved, developed triangular facet geomorphology, a major low-angle ductile shearing deformation	Pan and Kidd (1992)
18	Nyainqentanghla	30	90.5	8–3	^{40}Ar-^{39}Ar	The form of the isotopically derived thermal histories are similar to general form predicted by the thermal model, implying that the significant movement proceeded at ~ 3 mm/yr	Harrison et al. (1995)

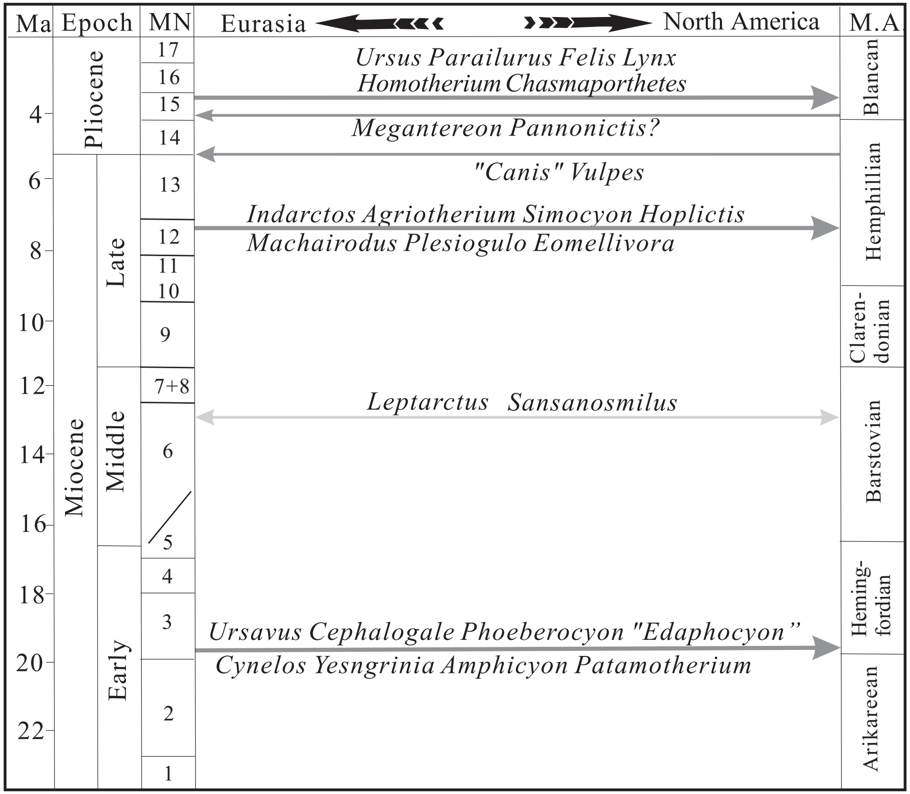

Figure 1. Migration events of Neogene carnivorans between Eurasia and North America, adapted from Qiu (2003).

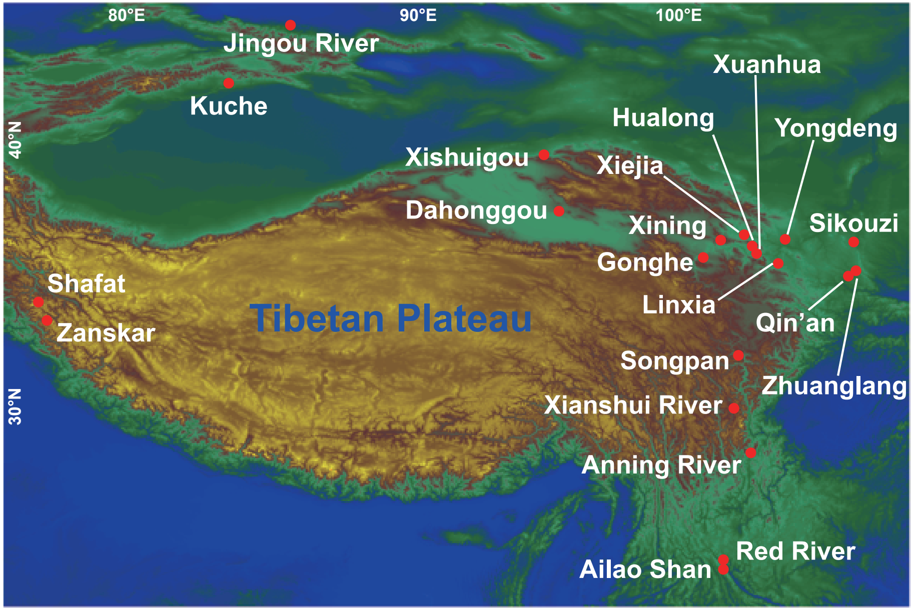

Figure 2. Distribution of 20 Early Miocene sites within and around the Himalaya–Tibetan Plateau discussed in this study, detailed information referring to Table 1 and text.

SED
7, 2445–2479, 2015

Carnivora dispersals between Asia and North America

H. Jiang et al.

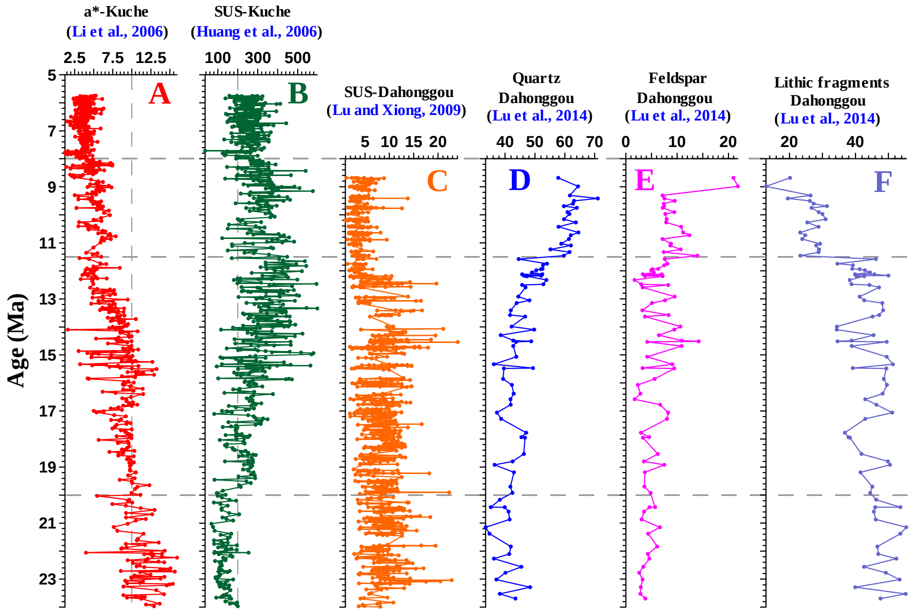

Figure 3. Comparison of **(a)** a* (Li et al., 2006) and **(b)** SUS of the Kuche Basin in Xinjiang Province (Huang et al., 2006) with **(c)** SUS (Lu and Xiong, 2009), **(d)** quartz content (Lu et al., 2014), **(e)** feldspar content (Lu et al., 2014), and **(f)** lithic fragments (Lu et al., 2014) of the Qaidam Basin in Qinghai Province, Northwest China.

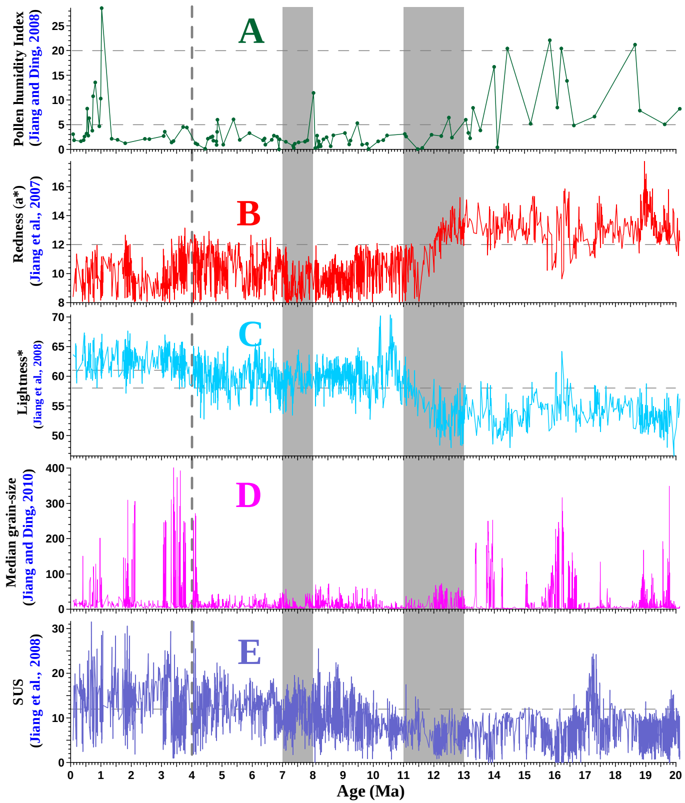

Figure 4. Comparison of **(a)** pollen humidity index (Jiang and Ding, 2008), **(b)** redness (a*, Jiang et al., 2007), **(c)** lightness (L*, Jiang et al., 2008), **(d)** median grain-size (Md, Jiang and Ding, 2010), and **(e)** susceptibility (SUS, Jiang et al., 2008) from the Sikouzi section at Guyuan, Ningxia Province, China.

SED
7, 2445–2479, 2015

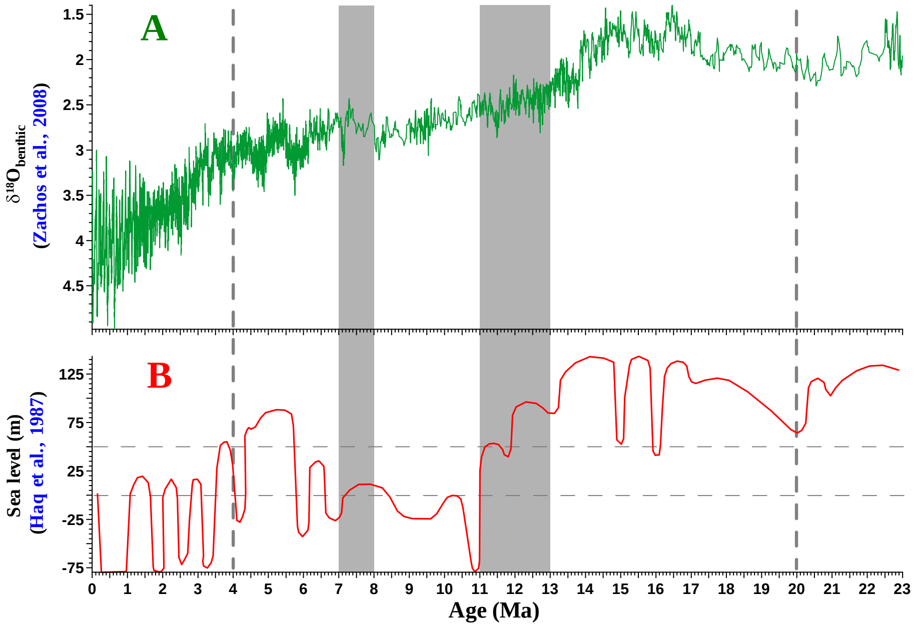

Figure 5. Correlation of **(a)** the composite oxygen isotope curve from Zachos et al. (2008) and **(b)** the Neogene sea-level record from Haq et al. (1987).

SED
7, 2445–2479, 2015

Carnivora dispersals between Asia and North America

H. Jiang et al.

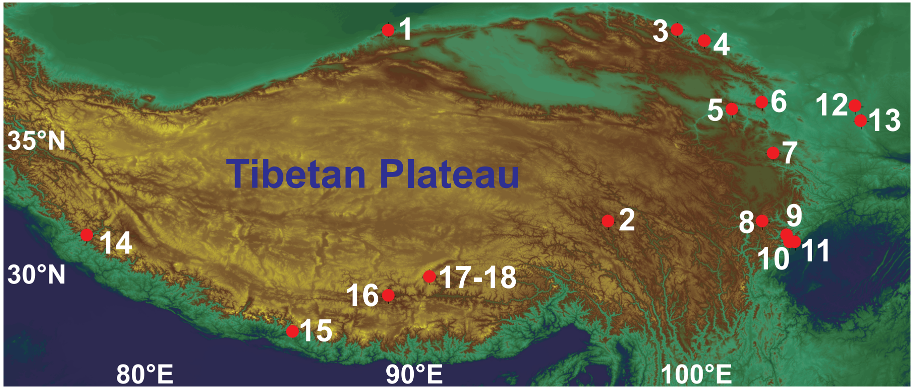

Figure 6. Distribution of 18 sites within and around the Himalaya–Tibetan Plateau revealing significant tectonic movements at 8.5–7.5 Ma, detailed information referring to Table 2 and text.

SED
7, 2445–2479, 2015

Carnivora dispersals between Asia and North America

H. Jiang et al.