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

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Received: 18 July 2015 – Accepted: 12 August 2015 – Published: 27 August 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.
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.
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, Lutras, 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, Pota-motherium*, and *Proailurus*. The second wave occurred at 7–8 Ma and the carnivorans migrating from Eurasia to North America included *Indarctos, Agriotherium, Simocyon, Eomelivora, Plesiogulo*, and *Machairodus*. The last wave took place at ∼4 Ma and the Eurasian emigrants found in North America are *Ursus, Paraillurus, 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
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.,
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 $6.7 \times 10^6$ km$^3$, have been denuded since $\sim 20$ 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 ($^{87}\text{Sr}/^{86}\text{Sr}$) 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 ($\delta^7\text{Li}_{SW}$) increased abruptly at $\sim 20$ 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 $\sim 20$ 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 $\sim 20$ 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 $\sim 20$ 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 $\sim 20$ 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 δ¹⁸O values of tooth enamel of rhinos shows a large positive shift during 13–11 Ma (Wang and Deng, 2005), well correlated with the substantial δ¹⁸O 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 $\delta^{18}O$ 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 $\sim 12$ 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
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 in-
crease of SUS values from 11 to 8 Ma (Fig. 4e, Jiang et al., 2008). The Sikouzi light-
ness (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 char-
acterized by slow cooling and gradual drying. This is well correlated with further en-
richment of the integrated $\delta^{18}$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 enhance-
ment 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 $\sim$ 8 Ma.

Previous studies indicate that the Tibetan Plateau experienced significant tectonic
movements at $\sim$ 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 move-
ment 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
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 δ¹⁸O 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 δ¹⁸O record of marine benthic foraminifera since ∼4 Ma (Fig. 5a,
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 Yeicheng 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
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.

Acknowledgements. This work was financially supported by the National Natural Science Foundation of China (Grants 40972117) and the State Key Laboratory of Earthquake Dynamics (LED2013A03).

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

<table>
<thead>
<tr>
<th>No.</th>
<th>Site</th>
<th>Location</th>
<th>Elevation (m)</th>
<th>Duration (Ma)</th>
<th>Inferred environment change or tectonic movement</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zanskar, India, western Himalaya (Noble and Searle, 1995)</td>
<td>33°25'N, 76°35'E (Zanskar); 34°05'N, 76°15'E (Shalaf)</td>
<td>21–19.5</td>
<td>Crustal melting occurred at 21–19.5 Ma and anatexivs occurred along the Himalaya at least from Kashmir–Zanskar to eastern Nepal at 24–19.5 Ma.</td>
<td>U-Pb age data</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Ailao Shan/Red River metamorphic belt (Harri-son et al., 1992b)</td>
<td>25°20’–23°20’ N, 100°30’–102° E</td>
<td>∼ 20</td>
<td>Left-lateral, strike-slip ductile deformation ceased by ∼ 20 Ma.</td>
<td>40Ar/39Ar age spectrums</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Red River Fault (Harrison et al., 1992a)</td>
<td>30°00’–30°24’ N, 100°40.8’–101°58’ E</td>
<td>25–20</td>
<td>Left-lateral, strike-slip ductile deformation appears to have ceased by ∼ 20 Ma.</td>
<td>40Ar/39Ar, K-Ar</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Xianshuihe fault (Xu et al., 1992, 2007)</td>
<td>29°16.6’–27°53.9' N, 102°17’–102°13.3’ E</td>
<td>2500–3169</td>
<td>Mio-Pleistocene</td>
<td>Onset of displacement at ∼ 20 MaNearby fold and thrust belts at 21–20 Ma</td>
<td>Exhumation accelerated on early initiation of rapid cooling</td>
</tr>
<tr>
<td>5</td>
<td>Anning River fault (Clark et al., 2005)</td>
<td>106°4.18’ E</td>
<td>1405–2857</td>
<td>20–0</td>
<td>The sizable deserts must have existed in the interior of Asia by ∼ 20 Ma and maintained from that time to present.</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Songpan–Ganzi Fold Belt (Arne et al., 1997)</td>
<td>31°37’–32°38’ N, 100–103°36’ E</td>
<td>∼ 20</td>
<td>Cooling and onset of variation between open and closed lake conditions at ∼ 20 Ma.</td>
<td>Exhumation accelerated and began cooling that had reached 20 Ma</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Linxia Basin (Ma et al., 1998; Fang et al., 2003; Dettman et al., 2003; Garzione et al., 2004)</td>
<td>35°10’–35°51’ N, 102°30’–104° E</td>
<td>2000–2400</td>
<td>30.6–5.0</td>
<td>Cooling and onset of variation between open and closed lake conditions at ∼ 20 Ma.</td>
<td>Significant increase in coniferous pollen and high frequency alternation between negative and positive values of δ18O and δ13C since ∼ 20 Ma</td>
</tr>
<tr>
<td>8</td>
<td>Zhuanglang section, Gansu Province (Zhang et al., 2011)</td>
<td>35°13.56’ N, 106°4.18’ E</td>
<td>1405–2857</td>
<td>20–0</td>
<td>The sizable deserts must have existed in the interior of Asia by ∼ 20 Ma and maintained from that time to present.</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Qin’an-III (Hao and Guo, 2007)</td>
<td>35°01’ N, 105°48’ E</td>
<td>∼ 1880</td>
<td>21.4–11.4</td>
<td>Onset of loess accumulation at ∼ 19.6 Ma</td>
<td>the portion older than 19.6 Ma being partially water-rewooded</td>
</tr>
<tr>
<td>10</td>
<td>Yongdeng section, Lanzhou Basin (Yue et al., 2001; Qiu et al., 2001)</td>
<td>36°23’ N, 103°30’ E</td>
<td>∼ 1800</td>
<td>51.0–16.5</td>
<td>Influenced by the uplift of the Tibetan Plateau at ∼ 20 Ma</td>
<td>Onset of white thick sandstone deposition since ∼ 20 Ma</td>
</tr>
<tr>
<td>11</td>
<td>Sikouzi, Ningxia (Jiang et al., 2007, 2008; Jiang and Ding, 2010)</td>
<td>36°16’ N, 105°59’ E</td>
<td>1550</td>
<td>20–0</td>
<td>Initial sedimentation at ca. 20 Ma</td>
<td>Parallel unconformity; from brick-red fluvial sandstones to dark brownish fluvio-lacustrine fine sediments</td>
</tr>
<tr>
<td>12</td>
<td>Dahonggou section, Qaidam basin (Lu and Xiong, 2009)</td>
<td>37°24.38’ N, 95°13.82’ E</td>
<td>3140</td>
<td>34–8.5</td>
<td>Rejuvenation of nearby fold and thrust belts at 21–20 Ma</td>
<td>Conglomerate deposits; from lacustrine to alternations of lake, overbank and alluvial fan deposits at 21–20 Ma</td>
</tr>
<tr>
<td>13</td>
<td>Gonghe Basin, north-eastern TP (Craddock et al., 2011; Lu et al., 2012)</td>
<td>35°69–35°77’ N, 100°23–100°43’ E</td>
<td>2839–3130</td>
<td>20.0–8.0</td>
<td>Initial sedimentation at ca. 20 Ma as a significant depocenter</td>
<td>Initial sedimentation at ca. 20 Ma as a significant depocenter</td>
</tr>
<tr>
<td>14</td>
<td>Xunhua Basin in Qinghai Province (Hough et al., 2011)</td>
<td>35°50.4’ N, 102°27.6’ E</td>
<td>∼ 2300</td>
<td>20.3–3.5</td>
<td>Significant tectonic movement at ∼ 20.3 Ma</td>
<td>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.</td>
</tr>
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Table 1. Continued.

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<tr>
<th>No.</th>
<th>Site Description</th>
<th>Location</th>
<th>Elevation (m)</th>
<th>Duration (Ma)</th>
<th>Inferred environment change or tectonic movement</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Hualong Basin in the Qinghai Province (Lease et al., 2012)</td>
<td>36°56.6′N, 102°18′E</td>
<td>~2850</td>
<td>30–9.3</td>
<td>Significant tectonic movement at ~20 Ma</td>
<td>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.</td>
</tr>
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<td>16</td>
<td>Xiejia Formation in the eastern Qinghai Province (Wang and Deng, 2009)</td>
<td>36°31.73′N, 101°50.98′E</td>
<td>2388</td>
<td>23.03–20.43</td>
<td>a cooling climate</td>
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<tr>
<td>17</td>
<td>Tashan, Xiejia and Shuiwan sections in the Xinjiang Basin (Xiao et al., 2012)</td>
<td>36.5°–36.65°N, 101.8°–101.9°E</td>
<td>~2400</td>
<td>19.7–25.3</td>
<td>a significant change in provenance during this peculiar period</td>
<td>Unstable accumulation and a marked permanent increase in magnetite content of the sediments</td>
</tr>
<tr>
<td>18</td>
<td>Xishuigou section, Danjue area, Subei (Gilder et al., 2001; Wang et al., 2003b)</td>
<td>39°27′–30′N, 94°3′–46′E</td>
<td>2500–3000</td>
<td>20–9.3</td>
<td>Onset of fine sediments at 20 Ma</td>
<td>Angular unconformity; cut off by the ramp fault F0</td>
</tr>
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<td>19</td>
<td>Kuche Depression of the Tarim Basin (Huang et al., 2006)</td>
<td>42°0′–10′N, 83°5′–20′E</td>
<td>1500–3000</td>
<td>31–5.5</td>
<td>Initiation of thrusting in the south of the Tianshan at ~20 Ma</td>
<td>Marked increase of Km at ~20 Ma suggesting influx of magnetite-rich detritus.</td>
</tr>
<tr>
<td>20</td>
<td>Jingouhe section, Xinjiang (Ji et al., 2008; Tang et al., 2012)</td>
<td>44°10.94′N, 85°27.18′E</td>
<td>1000–1500</td>
<td>30.5–4.6</td>
<td>Significant uplift of the Tianzhan at 23.3–20.0 Ma</td>
<td>Increased strain evidenced by more tightly grouped Kmax directions and Kmin largely distributed within a clear N–S girdle.</td>
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</table>
### Table 2. Locations of 18 sites with significant tectonic and/or environmental events at 8.5–7.5 Ma.

<table>
<thead>
<tr>
<th>No.</th>
<th>Sites</th>
<th>Lat.</th>
<th>Long.</th>
<th>Age (Ma)</th>
<th>Age control</th>
<th>Evidence</th>
<th>References</th>
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<td>1</td>
<td>Altun shan</td>
<td>39</td>
<td>89</td>
<td>~15–0</td>
<td>NAFT, (U-Th)/He</td>
<td>coarse conglomerate, mean surface uplift rate of nearly 100 m/Ma</td>
<td>Ritts et al. (2008)</td>
</tr>
<tr>
<td>2</td>
<td>Eastern Tibet</td>
<td>32</td>
<td>97</td>
<td>11–4</td>
<td>(U-Th)/He</td>
<td>erosion rates increase by an order of magnitude</td>
<td>Duvall et al. (2012)</td>
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<tr>
<td>3</td>
<td>Qilian Shan</td>
<td>39</td>
<td>99.5</td>
<td>~10–0</td>
<td>(U-Th)/He</td>
<td>vertical and horizontal fault slip rates of ~0.5 mm/yr⁻¹ and ~1 mm/yr</td>
<td>Zheng et al. (2010)</td>
</tr>
<tr>
<td>4</td>
<td>Chaka</td>
<td>38.6</td>
<td>101</td>
<td>11–3.8</td>
<td>Mag.</td>
<td>paleocurrent, conglomerate provenance, lithostratigraphic character of the basin fill increases in accumulation rates, gravel content and sizes of its components, changes of bedding dips and source rock types, and marginal growth faults</td>
<td>Zhang et al. (2012)</td>
</tr>
<tr>
<td>5</td>
<td>Guide</td>
<td>36.1</td>
<td>102</td>
<td>8–1.8</td>
<td>Mag.</td>
<td>differential rock uplift and progressive erosion that began ca. 8 Ma in the Laji Shan granite conglomerate, the dip angle decreases progressively since 7 Ma</td>
<td>Fang et al. (2005)</td>
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<td>6</td>
<td>Laji Shan</td>
<td>36.3</td>
<td>103</td>
<td>8</td>
<td>U/Pb Zircon</td>
<td>AFT data are clustered and yield intervals of accelerated cooling, and significant change in thrust-fault orientation</td>
<td>Lease et al. (2007)</td>
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<td>7</td>
<td>Linxia</td>
<td>34.5</td>
<td>103</td>
<td>8–5.4</td>
<td>AFT</td>
<td>AFT data are clustered and yield intervals of accelerated cooling, and significant change in thrust-fault orientation</td>
<td>Lease et al. (2011)</td>
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<td>8</td>
<td>Jishi Shan</td>
<td>32</td>
<td>103</td>
<td>13–0</td>
<td>AFT, (U-Th)/He</td>
<td>the erosional response reflected by rapid cooling to the deformation of the Tibetan Plateau margin rapid exhumation estimated from composite age-elevation transect</td>
<td>Kirby et al. (2002)</td>
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<td>9</td>
<td>Longmen Shan</td>
<td>31.5</td>
<td>104</td>
<td>11–5, 5–3</td>
<td>⁴⁰Ar–³⁹Ar, (U-Th)/He</td>
<td>high exhumation inferred from modelings increase in sedimentation rate and coarse conglomerate sedimentation</td>
<td>Godard et al. (2009)</td>
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<tr>
<td>10</td>
<td>Longmen Shan</td>
<td>31.3</td>
<td>104</td>
<td>10–0</td>
<td>FT, (U-Th)/He</td>
<td>AFT, (U-Th)/He</td>
<td>a rapid cooling event revealed by AFT ages</td>
</tr>
<tr>
<td>11</td>
<td>Longmen Shan</td>
<td>31.3</td>
<td>104</td>
<td>11–8</td>
<td>(U-Th)/He</td>
<td>AFT, (U-Th)/He</td>
<td>a rapid cooling event revealed by AFT ages</td>
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<td>12</td>
<td>Sikouzi</td>
<td>36.2</td>
<td>106</td>
<td>10.5–8, 3.4–0.07</td>
<td>(U-Th)/He</td>
<td>high exhumation inferred from modelings increase in sedimentation rate and coarse conglomerate sedimentation</td>
<td>Godard et al. (2009)</td>
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<td>Liupan Shan</td>
<td>35.7</td>
<td>106</td>
<td>7.3–8.2</td>
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<td>AFT data are clustered and yield intervals of accelerated cooling, and significant change in thrust-fault orientation</td>
<td>Lease et al. (2011)</td>
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<td>14</td>
<td>Sutlej</td>
<td>31.5</td>
<td>78</td>
<td>10–6</td>
<td>²⁶⁰Pb/²³⁸U</td>
<td>phase-equilibria constraints, mineral structures and compositions, and in-situ monazite geochronology</td>
<td>Caddick et al. (2007)</td>
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<td>Langtang</td>
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<td>85.5</td>
<td>10–7</td>
<td>⁴⁰Ar–³⁹Ar</td>
<td>a rapid cooling event revealed by AFT ages</td>
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<tr>
<td>16</td>
<td>Yarlung Zangbo</td>
<td>29.3</td>
<td>89</td>
<td>~11–8</td>
<td>(U-Th)/He</td>
<td>accelerating cooling and enhanced exhumation rates revealed by a new ⁴⁰Ar–³⁹Ar age-elevation transect Rapid exhumation revealed by age–elevation relationships and multisystem thermochronometers, was probably caused by Yarlung Zangbo rapid incision, north–south normal faulting, or both.</td>
<td>Wobus et al. (2008)</td>
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<td>Nyainqentanghla</td>
<td>30</td>
<td>90.5</td>
<td>11–5</td>
<td>⁴⁰Ar–³⁹Ar</td>
<td>metamorphosed granitic rocks involved, developed triangular facet geomorphology, a major low-angle ductile shearing deformation</td>
<td>Pan and Kidd (1992)</td>
</tr>
<tr>
<td>18</td>
<td>Nyainqentanghla</td>
<td>30</td>
<td>90.5</td>
<td>8–3</td>
<td>⁴⁰Ar–³⁹Ar</td>
<td>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</td>
<td>Harrison et al. (1995)</td>
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<tr>
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<td>North America</td>
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<td>Hemphillian</td>
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</table>

**Figure 1.** Migration events of Neogene carnivores 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.
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.
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).
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.