Evolution of Chinese mammalian faunal regions and elevation of the Qinghai-Xizang (Tibet) Plateau

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Abstract On the basis of mammal's high evolutionary rates and sensitivity to environment, this paper deals with the evolutionary history of the Chinese Cenozoic mammals and environmental changes, and explores the relationship between the uplift of the Qinghai-Xizang Plateau and the evolution of zoogeographic provinces of China, through studying fossil mammal and the lithological characters of fossil-bearing beds. Evolutionary tendency and distribution of the mammals demonstrate that the uplift of the Qinghai-Xizang region, onset of the Asian monsoon and differentiation of the mammalian distribution probably initiated in Oligocene. The elevation of the Plateau seems to be a gradual and relatively stable process, and the uplift not only has resulted in significant environmental changes in Asia, but also caused distinct regional differentiation of mammals in China since the middle Miocene, and as a consequence the modern zoogeographic provinces gradually took shape.

Keywords: Qinghai-Xizang (Tibet) Plateau, Cenozoic, zoogeographic provinces, mammals.

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Mammals multiplied rapidly with the coming of Cenozoic era. They took the dominant position occupied by reptiles during the Mesozoic and became a superior group of vertebrates during the Cenozoic.

Fossil mammals are useful for subdivision and dating of Cenozoic terrestrial deposits, by virtue of their high evolutionary rates and high probability for being fossilized. The widespread Chinese Cenozoic sediments, mainly pertaining to continental facies, contain abundant remains of mammals. The study of mammalian fossils, as an objective of Cenozoic biostratigraphy in China, has a history of more than a century. Up to now, more than 1500 taxa of fossil mammals have been recovered from the Chinese Cenozoic deposits. Large quantities of data in the systematics and evolutionary studies of mammals have been accumulated, and a preliminary framework of the Chinese Cenozoic biochrons based on fossil mammals has been established[1−9].

Investigations of fossils indicate that the taxonomic composition and faunal properties of the Chinese mammals in different regions are different in different ages, especially since the Miocene, and that distributions of the mammals are closely related to their environment[10,11]. Such a correspondence between zoogeographic distribution and environmental condition is also reflected among extant Chinese mammals that are adapted to particular ecological niches: those preferring warm and wet environments are generally distributed in the south and southwest, where the climate is affected by the summer monsoon and relatively low elevation; arid or subarid climate prevails, influenced

by the winter monsoon in the Mongolia-Xinjiang upland, where mammals are adapted to the dry environment; the Qinghai-Xizang Plateau is not suitable for most mammals and only a small number of mammals adapted to rigorous climate because of the high elevation, thin air, and low temperature. China occupies different climatic zones and is influenced by the monsoons in varying degrees, and shows distinct latitudinal ecological variation in the distribution of mammals. Distribution of extant land vertebrates indicates two distinct zoogeographic provinces in China. Roughly, a line of Huaihe River, Qinling Mt. and Hengduan Mt. separates the Palearctic Province in the north, where mammals live in frigid- to temperate climates, from the Oriental Province in the south, where mammals live in tropical or subtropical zones[12]. The questions then arise: when were the modern mammalian provinces initiated, how did they evolve from the Paleocene to the present, and what were the factors that affected the development of the provinces? These are questions that concern people interested in the mammalian evolution, the changes of paleoenvironment and paleozoogeographical provinces, which form the subject of discussion in this paper.

The importance of paleozoogeographic divisions is increasingly appreciated in Chinese geoscientific circles. A well-established theory on the initiation and development of the Chinese zoogeographic provinces has not yet been fully formed. Nevertheless, close relationships between mammalian distributions and their environments, as well as dynamic environmental changes as important controlling factors in the turnover of faunas, are well recognized by Chiese scientists. During the Cenozoic, east Asia was affected by global climate changes, Himalayan tectonic movements, and elevation of the Qinghai-Xizang Plateau[13,14]. These events would have profound impact on mammal distribution and evolution of mammalian zoogeographic provinces, which must have been recorded by the fossils. Mammal remains, therefore, can serve as a tool of paleoenvironmental and paleozoogeographic reconstructions.

Scientists both from China and abroad have made many investigations in various methods and approaches on the elevation of the Qinghai-Xizang Plateau and the environmental changes resulting from its uplift, and acquired numerous important evidence and valuable data[15−17]. The intention of this paper is, through the mammalian fossil records, to explore the history of the environmental changes in the Cenozoic and the elevation of the Qinghai-Xizang Plateau, and to detect the effects of the uplift of the Plateau on the formation and evolution of the Chinese zoogeographic provinces. At present, it is difficult to trace the Chinese Cenozoic biological history in detail, nor is it easy to define precisely the limits of paleozoogeographic provinces, because of the bias of fossil accumulation and the small or absent fossil records in some areas of the country. An attempt is made to analyze and inquire into these matters preliminarily based on existing data.

1 Cenozoic mammalian faunas, distribution, and paleoenvironment

Mammals made their appearances, evolved and became extinct with the passage of time. There were different mammal faunas and paleogeographic patterns in different geological time. Thus, exploration of the evolutionary history of the Chinese Cenozoic mammals and reconstruction of the paleoenvironments and paleozoogeographic provinces are made through the discoveries of mammalian faunas in different geological ages, combined with lithological characters of the fossil bearing-beds.

Figure 1 shows the distribution of Chinese mammal fossil localities, the contours of zoogeographic provinces and the geomorphic outlook in different epoch of Cenozoic. Table 1 presents the Chinese representative mammalian taxa listed by family and epoch.

1.1 Paleocene

The known localities attributed to the Paleocene are mainly concentrated in the central and southern parts of China, and are scattered in Nei Mongol (Inner Mongolia) (Fig. 1(a)). All Paleocene mammalian fossil-bearing beds are of red terrestrial deposits, resting directly on the Cretaceous system.

Most mammals recovered are extinct orders, usu-

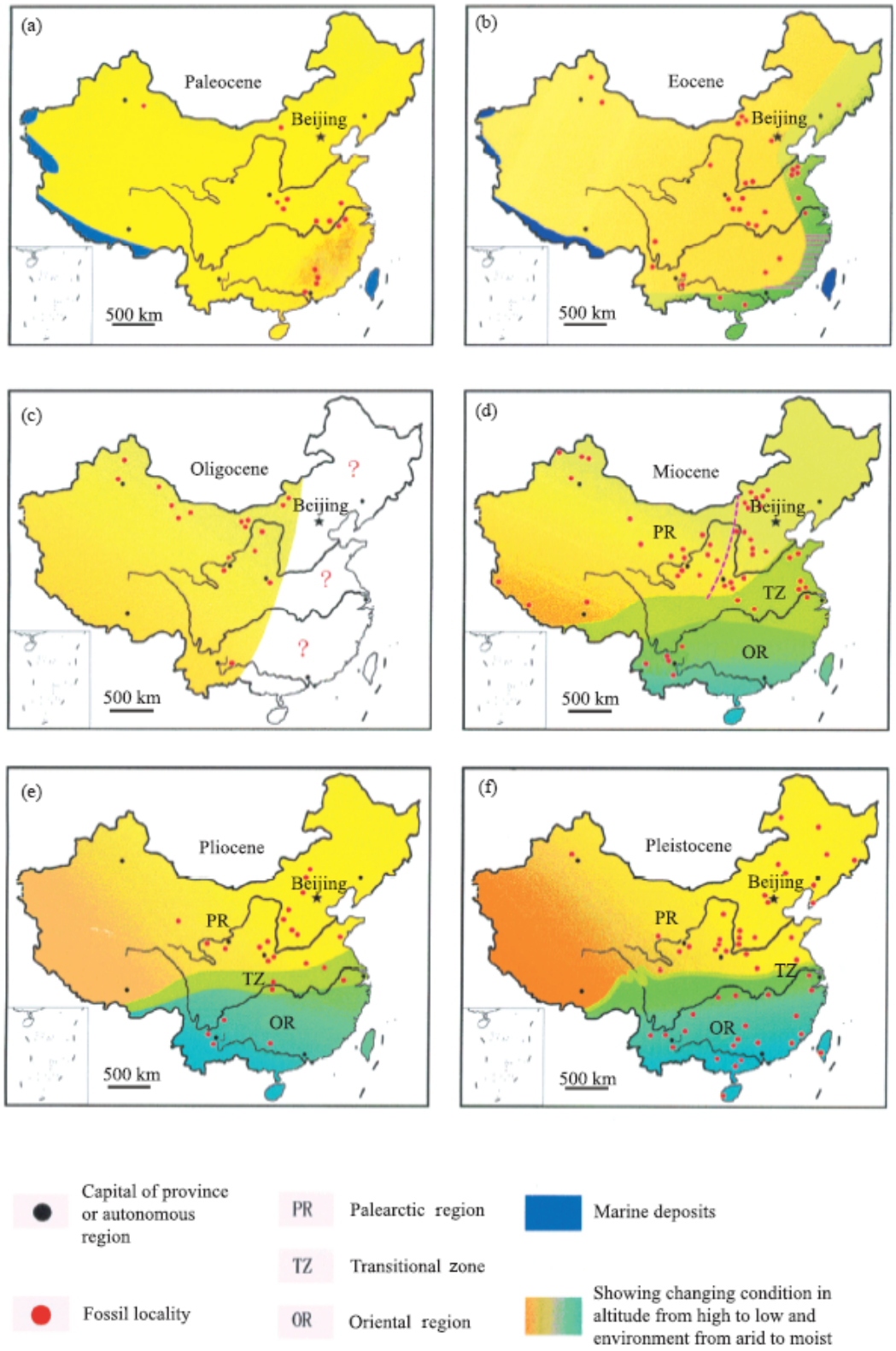

Fig. 1. Maps showing Cenozoic localities, contours of paleozoogeographic provinces and geomorphic outlook in different ages of China.

ally of small body size with primitive characters, including Multituberculata, Pantodonta, Dinocerata, Tillodonta, Condylarthra, Creodonta and Glires, etc. These archaic mammals, from a period of 56—65 million years ago, can be referred to more than 10 families, such as Bemalambdidae, Anagalidae, Viverravidae, Astigalidae, Pseudictopidae, etc., and are commonly known in the early Paleocene. In the late Paleocene, Bemalambdidae, the well known family in the early Paleocene became extinct and were replaced by more advanced families such as Phenacolophidae, Arctostylopidae, Prodinoceratidae, Eurymylidae, and Mimotonidae. All Paleocene faunas found in the central and southern China are quite consistent in composition at the family and genus level. Minor differences can be seen in the faunas from the Mongol-Xinjiang areas. For example, Taeniolabididae, belonging to the order Multituberculata is present in Nei Mongol, but is not known in the central and southern parts of China, and the genera of dinoceratids and coryphodontids from Xinjiang differs from those of other places.

All the families and the overwhelming majority of the orders in the Paleocene faunas became extinct, and therefore, it is impossible to make confident inferences about the environments in which these mammals lived, and difficult at this moment to make any ecological reconstruction based on their skeletons. Nevertheless, judging from the natures of deposits, the Paleocene sedimentations are often continuations of Cretaceous interior basin depositions, in a hot and arid climate. The basically consistent compositions of faunas may be indicative of a unified zoogeographic region during the Paleocene. The consistency of mammals in distribution might imply that the Paleocene environmental patterns in most of the areas, especially in the vast central and southern China were dominated by the east-westerly planetary wind system[18]. During the Paleocene, Taiwan was still under the water, the southern Xizang was a corner of the Tethys and the southwestern Tarim was a bay of Turgai[19]. Topographically, China was thought to be tilted from east the to the west, opposite to the present day[13], but this can neither be confirmed nor denied by mammals, because of the nearly complete absence of fossil remains in the west. However, similarities in faunal compositions from Xinjiang and the intermountain basins of Nanling, Qinling and Dabie Mt. seem to indicate no obvious topographic differences between the east and the west.

1.2 Eocene

The fossil localities are principally distributed in the eastern part, and also scattered in the northwest and southwest (Fig. 1(b)). The fossil-bearing beds are of brownish red continental deposits, consisting mainly of lacustrine and swamp mudstones and marls, with frequent occurrence of gypsum in the west, and lignite and oil shale in the east. The grains of the sediments are fine and the color is usually lighter than that of the Paleocene.

In the evolutionary history of vertebrates, Eocene was an initial time of modernization of mammals: most of the Paleocene families failed to persist into the Eocene; some common orders in Paleocene, such as Pantodonta, Dinocerata and Anagalita die out one after another; several widely distributed extant orders, e.g., Rodentia, Primates, Perissodactyla and Artiodactyla, made their first appearance and started to dominate the archaic orders in the faunas. Early in the beginning of Eocene, some newly emerging families, such as Cocomyidae and Tamquammyidae in Rodentia, Miacidae in Carnivora, and Equidae in Perissodactyla appeared. With the decline of archaic ungulates, Perissodactyla began a major radiation in the middle Eocene with the occurrences of Brontotheriidae, Lophialitidae, Deperetellidae, Amynodontidae, Rhinocerotidae, etc. Artiodactyla at this time made their appearance in the families of Helohyidae and Anthracotheriidae and showed a tendency of the beginning of a radiation. Rodentia started a diversity of Cricetidae and Zapodidae and gradually replaced the archaic glires. During the late Eocene, Artiodactyla had an initial diversification and broke the dominance of Perissodactyla in the middle Eocene, and Rodentia gradually flourished.

The Eocene fossil deposits in China are widespread and contain abundant and diverse mammal remains. There were some regional differences in faunal composition in Eocene, such as more diversity of anthracotheriids in the faunas of southern China (Baise,

Guangxi), more taxa preferring forested, warm and wet environments (insectivores and primates) from the east (Wutu, Shandong; Huadian, Jilin) than the central (Lushi, Henan) and the northwest (Hami, Xijiang) regions. Generally speaking, however, faunal composition of South China basically corresponds to that of North China, and mammals from the south in Eocene are identical to those of the north at the family level, or even at the genus level. The faunal composition between the two parts was more similar in the Eocene than in any later intervals. Such a similarity might suggest a similar natural environment between the southern and northern China during the Eocene. There seemed to be neither great topographic barrier for the spread of most mammals, nor distinct regional differentiation in faunal elements. It is likely that most areas of China in Eocene belonged to one zoogeographic province, which was consistent with the limits of the arid para-tropical region of the phytogeographic province[20]. It is worth mentioning the existence of a narrow distribution of mammals preferring moist, forested habitats in the eastern coast and the southern part during the Eocene (Fig. 1(b)). This area ranges from Huadian of Jilin, Benxi of Liaoning, Changle of Shandong, Liyang of Jiangsu to Mouming of Guangdong and Baise of Guangxi, and contains forest dwellers such as primates and insectivores in the faunas and is often associated with plentiful of organic sediments such as lignite and oil shale in the deposits (except for the fissure-fillings at Liyang).

Depositional characteristics (color, composition, and grain size), seem to reflect not only a rather stable sedimentation, but also a hot climate with plentiful rainfall locally, conditions that were optimal for animals and plants. The abundance of mammal fossils also indicates that the climate and environment were quite suitable for mammals to live at that time. Eocene was one of the periods that mammals were most diverse and flourished in China.

Both the composition of faunas and the characters of sediments are indicative of a relatively flat surface relief of the whole country in Eocene. Moreover, there was no sign of its elevation in the Qinghai-Xizang area, and the climate was still dominated by the east-westerly planetary wind system at this interval.

1.3 Oligocene

The localities are concentrated in the northwestern areas and scattered in the southwest, but nothing was known from the eastern, nor the hinterland of the Qinghai-Xizang Plateau. The fossiliferous beds are consisting mainly of red, yellowish brown, grayish yellow and green fluviolacustrine deposits, usually with some intercalated beds of conglomerates even gravel conglomerates. The Oligocene deposits are in lighter color and coarser grained than those of Eocene. In some Paleogene basins in the north edge of the Qinghai-Xizang Plateau, such as in the Lanzhou Basin, Gansu, sediments are rather fine in the Paleocene and Eocene, but are distinctly coarse and contain frequently thick-bedded poorly-rounded conglomerates starting from the middle Oligocene. In basins that contain no Paleocene and Eocene deposits, coarse clastic materials begin to appear in the middle Oligocene, such as in the Linxia Basin, Gansu and basins of eastern Qinling Mt.[21]. Similar condition also can be seen in Ningxia.

Oligocene represents a turning point in the course of modernization of mammals: all archaic ungulates in Eocene are nearly absent; the highly flourished Perissodactyla in Eocene begin to decline gradually; Lophialetidae, Deperetellidae, Amynodontidae, Eomoropidae, etc., which were quite prosperous in Eocene, failed to persist into the Oligocene; Artiodactyla began a major radiation; and Rodentia started a new development stage. Nevertheless, the Oligocene faunal turnover mainly happened at the family and genus level. In the early Oligocene, a remarkable change (relative to the Eocene faunas) is the appearance of Ochotonidae in the Mongol-Xinjiang Region, which are adapted to the temperate grassland today. A great turnover of taxa in the mammalian faunas took place at the end of early Oligocene (about 30 Ma): all of the families of Paleocene origin, such as Mesonychidae and Mimotonidae, and about half of the families present in Eocene, such as Brontotheriidae, Miacidae and Ischyromyidae, were extinct; and some primitive rodents appeared, for example, Tsaganomyidae, Aplo-

dontidae and Tataromyidae. A so-called "*Indricotherium* Fauna", consisting mainly of indricotheriines and brontotheriids in the large mammals and tsaganmyids, tataroyids and ochotonids in the small mammals, was formed in this interval. In late Oligocene, two new steppe-adapted groups, Tachyoryctoididae and Distylomyidae, joined the fauna.

Two obvious phenomena appear to exist in the evolution of Oligocene mammals, i.e. disappearance of a great quantity of archaic taxa, and appearance of higher-crowned and steppe- adapted small mammals (tsaganomyids and ochotonids) in the Mongol-Xinjiang region adjacent to the Qinghai-Xizang Plateau. The turnover of mammals and the changes of sedimentations took place almost simultaneously. There is no doubt that the coincidence was caused by the change of ecological and geographic environment. This may also imply that great changes had taken place in environment during the middle Oligocene. These changes include the topographic trend from a relatively flat Eocene landscape to a west-tilting topography, an appearance of cooler and arider climate with a steppe biota in the northwest. Such a dramatic change, called "Mongolian Remodelling"[22], also can be observed in the Mongolian Plateau. It is obvious that these changes are related to the result of initial uplift of the Qinghai-Xizang Plateau in Oligocene, because the elevation changed the landform and surface relief, which changed not only the sedimentary environment and deposition fabric, but also the climatic pattern, e.g. the inception of monsoon and decrease of the east-westerly planetary wind. With the changes of environment, the composition and distribution of floras and faunas changed accordingly. Based on the increase of steppe-adapted rodents and ochotonids in the late Oligocene, one can infer that the elevation of the Qinghai-Xizang Plateau was probably high enough to affect the climate of China. However, judging from the recovered indricotheriines of late Oligocene in Xinjiang and Yunnan of China and in the Indian subcontinent, the altitude of the Plateau did not hinder the migration and spread of some mammals between the central and southern Asia.

1.4 Miocene

Quite a number of localities attributed to the Miocene are known from northern and northwestern China, and a few are scattered in Yunnan and Xizang (Fig. 1(d)). The fossil-bearing beds mainly consist of grayish and brownish yellow fluviolacustrine deposits on the lower part and brownish red mudstone deposits on the upper part, with rich lignite in southwestern China.

All the mammals from the Miocene are of extant orders, and living families are dominant in the faunas. The Miocene was an important time of transformation toward the modern mammals. Most of the Chinese extant mammalian families appeared one after another at this time. The early Miocene ushered in a new era of mammals: the dominance of Protrogomorpha was replaced by Sciuromorpha and Myomorpha in Rodentia; modern carnivores completely replaced archaic ones; Proboscidea invaded from Africa; archaic Perissodactyla became extinct and Artiodactyla diversified distinctly. In the middle Miocene, proboscideans and artiodactyls increased greatly, some taxa of rodents commonly known in northern China during the late Oligocene and early Miocene, such as ctenodactylids and tachyoryctoids, disappeared and replaced by drought adapted new comers, such as gerbillids and dipodids. A so-called "*Platybelodon* Fauna", consisting mainly of cricetodonts, *Anchitherim*, rhinoceros, proboscideans, *Kubanochoerus* and *Stephanocemas*, was formed in this interval. During the late Miocene mammals became more modernized: myomorphs were dominant in rodents, cricetodonts were replaced by cricetids; rodent families Muridae, Siphneidae, Rhizomyidae and Hystricidae rose abruptly; Mustelidae, Hyaenidae and Felidae in Carnivora sprang up; Proboscidea further diversified; *Hipparion* and *Chilotherium* were dominant for Perissodactyla; Artiodactyla flourished to an unprecedented degree. Mammals in this interval formed the well-known "*Hipparion* Fauna", which featured the modern mammal pattern in community structure at higher taxonomic ranks. The late Miocene probably is the most flourished period in the history of the Chinese mammals, and the diversity and abundance of mammals in northern and north-

western China could be comparable to those in the African prairie today.

During the Miocene, mammals differentiated distinctly in distribution between North and South China. Such a differentiation is rather remarkable in the small mammals. For example, the micromammals in the Xiejia Fauna (early Miocene), the Tunggur Fauna (middle Miocene) and the Ertemte Fauna (late Miocene) of northern China are restrocted to or mainly distributed over the Holarctic or Palearctic Regions, except a few extinct and wide-ranging ones, but none is found in the present Oriental Region at the family level. These mammals are Castoridae, Aplodontidae, Gliridae, Zapodidae, Dipodidae, Gerbillidae, Ochotonidae, etc. The Yuanmou and Lufeng faunas in the south, however, contain the extant families which live nowadays in the Oriental Region or mainly in tropical-subtropical zones, except Castoridae and Cricetidae. These are Tupaiidae, Echinosoricinae, Pteropidae, Platacanthomyidae, Rhizomidae and Hystricidae, etc. The northern faunas reflect a temperate, relatively arid steppe environment, similar to the present Palearctic Region, while the faunas in the south indicate a tropical or subtropical forest environment with characteristics of the Oriental Region. This also implies the initiation of the Oriental Region in the Miocene. Since there was no physical barrier preventing the mammals from migration between the north and the south during the Miocene, there was a "ransitional Zone" of zoogeographic region in the central China, which is characterized by fauna derived from adjacent faunal regions. The early Miocene Sihong Fauna suggests the existence of such a transitional zone, which contains either the taxa from the modern Holarctic and Palearctic Regions, such as Castoridae, Gliridae and Ochotonidae, or the members restricted to the Oriental Region, such as Echinosoricinae, Rhizomyidae and Platacantomyidae. The taxonomic composition of the Chinese Miocene mammals is characterized by not only the latitudinal ecological variation, but also the longitudinal variation. Take the earlier Miocene faunas for example, the Sihong Fauna and the Shanwang Fauna consist mainly of mammals preferring warm and moist habitats, while the Xiejia Fauna of Qinghai and the Quantougou Fauna of Gansu are composed of taxa that can withstand dry and cold climate.

The Miocene differentiation between the east and the west is shown by the feature of deposits, as well as the faunal composition. As implied by the so-called "*Hipparon* Clay" of late Miocene, the "clay" from the east is red in color, whereas it is more yellowish from the west. This is probably caused by the more arid climate in the west than the east. Furthermore, the eolian silt deposits appeared in eastern part of Gansu at about 22 Ma ago (early Miocene), that is 10 Ma earlier in the west than the occurrence of "*Hipparion* Clay" in the east[23]. A similar regional differentiation as the mammalian faunas can also be observed in the Chinese Miocene floras[24,25].

Evidently, the conspicuous differentiation of mammals and deposits in distribution, and the earlier appearance of silt deposits in the west were resulted from the continued elevation of the Qinghai-Xizang Plateau and the adjacent areas after the Oligocene. It is also a significant sign for the formation of monsoon. The middle Miocene "*Platybelodon* Fauna" reflects a rather warm and moist environment, which might be caused by the global warming at 15 Ma. The late Miocene "*Hipparion* Fauna", accompanied by the wide distribution of red or reddish clay in northern and northwestern China indicates an arid and warm environment. Such a change was certainly resulted mainly from global environmental changes, but partly correlated with elevation of the Plateau. It is clear that the altitude of the Plateau in this interval had made a notable impact on the monsoon, led the distinct differentiation of faunas and floras, and brought about the initiation of the modern Palearctic and Oriental regions. At this interval, the Mongol-Xinjiang area was high enough in elevation that the influence of the summer monsoon is lessened, and arid or sub-arid climate that prevailed in the region, which was only suitable for the aridity-adapted mammals and prevented presence of those preferring warm and wet climates.

1.5 Pliocene

The Pliocene interval is short (5.30 Ma—1.75/2.47

Ma)[26,27]. The fossil localities are fewer in number than those of Miocene and distributed mainly in North China (Fig. 1(e)). Characters of the fossiliferous sediments are similar to those of the late Miocene, mainly consisting of fluviolacustrine and reddish silty deposits in the north, with frequent occurrence of thick-bedded conglomerates in the northern edge of the Qinghai-Xizang Plateau, such as the thick "Jishi Conglomerates" and the widespread "Yumen Conglomerates" in Gansu.

The faunas show a continued development of the late Miocene faunas, with faunal turnover only at the family and genus level. Obvious changes in the larger mammals are the replacement of new carnivores, the decline of some perissodactyls such as *Hipparion* and *Chilotherium*, the continued diversity of artiodactyls and the appearance of Caninae, Elephantidae and Camelidae. In the small mammals, protrogomorphs were completely extinct, with the late Miocene survivors such as Aplodontidae and Eomyidae disappeared at this time; sciuromorphs declined greatly; myomorphs were highly diversified along with the flourishing late Miocene-originated families, Dipodidae, Gerbillidae, Siphneidae and Muridae, and a new family with high crowned cheek teeth, Arvicolidae, appeared. All the families of the Chinese extant mammals were present until the late Pliocene，but only some genera were carried to the present day.

The Pliocene remains from southern China are scarce, but according to the collections from Yuanmou, Yunnan and Huainan, Anhui, there were still clear differences in composition between the southern and northern China, indicating the existence of mammal differentiation in distribution during the Pliocene[28]. The Pliocene zoogeographic regions continued the late Miocene ones, with mammals adapted to temperate grasslands in the northern part, such as hipparion horses, camels, antelopes, jerboas, jirds, zokers, mouse hares, etc. Compared with those of late Miocene, rodents in Pliocene not only increased in diversity and abundance, but also strengthened their ability to adapt to hard-vegetation through heightening of crowns. Such a phenomenon might imply an environment of drier and more grassland condition during the Pliocene than Miocene in northern and northwestern China.

The composition and feature of faunas and the thick conglomerates widely distributed in the northern edges of the Qinghai-Xizang Plateau suggest that the plateau intensified its elevation after the late Miocene, and achieved a rather high altitude in Pliocene. It is likely that the Chinese modern environmental pattern, as well as the community structure of the modern mammals, was initiated at the end of late Pliocene.

1.6 Pleistocene

The localities of Pleistocene are widely spread in China, producing abundant fossils (Fig. 1(f)). The Pleistocene deposits are varied from loose, silty, eolian, fluviolacustrine to cave deposits.

In this interval, Proboscidea and Perissodactyla further declined, Cervidae and Bovidae in Artiodactyla further flourished, and Myomorpha in Rodentia diversified. The evolution of mammals is characterized by the faunal turnover at the genus and species level, with gradual disappearance of the Pliocene genera and appearance of extant genera and species. Differentiation in the mammalian composition between the south and the north is more distinct than before, with a so-called "*Ailuropoda-Stegodon* Fauna" composed mainly of mammals adapted to warm and humid environments, such as *Tapirus*, *Rhinoceros*, *Rhizomys* and *Hystrix*, in South China. In North China, however, common mammals include forms accustomed to temperate and dry conditions, such as Bovidae, Cricetidae, Siphneidae, Avicolidae, Dipodidae，and Ochotonidae. Almost all the late Pleistocene taxa can be grouped into the extant genera, and distribution of the late Pleistocene mammals at the family level is basically consistent with that of the present day.

The composition and distribution of the Pleistocene mammals are highly suggestive that the line of the two zoogeographic divisions, the Palearctic realm and the Oriental realm, was quite distinct in this interval (Table 1). It is probable that the line of dividing the two provinces shifted more or less northward or conversely due to the frequent occurrence of glacial periods and

Table 1 Ranges of Chinese representative Cenozoic mammals at family level

Taxa	Paleocene	Eocene	Oligocene	Miocene	Pliocene	Pleistocene
Omomyidae						
Pongidae						
Tupaiidae						
Avicolidae						
Muridae						
Hystricidae						
Siphneidae						
Gerbillidae						
Dipodidae						
Platacanthomyidae						
Rhizomyidae						
Zapodidae						
Cricetidae						
Castoridae						
Aplodontidae						
Tataromyidae						
Ctenodactylidae						
Yuomyidae						
Ischyromyidae						
Alagomyidae						
Ochotonidae						
Leporidae						
Eurymylidae						
Mimotonidae						
Elephontidae						
Gomphotheriidae						
Mustelidae						
Hyaenidae						
Canidae						
Falidae						
Ursidae						
Miacidae						
Camelidae						
Bovidae						
Cervidae						
Suidae						
Tayassuidae						
Anthracotheriidae						
Rhinocerotidae						
Amynodontidae						
Brontotheriidae						
Lophialetidae						
Equidae						
Coryphodontidae						
Taeniolabididae						
Prodinoceratidae						
Phenacolophidae						
Pseudictopidae						
Anagalidae						
Mesonychidae						
Archaeolambdidae						
Bemalambdidae						

global climatic changes, or that the limits of the "transitional zone" between the two regions change by the climatic shifts[29]. Nevertheless, the two zoogeographic provinces were roughly separated by a narrow zone from the Huaihe River through the Qinling Mt. to the Hengduan Mt. With the continuous uplift of the Qinghai-Xizang Plateau in Pleistocene, the Yangtze River and the Yellow River gradually merged. The Yangtze River seemed to prevent some mammals from spreading and migrating to a certain extent.

2 On the elevation of the Qinghai-Xizang Plateau, and impact of the uplift on the evolution of mammalian provinces

Composition and distribution of the Chinese Cenozoic mammalian faunas show an essentially united zoogeographic province and similar environment between South and North China during the Paleocene and Eocene time, demonstrate the appearance of a great quantity of taxa adapted to temperate steppe in Oligocene, display the progressive differentiation of mammalian faunas since Miocene, and exhibit the gradual increase of mammals adapted to abrasive diet in the north and inhabited tropic and subtropic forests in the south during the Pliocene and Pleistocene. The mammal evolution and environmental changes obviously indicate a gradual uplift of the Qinghai-Xizang Plateau since the Oligocene. This is because the uplift changed the environment that resulted in the differentiation of animals and plants in distribution and the changes of adaptation of the creatures.

The 10 ° higher latitude for the boundary of the Palearctic Region with the Oriental Region in China compared to that boundary between the Palearctic Region and the Ethiopian Region in Africa is another evidence for the elevation of the Plateau. The uplift not only resulted in the initiation of monsoon, but also in the strengthening of the summer monsoon from the Indian Ocean along with the progressive uplift of the Plateau. The strengthened summer monsoon caused the southeastward flinch of the desiccation and the northwestward expansion of the distribution of mammals from the Oriental Province. As a result, the latitude of the boundary between the Palearctic Region and the Oriental Region was heightened[13].

Immigration of mammals in the Palearctic Region has increased since Miocene. Both North China and Europe are of the same region, but Europe lacked an arid area as does in Central Asia, and as a result, some families adapted to arid steppe environment, such as Tsaganomyidae, Tachyoryctoidae, Tataromyidae, and Siphneidae were absent. The relatively moist climate in Europe caused Ochotonidae to fail from carrying into the Pliocene and kept Spalacidae from invading Asia. Dipodidae only occurred in the eastern part of Europe during the arid interval of Quaternary. The high diversity of these taxa adapted to steppe in Asia since Oligocene seems to be closely related to the distinct uplift of the Qinghai-Xizang Plateau since Miocene.

The evolution of mammalian faunas indicates that great changes had taken place in the Chinese zoogeographic provinces and in the environment during the Cenozoic. Strictly speaking, evolution of animals is a multiple interaction resulting from genes and environmental changes, and formation of zoogeographic region is closely related to the global environmental changes. The facts mentioned above, however, reveal that the uplift of the Qinghai-Xizang Plateau made a notable impact on the environmental changes of Asia, the evolution of mammals, and the development of zoogeographic provinces of China. The elevated plateau formed an effective barrier to the penetration of moist air from the Indian Ocean and the Pacific Ocean. As a result, aridity increased in Central Asia, including the northwestern part of China, and warmth and moisture stayed in the southeast and southwest, which were effected by the summer monsoon from the two oceans. It is the uplift and climatic changes that made the environmental differentiation in China: high altitude and cold temperature in the Qinghai and Xizang areas; gradual aridity in Nei Mongol and Xinjiang regions; warmth and moisture in the south and southwest. With the environmental changes, distribution of mammals and plants progressively differentiated and biogeographic provinces formed. With the continual rise of the plateau, the two zoogeographic provinces in China got more and more distinct.

The elevation of the Qinghai-Xizang Plateau in the late Cenozoic deeply affected the evolution of mammals in southeastern Asia. The strengthened summer monsoon from South Asia and winter monsoon from North Asia, caused by the uplift of the Plateau, made the climate drier and drier in the northwestern part, and colder and colder in the Qinghai and Xizang areas. The aridity had brought about a grassland condition in the northwest till the Miocene, and a harsh ecological environment in the Qinghai-Xizang Plateau. The high altitude and cold climate have made the Plateau an impassable barrier for many mammals since the Pliocene.

3 Conclusions

(1) Faunal composition and distribution can reflect environment to a certain extent, because of the high evolutionary rates of mammals and good correspondence to environment. Therefore, it is a potential fruitful approach to the paleoenvironmental changes by means of studying evolution of mammals in different ages. The evolutionary history of the Chinese Cenozoic mammalian faunas appears to be consistent with the climatologic changes from the planetary wind system to the monsoon system in Paleogene, reflects the processes of elevation of the Qinghai-Xizang Plateau, and demonstrates the impact of the uplift on the environment.

(2) The relatively consistent composition of faunas and the stable sedimentation in the Paleocene and Eocene times indicate the similar environment and surface relief of the whole country at that period. Great turnover in faunal composition and sedimentary environment took place in the middle Oligocene, with simultaneous appearance of numerous steppe taxa and coarse clastic rock sedimentation in the northwest. There is no doubt that this was caused by the changes in paleogeography and paleoecology, and these dramatic changes also suggest the uplift of the Qinghai and Xizang regions. Thus, the uplift probably initiated in Oligocene, and the elevation of the Plateau was high enough to initiate inception of monsoon climates and the initial differentiation of zoogeographic regions in the middle of Oligocene.

(3) There are quite a lot of fossil localities with rather rich mammal records of different ages in the northern part of China, which is ideally suited for studying the evolution of mammals and paleoenvironmental changes. In these areas, the community structure of mammalian faunas has been relatively stable and the faunas have changed rather smoothly since Oligocene. Such a stability and gradualness are also shown in the evolution of some mammal families, such as the Ochotonidae originated in central Asian Oligocene and the Siphnidae originated in late Miocene and confined in Central Asia and northern China. The progressive changes in their dietary adaptation, as reflected in their dental pattern, clearly demonstrated their gradualness in change[30,31]. Gradual increases in complexity of teeth and height of crowns, as time went on and with increasingly rigorous environment, can be also seen in some other herbivores. These changes in the plant-eating animals are resulted from adaptation to the changes of ecological environment. Consequently, the stability of faunal community structure in northern China and the gradualness of faunal changes since the Oligocene are probably indicative of a relatively gradual and stable process of the uplift of the Qinghai-Xizang Plateau.

(4) Distinct differentiation of mammalian faunas in composition and distribution and initiation of the modern Palearctic and Oriental provinces happened in Miocene. This suggests that the elevation of the Qinghai-Xizang Plateau at the end of Miocene was high enough to make a conspicuous impact on the environment. Based on the remains of hipparion horses, the elevation of the Plateau has been conjectured by some scholars, suggesting that the altitude was less than 1000 m in the Pliocene and reached to an average of 4000 m in the Pleistocene. One of the reasons is the simultaneous occurrence of *Hipparion* both in Xizang and North China[14,15]. The evolutionary trend of mammalian faunas does not suggest such a rapid elevation during the Pleistocene. Nevertheless, the ability for the herbivores from the Mongol-Xinjiang region to adapt to abrasive diet was progressively strengthened in the Pliocene and Pleistocene. This might imply that the Qinghai-Xizang Plateau had been continuously

elevated after Miocene, and achieved a high altitude that resulted in a rather arid environment in the Pliocene and Pleistocene. However, it is not necessarily accurate to measure the altitude of the elevation based on *Hipparion*, because these mammals, like the extant *Equus*, were a wide-ranging genus distributed over a widely ranging altitude. With today's technique, mammals can be used to appraise elevation and height of the Plateau only qualitatively, but not quantitatively.

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