

哺乳动物化石群落线指示的甘肃临夏盆地 晚新生代环境演变¹⁾

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摘要:哺乳动物群的演替过程在重建古环境和古气候中具有重要的作用。群落线(cenogram)是将陆生哺乳动物群中非肉食性种类按体重分布顺序排列的一种曲线,并可在图中将肉食性种类单独排序,以便显示动物群的整体组成。通过与现生哺乳动物群的比较,化石动物群的群落线已经被用来推断古环境及其在地质历史时期的变化。基于甘肃临夏盆地晚新生代哺乳动物群的群落线进行古环境重建,时代从晚渐新世直到早更新世。大多数化石种类的体重通过下第一臼齿面积与体重的回归公式来估计,少数种类用其他牙齿或肢骨来估计。大多数体重估计的测量数据来自临夏盆地的化石,少数取自文献。对7个化石动物群分别计算群落线的统计结果,在此基础上进行古环境解释。这些分析揭示了临夏盆地在晚中新世、早上新世和早更新世具有开阔的环境,晚渐新世是半开阔的林地,而中中新世为比较紧密的森林;在晚渐新世和晚中新世早期气候干燥,晚中新世的其他时段以及早上新世和早更新世为半干旱环境,而中中新世时期相当湿润。

关键词:临夏盆地,晚新生代,哺乳动物,古环境,群落线

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LATE CENOZOIC ENVIRONMENTAL CHANGES IN THE LINXIA BASIN (GANSU, CHINA) AS INDICATED BY CENOGRAMS OF FOSSIL MAMMALS

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Abstract The evolutionary history of mammalian communities is significant for reconstructing past environments and climate. A cenogram is a rank-ordered body mass distribution of non-predatory terrestrial mammal species within a fauna. Based on comparisons with modern faunas, cenograms of fossil faunas have been used for inferring environments and their changes through geological time. In this paper, an environmental reconstruction based on the Late Cenozoic mammalian faunas of the Linxia Basin (Gansu, China), ranging in age from the Late Oligocene to the Early Pleistocene, is presented using the cenogram method. Body sizes for fossil taxa were estimated using regressions of body weight based on the area of the first lower molar for most species and on other teeth or limb bones for a few species. Most

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measurements for the body estimations are from the Linxia fossils, while a few are from the literature. Cenogram statistics are calculated for seven fossil faunas, allowing paleoenvironmental interpretations to be made. These analyses reveal open conditions during the Late Miocene, Early Pliocene and Early Pleistocene; less open conditions during the Late Oligocene but a closed environment during the Middle Miocene; arid conditions during the Late Oligocene and earliest Late Miocene; less arid during the Late Miocene, Early Pliocene, and Early Pleistocene but humid during the Middle Miocene.

Key words Linxia Basin, Late Cenozoic, mammal, paleoenvironment, cenogram

1 Introduction

A well-developed successive sedimentary sequence ranging from the Oligocene to the Pleistocene is exposed in the Linxia Basin in Gansu, northwestern China, and contains a large number of mammal fossils. The Linxia Basin is located in the transitional zone between the Tibetan and Loess plateaus, so it provides a very good site for studying the uplift history of the Tibetan Plateau and its influence on the environment. Mammals are very sensitive to environmental changes. The strong uplift of the Tibetan Plateau during the Late Cenozoic may have dramatically affected the environment, which must be reflected in the evolution of mammalian faunas.

Valverde (1964) firstly showed vertebrate body sizes within a fauna in a univariate plot according to a decreasing rank order, and he called this method as cenogram. Valverde (1964, 1967) studied predator-prey body size relationships in modern faunas based on cenograms. As a result, he considered that cenogram curves of terrestrial vertebrates in different habitats had different shapes. The cenogram method for mammalian faunas was used in paleoecological studies by some authors (Legendre, 1986, 1989; Montuire and Desclaux, 1997; Montuire, 1999).

In the last decade, numerous paleoclimatic interpretations have been proposed based on the rich Late Cenozoic fossils and sedimentary records in China (Qiu et al., 1999; Qiu, 2003; Qiu and Li, 2003, 2005; Deng and Downs, 2002; Guo et al., 2002; Wang and Deng, 2005), but most of the methods used have been based on more or less restricted taxonomical subsets of the total fossil fauna (e. g., rodents, large mammals, etc.). In this sense, it is important to point out that different mammal groups may offer different paleoecological information. Particularly, large and small mammals usually provide slightly different paleoenvironmental reconstructions due to disparities in scale of landscape perception and physiological constraints (Hernández Fernández et al., 2006).

Legendre (1986) used cenograms to study the paleoecological features of fossil mammals. Other authors studied more Cenozoic mammalian faunas (Gingerich, 1989; de Bonis et al., 1992; Gunnell, 1994, 1997; Montuire and Desclaux, 1997; Wilf et al., 1998; Croft, 2001; Montuire and Marcolini, 2002). However, few of these studies have dealt with Asian localities, and none have included fossil faunas from China.

We also use the cenogram method to study paleoecological conditions for the abundant fossils of the Late Cenozoic mammalian faunas from the Linxia Basin. The time span in this study ranges from the Oligocene to the Pleistocene. Our analyses are also compared to other paleoenvironmental evidences from fossil morphology, lithology, paleoclimatology, and stable isotopes in order to examine the accuracy of paleoecological reconstruction based on cenograms.

2 Materials

The Linxia Basin is located on the northeastern edge of the Tibetan Plateau, and the locations of the studied sites are shown in Fig. 1. Seven Late Cenozoic faunas dated between 25 and 2.16 Ma were used in this study. Their stratigraphic position and age are listed in Table 1. The complete faunal lists of the localities quoted in this study can be found in; Qiu et al. (1990, 2004b) and Deng (2004a) for the Late Oligocene Jiaozigou fauna; Guan (1988), Cao et al.

(1990) and Deng (2003, 2004b) for the Middle Miocene Laogou fauna; Deng (2006) for the Late Miocene Guonigou, Dashengou, and Yangjiashan faunas; Deng (2005a) for the Early Pliocene Shilidun fauna; Qiu et al. (2004a) and Wang (2005) for the Early Pleistocene Longdan fauna.

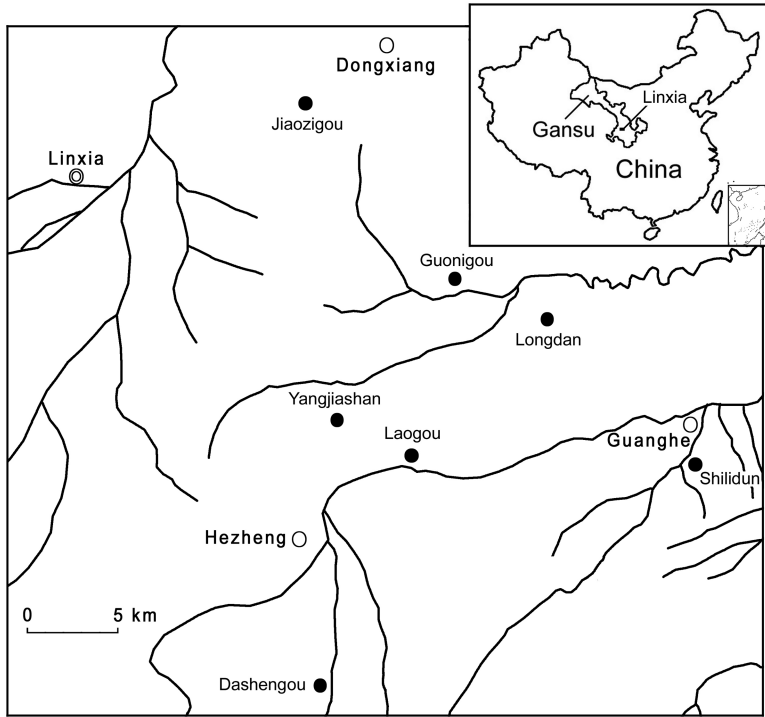


Fig. 1 Geographical map of the Linxia Basin of northwestern China showing seven mammal fossil localities of the Late Cenozoic

Table 1 Position of the faunas in the Chinese and European biochronological time scales

Fauna	Age	Chinese Stage	European Stage	Mammalian Zone
Longdan	Early Pleistocene	Nihewanian	Villanyian	MN 17
Shilidun	Early Pliocene	Gaozhuangian	Ruscinian	MN 14
Yangjiashan	Late Miocene	Baodean	Turolian	MN 11
Dashengou	Late Miocene	Bahean	Vallesian	MN 10
Guonigou	Late Miocene	Bahean	Vallesian	MN 9
Laogou	Middle Miocene	Tunggurian	Astaracian	MN 6
Jiaozigou	Late Oligocene	Tabenbukian	Chattian	MP 27

The Jiaozigou fauna (corresponding to MP 27 of Mammal Paleogene European Chronostratigraphic Scale) is preserved in brown fluvial sandstones; the Laogou fauna (corresponding to MN 6 of Mammal Neogene European Chronostratigraphic Scale) is in grayish-brown channel sandstones and conglomerates; the Guonigou (MN 9), Dashengou (MN 10), and Yangjiashan (MN 11) faunas are in red clays; the Shilidun fauna (MN 14) is in yellowish-red clays; and the Longdan fauna (MN 17) is in eolian loess. Li et al. (1995), Fang et al. (2003), and Gong et al. (2005) studied the sedimentological/depositional characteristics of the Linxia Basin. The chronology of these faunas follows Deng (2005b). Among these fossil localities, large mammals have been well represented throughout repeated searches over many years. On the

other hand, small mammals have rarely been recorded as a result of few screen washings, because clay and loess are very difficult to wash.

Van Kolfshoten (1995) emphasized that fossil faunas cannot be exact reflections of original faunas, but they can help in understanding paleoenvironmental changes. It is generally assumed that past macroclimatic factors and landscape features may be predicted by the study of fossil mammal faunas. Although constructing cenograms for modern faunas is relatively straightforward, constructing accurate cenograms for fossil faunas is much more difficult. Following Croft (2001), seven mammalian faunas from the Linxia Basin were chosen as most likely to be reliable based on the following characteristics: 1) there should be a restricted time interval represented; 2) they should be collected from a restricted geographical area; 3) there should be a high sampling intensity; and 4) there should be availability of up-to-date taxonomic information. If a fauna included mammal fossils collected from more than one locality, only specific localities in the Linxia Basin at the same horizon with a strict stratigraphic correlation were used to minimize problems associated with time-averaging of deposits. Such time-averaging may obscure or alter patterns in cenogram curves. The Longdan fauna comes from restricted intervals after a detailed biostratigraphic study of these deposits (Qiu et al., 2004a) and, therefore, probably represents the ideal stratigraphic precision for a cenogram study. The same can be said for the Laogou fauna, which has excellent stratigraphic control and sampling (Deng, 2003, 2004b). The Jiaozigou fauna has been collected from a single fossil-bearing unit of equal temporal length (Qiu et al., 1990, 2004b).

3 Method

A cenogram is illustrated by a graph that describes a mammalian fauna using the body size distribution of species within the community and it is constructed by plotting the natural logarithm of the mean body weight of each mammal species, except for bats and carnivorous species (carnivores, creodonts, and carnivorous condylarths). The estimated body weights are plotted on the Y-axis and the species are ranked in decreasing size order on the X-axis. Investigations of a very large number of present-day faunas have demonstrated that body size distribution is closely correlated with environment (Legendre, 1989), resulting in the designation of four main categories of cenograms (Fig. 2), which characterize types of environments (open or closed) and climatic conditions (arid or humid).

A continuous distribution of weight [numerous medium weight species with a body weight between 500 g and 8 kg, $\ln(\text{weight}): 6.2-9$] is characteristic of a closed environment, whereas a paucity of medium weight species is observed in open landscapes. An abundance of large species (with a body weight of more than 8 kg) characterizes humid conditions, whereas a steep slope is associated

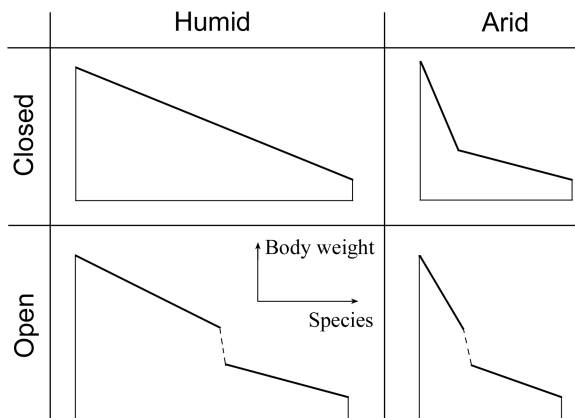


Fig. 2 Schematic large categories of cenograms (after Legendre, 1989)

In closed environments, the distribution of the species in terms of their body weight is continuous (top), whereas in open habitats the medium-weight species (with a mean body weight between 500 g and 8 kg) are absent or rare (bottom); in humid conditions, the large species (mean body weight over 8 kg) are numerous (left), whereas they are rare in arid conditions (right)

with arid conditions. This method has previously been applied to many fossil mammal sequences from Europe, America, Africa, and Asia, that range from the Oligocene to the Holocene (e. g., Legendre, 1989; Gingerich, 1989; Legendre and Hartenberger, 1992; Gunnell, 1994, 1997; Gunnell and Bartels, 1994; Gibernau and Montuire, 1996; Montuire and Desclaux, 1997; Wilf et al., 1998; Croft, 2001; Montuire and Marcolini, 2002; Storer, 2003; Tsubamoto et al., 2005).

Cenogram analyses have the clear advantage of using nearly complete mammalian associations to obtain paleoenvironmental information. On the other hand, this methodology has been recently criticized because the relationships between the cenogram's structure and the climate are not statistically significant (Rodríguez, 1999). Nevertheless, while Rodríguez centered his test on the study of the quantitative relationships between different analyzed variables, a qualitative statistical approach in order to infer biomes has never been undertaken with this methodology. Hernández Fernández et al. (2006) considered that the general structure of the cenogram may yield unique information about the body size structure of the non-carnivorous mammal community and, therefore, its use should not be omitted, although some problems arise when applying to fossil assemblages.

4 Body weight data and estimations

In order to make an analysis, some consistent and reasonably accurate means of estimating body weight from fossils are required. The only adequate method of estimation available at present uses allometric equations that primarily relate weight with dental surface (Creighton, 1980; Legendre, 1989). Although there are some problems in using teeth as a basis for body weight estimation (Gould, 1975; Smith, 1984, 1993; Damuth, 1990), species are, in general, more easily identified by their teeth than they are by post-cranial elements and teeth are often the only parts of an animal that are preserved in sufficient numbers to be useful.

In this paper, except for proboscideans, weights for most of the fossil taxa (90% of included species) were estimated using regressions of body weight based on m1 area (length \times width) calculated for recent mammals (see Legendre, 1986). Some forms without an m1 are replaced by an m1 of the same species with the same age from an adjacent area of the Linxia Basin. Weights of only a few forms are estimated by an m1 of an allied species of the same genus.

The m1 morphology is generally considered to be the least variable in mammals (Gingerich, 1974). Sexual dimorphism was not taken into account in the analyses of the Late Cenozoic mammals from the Linxia Basin; the mean size was calculated from all tooth samples for each species. Similarly, the body weight used corresponds to a mean for all specimens (males and females), e. g., *Iranotherium morgani* of the Dashengou fauna (Deng, 2005c) and *Canis teilhardi* of the Longdan fauna (Qiu et al., 2004a).

For fossil proboscideans, some weights were estimated by using cheek teeth, but in most cases, weights were estimated by using a regression equation of body weight based on the length of the humerus or femur (see Roth, 1990). A postcranial measurement was used for this group instead of a dental measurement because dental regressions are not appropriate for estimating body size in proboscideans. Dimensions of elephant teeth change as they continually undergo attrition and shed plates, and the particular teeth that are present depend upon the stage of ontogeny (Roth, 1990). Length of the humerus or femur was chosen because their dimensions are usually highly correlated with body weight (Anderson et al., 1985).

5 Results

Gingerich (1989) indicated that the slope of the medium-sized mammals with weight be-

tween 500 g and 8 kg and the vertical offset at the break between the medium and small mammals in cenograms are quantifiable and correlated with habitat. The decreasing number of large-sized mammals in a fauna indicates the decreasing annual rainfall, showing a steeper slope in the left part of the cenogram (Fig. 2). The gap between mammals larger and smaller than 500 g is wide in open environments (e. g., savannas and steppes) and is narrow in closed environments (e. g., woodlands and forests; Fig. 2). In Appendices 1–7, the estimated mean body weights of all Linxia mammal species ranged from 17 g for the smallest species (*Megacricetodon sinensis*), to 24030 kg for the largest (*Dzungariotherium orgosense*). The cenogram sequences obtained for the faunas of the Linxia Basin, are shown in Figs. 3–9.

The cenogram of the Late Oligocene Jiaozigou fauna (the oldest fauna in the Linxia Basin, dated at approximately 25 Ma) shows a small number of large forms (weighing more than 8 kg), but includes several huge species (e. g., two giant rhinoceroses, *Dzungariotherium orgosense* and *Paraceratherium yagouense*) (Appendix 1). This cenogram is truncated because no small species were found, but one medium species (a large rodent, *Tsaganomys altaicus*) was present, indicating a partially closed habitat (e. g., woodland). Although small mammals are absent due to collecting factors, the curve well reflects the left part of the cenogram, and its slope is very steep (Fig. 3). As a result, the cenogram is completely consistent with the expected features of large mammals in an arid habitat. Because the environment was apparently an arid habitat, this analysis agrees well with traditional interpretations of the Late Oligocene environment (Deng, 2004a).

Compared to the Jiaozigou fauna, the number of large species increased in the Middle Miocene Laogou fauna (dated at approximately 14.5 Ma). The slope of the cenogram for the Middle Miocene Laogou fauna is shallow. This cenogram decreases smoothly from the large sized through the medium sized species without any major distinct gap, although a small gap can be observed within the medium sized species between *Moschus* sp. (10.2 kg; rank 29) and *Castor* sp. (1.2 kg; rank 8) (Fig. 4; Appendix 2). The slope of the Laogou fauna is consistent with that for modern faunas of humid to subhumid and forested or closed environments (Legendre, 1989; Gingerich, 1989; Gunnell, 1994, 1997). In general, a change in landscape occurred and the environment tended to transform to forest, indicating a more closed and humid environment than that of the Jiaozigou fauna and suggesting abundant rainfall. The relatively humid and closed environment characteristics of the Middle Miocene sequence have been previously pointed out by Deng and Downs (2002) and Qiu and Li (2005) based on different mammal groups.

The early Late Miocene Guonigou fauna of 11.1 Ma has fewer large species than the Laogou fauna, but includes huge species, such as two elasmotherine rhinoceroses, *Parelasmothierium linxiaense* and *Ningxiatherium euryrhinus* (Appendix 3). There are no medium weight species in the Guonigou fauna, indicating an absolutely open environment. The cenogram of the Guonigou fauna is similar to that of the Jiaozigou fauna, but its slope is shallower than that of the Jiaozigou fauna (Fig. 5), indicating that it is less arid than the latter. The presence of the earliest East Asian three-toed horse, *Hipparion dongxiangense*, at Guonigou, would seem to

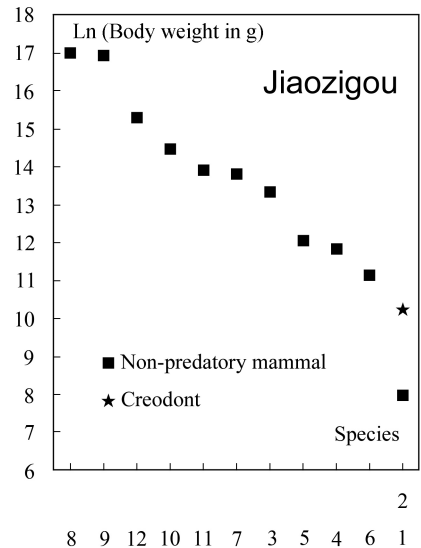


Fig. 3 Cenogram of the Jiaozigou fauna. Numbers under the abscissa are rank numbers allocated to each species in Appendix 1

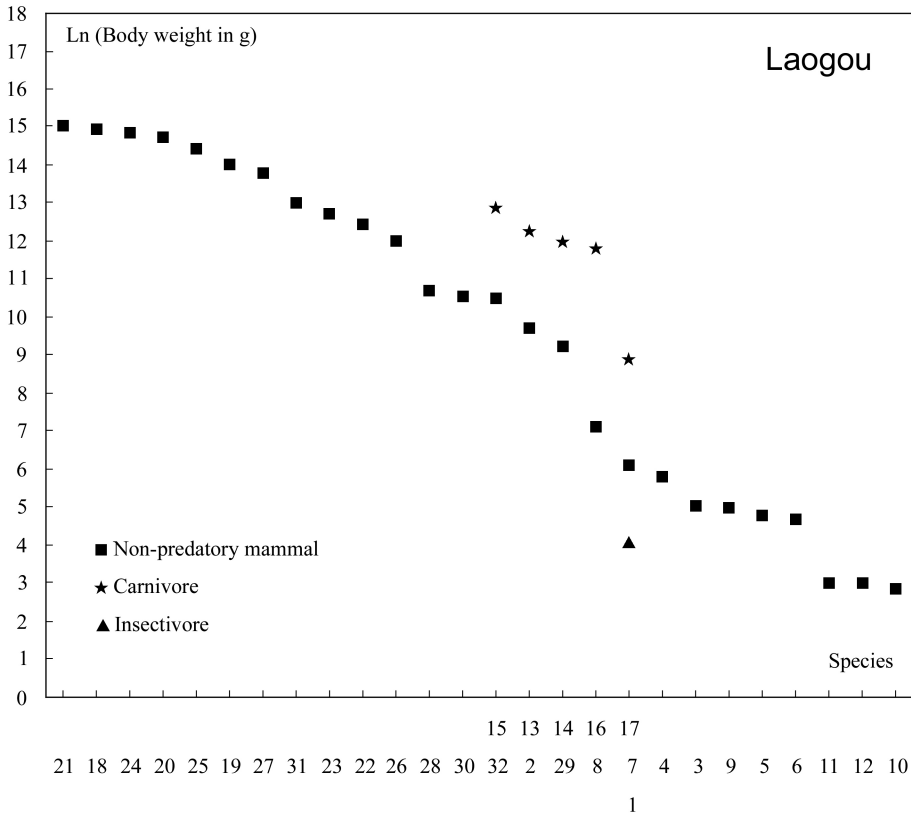


Fig. 4 Cenogram of the Laogou fauna
Numbers under the abscissa are rank numbers allocated to each species in Appendix 2

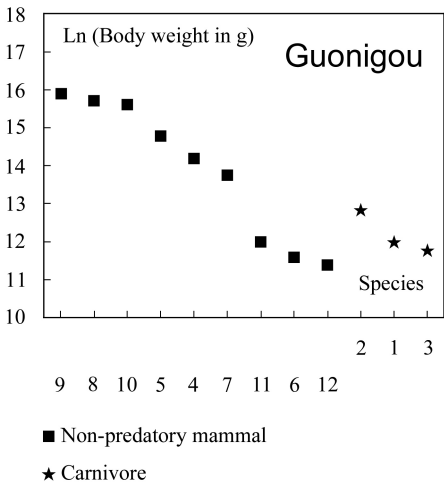


Fig. 5 Cenogram of the Guonigou fauna
Numbers under the abscissa are rank numbers allocated to each species in Appendix 3

support the interpretation of at least a moderately dry environment with few trees. The presence of hypsodont and presumably open-country adapted taxa (*Hipparion*, *Parelasmotherium* and *Ningxiatherium*) at Guonigou implies that open areas were present, indeed (Qiu and Xie, 1998; Deng, 2001, 2007).

Environments were more open for the Late Miocene faunas of the Linxia Basin, but conditions became somewhat humid during this period. The Late Miocene faunas are often incomplete for small species due to the taphonomy of red clays (Liang and Deng, 2005), but the abundance of large species in the Dashengou fauna suggests that the environment was more humid than which existed at the beginning of the Late Miocene. The discontinuous distribution of weights in the Dashengou fauna indicates that the environment was also open (Fig. 6). The results for the two faunas from the Late Miocene, Dashengou (dated at 9.5 Ma; Appendix 4) and Yangjiashan

(dated at 8.3 Ma; Appendix 5) with *Hipparion*, are somewhat similar, but the habitat of the former was more humid than that of the latter. Although usually interpreted as a savanna habitat due to the presence of many (presumably) savanna-adapted mammals (Kurtén, 1952), the cenogram statistics suggest that the area was less arid than previously thought, and it should be considered a temperate steppe (Figs. 6, 7). This analysis suggests greater rainfall in the upper *Hipparion* zone, as indicated by the richness of large-sized mammals. Sedimentological data support this interpretation because the Late Miocene faunas of the Linxia Basin belong to a fluvial sequence, where many cycles of flooding and desiccation have been observed. Furthermore, horizons with significant concentrations of carbonates have been recorded at these fossil sites, which indicate the presence of significant steppe, at least in grassland environments (Gong et al., 2005). The position of the Late Miocene *Hipparion* faunas suggests a unique combination of a moist yet relatively open environment.

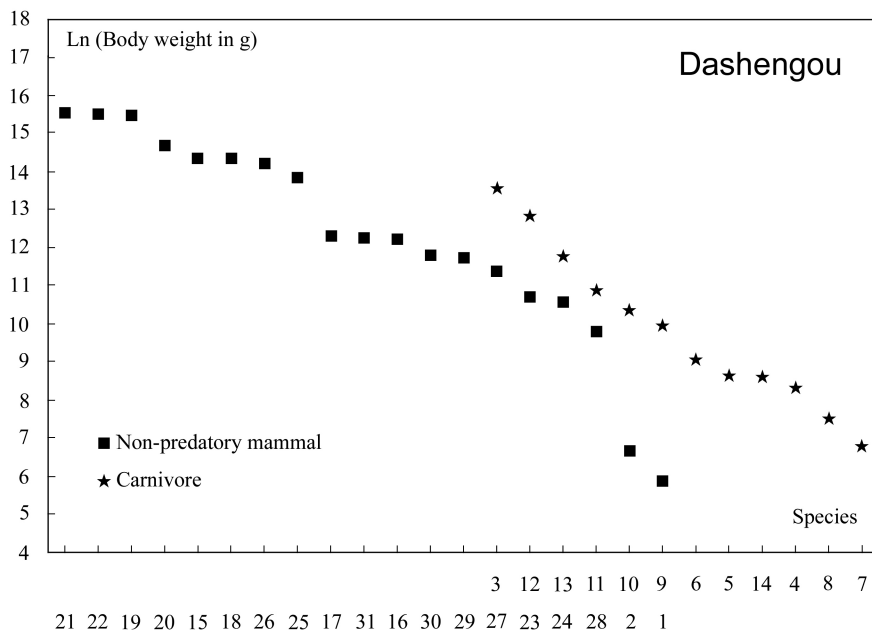


Fig. 6 Cenogram of the Dashengou fauna

Numbers under the abscissa are rank numbers allocated to each species in Appendix 4

In the cenogram of the Early Pliocene Shilidun fauna (Fig. 8; Appendix 6), the number of large species decreases compared to the Dashengou and Yangjiashan faunas and the slope of the cenogram becomes slightly steeper than that of the left part of the cenograms of the Dashengou and Yangjiashan, implying that the environment becomes a little more arid during the Early Pliocene than during the Late Miocene. It seems best described as a steppe habitat, as suggested by the high-crowned *Hipparion* and *Shansirhinus* (Deng, 2005a).

For the Early Pleistocene Longdan fauna, the distribution of weights on the cenogram is discontinuous (Fig. 9; Appendix 7), which indicates the presence and persistence of open habitats. The number of large species in the Longdan fauna is close to that of the Shilidun fauna, which suggests the same subarid conditions. The Longdan fauna is one of the two most diverse faunas of the Linxia Basin, the other is the Late Miocene Yangjiashan fauna. The model based on cenogram variables classifies the Longdan faunal environment as an alpine grassland, which agrees with the interpretation made by An et al. (2001) of eolian deposits, and with the vege-

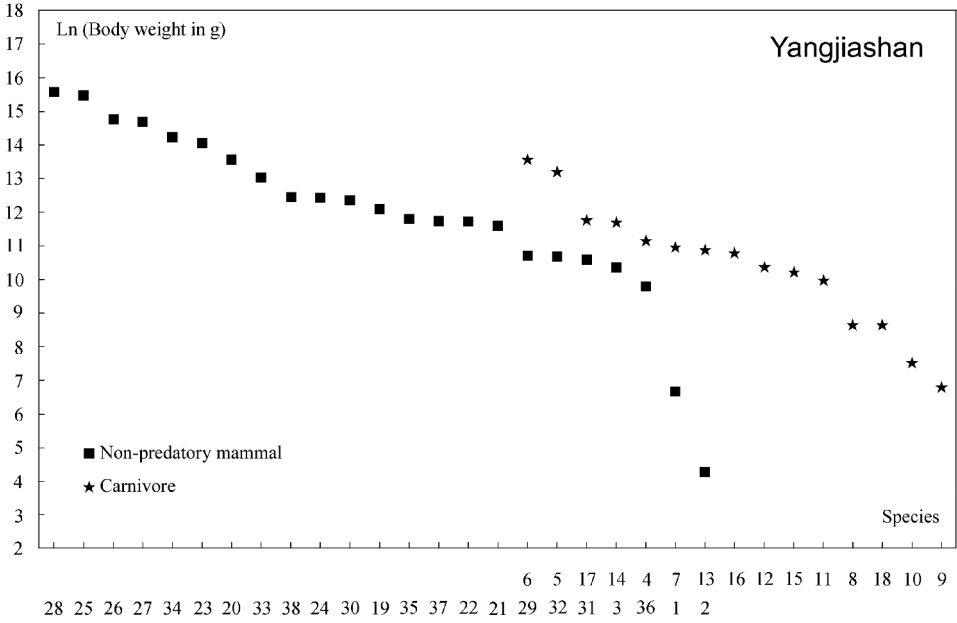


Fig. 7 Cenogram of the Yangjiashan fauna
 Numbers under the abscissa are rank numbers allocated to each species in Appendix 5

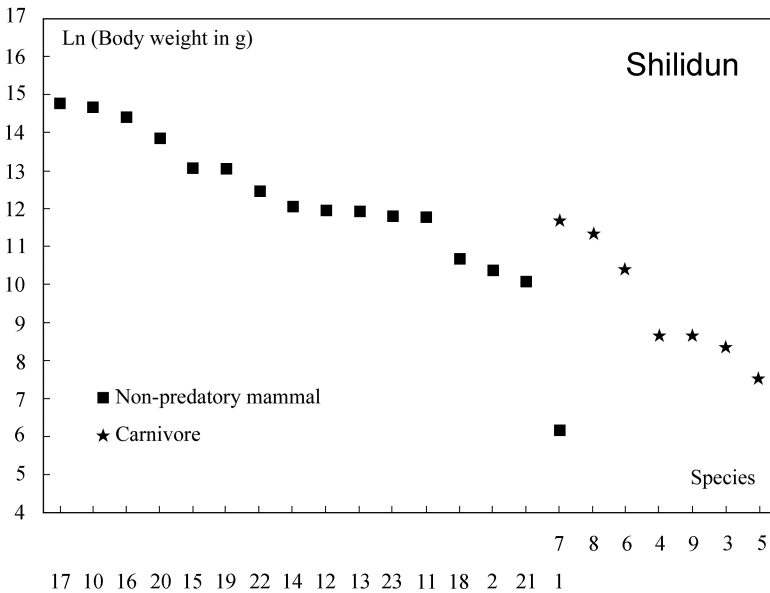


Fig. 8 Cenogram of the Shilidun fauna
 Numbers under the abscissa are rank numbers allocated to each species in Appendix 6

tation record based on palynological analyses (Ma et al., 2004). Its interpretation as an alpine grassland also supports paleoecological studies of the feeding habits of Longdan's large mam-

mals (Qiu et al., 2004a).

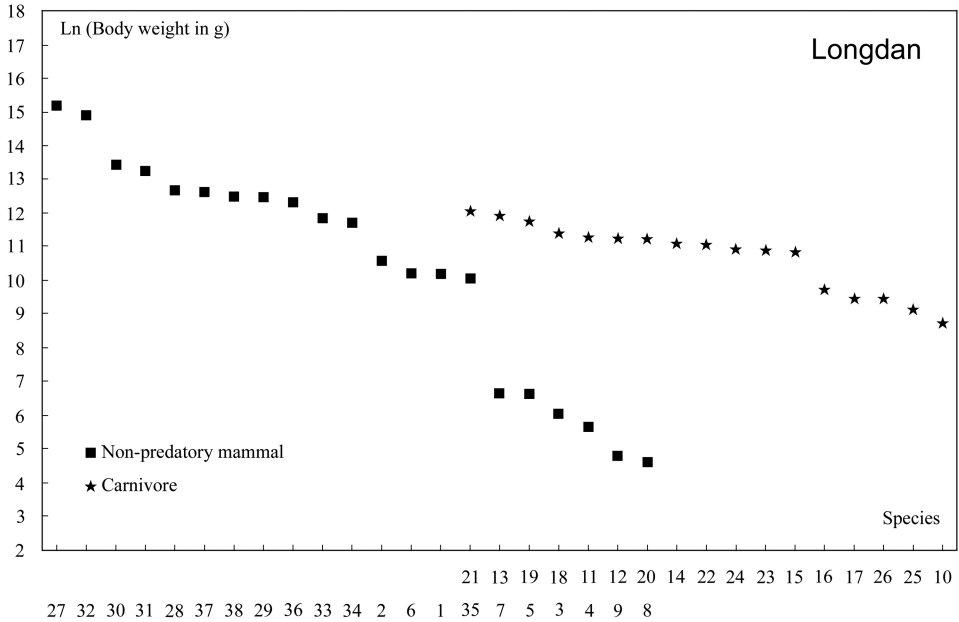


Fig. 9 Cenogram of the Longdan fauna

Numbers under the abscissa are rank numbers allocated to each species in Appendix 7

In fact, the cenograms of the mammalian faunas in the Linxia basin show variable conditions that are probably related to the Late Cenozoic climatic cycles affected by the uplift of the Tibetan Plateau. For example, closed environments and humid conditions are reported for the Middle Miocene Laogou fauna in the Linxia Basin, in contrast with the open environments and arid conditions found in the earliest Late Miocene Guonigou fauna. During most of the Late Miocene, however, conditions were more humid and environments more open, with the presence of more large species and the absence of medium-weight species.

In some deposits, such as sandstones and red clays, micromammals are rarely preserved as fossils. For example, only a few rodents are found in the Late Oligocene and Late Miocene faunas. On the other hand, the Laogou and Longdan faunas include macro- and micromammals. However, since cenogram statistics rely primarily on the diversity of mammals 500 g or larger, an artificially small sample of the smallest mammals (those less than 500 g) should not have a significant effect on paleoenvironmental interpretations (Croft, 2001).

Medium-sized animals are easier to fall preys to predators in an open (savanna or steppe) environment than in a more closed one (woodland or forest), so they have a lower diversity in the former. For a given number of predators, there are generally fewer medium-sized mammals in open habitats than in the closed ones (Croft, 2001). This feature is very obvious in the Longdan fauna: the carnivores are so abundant that the medium-sized preys (500 g ~ 8 kg) are very scarce and the herbivores tend to become enormous, such that *Equus eisenmannae* becomes a dominant form (Qiu et al., 2004a). The number of mammalian predators in the Late Cenozoic faunas of the Linxia Basin ranges from one (10% in the Late Oligocene large mammals) to a maximum of 17 (55% in the Early Pleistocene large mammals). Given the observations regarding predator and prey diversity in modern faunas (Croft, 2001), it can be hypothesized that the Oligocene fauna could have had greater-than-expected numbers of medium-sized mammals due

to the low diversity of mammalian predators (only a creodont, *Megalofterodon* sp.).

6 Conclusions

The sequences of cenograms for the Linxia Basin show some environmental changes, such as alternating ecological and climatic conditions during the Late Cenozoic. The analyses reveal open conditions during the Late Miocene, Early Pliocene, and Early Pleistocene, less open conditions during the Late Oligocene, but closed conditions during the Middle Miocene, as well as arid conditions during the Late Oligocene and earliest Late Miocene, less aridity during the Late Miocene, Early Pliocene, and Early Pleistocene, but higher humidity during the Middle Miocene.

The cenograms for the Late Cenozoic mammalian faunas of the Linxia Basin have some differences compared with other paleoecological evidences. The cenogram results for the Late Oligocene and Middle Miocene faunas are rather identical, but those for the Late Miocene, Early Pliocene, and Early Pleistocene faunas are relatively different. These results are roughly correlated with those by Deng and Downs (2002), based on the taxonomic structure of the paleocommunities of large herbivores from the Neogene of China.

This study shows a change from closed to open conditions around the transition from the Middle Miocene to the Late Miocene, followed by an alternating pattern of a more humid environment during the Middle Miocene and a more arid environment since the Late Miocene. These results are consistent with those of other studies conducted in the Linxia Basin and show the same patterns of environmental change as those obtained by similar methods in other parts of China.

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Appendices Estimated mean body weights of the mammals of the Linxia Basin

(* Estimated by comparing the size of the same species from the adjacent area or the allied species of the same genus)

Appendix 1 Jiaozigou fauna

Order	Family	Species	Weight (g)	Rank
Rodentia	Tsaganomyidae	<i>Tsaganomys altaicus</i>	2905	1
Creodonta	Hyaenodontidae	<i>Megalopteron</i> sp.	28507	2
Perissodactyla	Chalicotheriidae	<i>Schizotherium ordosium</i>	619804	3
	Hyracodontidae	Hyracodontidae gen. et sp. indet.	140359 *	4
		<i>Ardynia aldidentata</i>	169248	5
		<i>Ardynia</i> sp.	69164 *	6
		<i>Allacerops</i> sp.	985935	7
	Paraceratheriidae	<i>Dzungariotherium orgosense</i>	24030124	8
		<i>Paraceratherium yagouense</i>	22258121	9
	Rhinocerotidae	<i>Ronzotherium</i> sp.	1911407	10
		<i>Aprotodon lanzhouensis</i>	1098237	11
Artiodactyla	Entenodontidae	<i>Paraentelodon macrognathus</i>	4351615	12

Appendix 2 Laogou fauna

Order	Family	Species	Weight (g)	Rank
Insectivora	Talpidae	Talpidae gen. et sp. indet.	58	1
Primates	Pliopithecidae	<i>Pliopithecus</i> sp.	16300 *	2
Lagomorpha	Ochotonidae	<i>Alloptox chinghaiensis</i>	153	3
		<i>Alloptox guangheensis</i>	328	4
		<i>Alloptox minor</i>	119	5
		Ochotonidae gen. et sp. indet.	108	6
Rodentia	Sciuridae	<i>Atlantoxerus</i> sp.	440	7
	Castoridae	<i>Castor</i> sp.	1219	8
	Ctenodactylidae	<i>Sayimys</i> cf. <i>obliquidens</i>	146	9
	Cricetidae	<i>Megacricetodon sinensis</i>	17	10
	Zapodidae	<i>Heterosminthus orientalis</i>	20	11
	Dipodidae	<i>Protalactaga tungurensis</i>	20	12
Carnivora	Amphicyonidae	<i>Amphicyon tairumensis</i>	213867	13
		<i>Gobicyon</i> sp.	162664	14
	Ursidae	<i>Hemicyon teilhardi</i>	391986	15
	Hyaenidae	<i>Percrocuta tungurensis</i>	134654	16
	Felidae	<i>Pseudaelurus guangheensis</i>	7295	17
Proboscidea	Gomphotheriidae	<i>Gomphotherium</i> sp.	3009953	18
		<i>Serbelodon</i> sp.	1225585 *	19
		<i>Platybelodon grangeri</i>	2518920 *	20
	Mammutidae	<i>Zygodolophon</i> sp.	3418146 *	21
Perissodactyla	Equidae	<i>Anchitherium gobiense</i>	254695	22
	Chalicotheriidae	<i>Chalicotherium</i> sp.	328973	23
	Rhinocerotidae	<i>Alicornops laogouense</i>	2732138	24
		<i>Hispanotherium matritense</i>	1817159	25
Artiodactyla	Suidae	<i>Listriodon mongoliensis</i>	162678	26
		<i>Kubanochoerus gigas</i>	973498	27

Continued

Order	Family	Species	Weight (g)	Rank
Artiodactyla	Tragulidae	<i>Dorcatherium</i> sp.	44019	28
	Cervidae	<i>Moschus</i> sp.	10177	29
		<i>Stephanocemas thomsoni</i>	38131	30
	Giraffidae	<i>Palaeotragus tungurensis</i>	439666	31
	Bovidae	<i>Turcocerus</i> sp.	36005	32

Appendix 3 Guonigou fauna

Order	Family	Species	Weight (g)	Rank
Carnivora	Amphicyonidae	<i>Gobicyon</i> sp.	162664	1
	Hyaenidae	<i>Dinocrocuta gigantea</i>	381105	2
	Felidae	<i>Machairodus palanderi</i>	131099	3
Proboscidea	Deinotheriidae	<i>Prodeinotherium sinense</i>	1463172 *	4
	Gomphotheriidae	<i>Tetralophodon exoletus</i>	1717728	5
Perissodactyla	Equidae	<i>Hipparion dongxiangense</i>	109432 *	6
	Rhinocerotidae	<i>Chilotherium primigenius</i>	944266	7
		<i>Parelasmotherium simplym</i>	6727718 *	8
		<i>Parelasmotherium linxiaense</i>	8146891	9
Artiodactyla		<i>Ningxiatherium euryrhinus</i>	6041953 *	10
	Suidae	<i>Listriodon mongoliensis</i>	162678	11
	Bovidae	<i>Shaanxispira</i> sp.	87985	12

Appendix 4 Dashengou fauna

Order	Family	Species	Weight (g)	Rank	
Rodentia	Siphneidae	<i>Prosiphneus</i> sp.	361	1	
	Rhizomyidae	<i>Pararhizomys hipparionum</i>	792	2	
Carnivora	Ursidae	<i>Indactos</i> sp.	790536	3	
		Mustelidae	<i>Sinictis</i> sp.	4182	4
	<i>Parataxidea sinensis</i>		5749	5	
	<i>Melodon majori</i>		8708	6	
	<i>Promephitis parvus</i>		901	7	
	<i>Promephitis hootoni</i>		1867	8	
	Hyaenidae		<i>Ictitherium</i> sp.	21828	9
			<i>Hyaenictitherium wongii</i>	32354	10
			<i>Hyaenictitherium hyaenoides</i>	53989	11
	Felidae	<i>Dinocrocuta gigantea</i>	381105	12	
		<i>Machairodus palanderi</i>	131099	13	
		<i>Felis</i> sp.	5696	14	
	Proboscidea	Gomphotheriidae	<i>Tetralophodon exoletus</i>	1717728	15
	Perissodactyla	Equidae	<i>Hipparion chiai</i>	204038	16
<i>Hipparion weihoense</i>			224749	17	
Chalicotheriidae		<i>Chalicotherium</i> sp.	1701080 *	18	
Rhinocerotidae		<i>Acerorhinus hezhengensis</i>	5259194	19	
		<i>Chilotherium wimani</i>	2411613	20	
		<i>Iranotherium morgani</i>	5712059	21	
		<i>Diceros gansuensis</i>	5443095	22	
		Suidae	<i>Chleuastochoerus stehlini</i>	44833	23
		Cervidae	<i>Dicrocerus</i> sp.	39863	24
Giraffidae			<i>Samotherium</i> sp.	1029299	25
		<i>Honanotherium schlosseri</i>	1512330	26	
Artiodactyla	Bovidae	<i>Shaanxispira</i> sp.	87985	27	
		<i>Gazella</i> sp.	18033	28	
		<i>Miotragocerus</i> sp.	125567	29	
		<i>Hezhengia bohlini</i>	134376	30	
		Bovidae gen. et sp. nov.	211341	31	

Appendix 5 Yangjiashan fauna

Order	Family	Species	Weight (g)	Rank
Rodentia	Rhizomyidae	<i>Pararhizomys hipparionum</i>	792	1
	Muridae	<i>Micromys</i> sp.	71	2
	Hystriidae	<i>Hystrix gansuensis</i>	31815	3
Carnivora	Procyonidae	<i>Simocyon</i> sp.	70476	4
		<i>Agriotherium inxpetans</i>	556090	5
	Mustelidae	<i>Indactos</i> sp.	790536	6
		<i>Plesiogulo</i> sp.	58374	7
		<i>Parataxidea sinensis</i>	5749	8
	Hyaenidae	<i>Promephitis parvus</i>	901	9
		<i>Promephitis hootoni</i>	1867	10
		<i>Ititherium</i> sp.	21828	11
		<i>Hyaenictitherium wongii</i>	32354	12
		<i>Hyaenictitherium hyaenoides</i>	53989	13
		<i>Adcrocuta eximia</i>	122585	14
		<i>Metailurus minor</i>	27709	15
	Felidae	<i>Metailurus</i> sp.	49428	16
		<i>Machairodus palanderi</i>	131099	17
		<i>Felis</i> sp.	5696	18
Hyracoidea	Procaviidae	<i>Pliohyrax</i> sp.	177549	19
Perissodactyla	Equidae	<i>Sinohippus robustus</i>	784185	20
		<i>Hipparion coelophyes</i>	109148	21
		<i>Hipparion dermatorhinum</i>	124219	22
	Chalicotheriidae	<i>Ancylotherium</i> sp.	1277050	23
	Tapiridae	<i>Tapirus hezhengensis</i>	250402 *	24
	Rhinocerotidae	<i>Acerorhinus hezhengensis</i>	5259194	25
		<i>Shansirhinus ringstroemi</i>	2601720	26
		<i>Chilotherium wimani</i>	2411613	27
		<i>Dicerorhinus ringstroemi</i>	5814225	28
		<i>Chleuastochoerus stehlini</i>	44833	29
	Artiodactyla	Suidae	<i>Microstonyx major</i>	232003
<i>Metacervulus</i> sp.			40136	31
<i>Cervavitus novorossiae</i>			43320	32
Giraffidae		<i>Palaeotragus microdon</i>	462529	33
		<i>Honanotherium schlosseri</i>	1512330	34
Bovidae		<i>Protoryx</i> sp.	134234 *	35
		<i>Gazella</i> sp.	18033	36
		<i>Miotragocerus</i> sp.	125567	37
		<i>Sinotragus</i> sp.	255354 *	38

Appendix 6 Shilidun fauna

Order	Family	Species	Weight (g)	Rank	
Lagomorpha	Leporidae	<i>Alilepus</i> sp.	482	1	
Rodentia	Hystriidae	<i>Hystrix gansuensis</i>	31815	2	
Carnivora	Mustelidae	<i>Sinictis</i> sp.	4182	3	
		<i>Parataxidea sinensis</i>	5749	4	
		<i>Promephitis</i> sp.	1867	5	
	Hyaenidae	<i>Hyaenictitherium wongii</i>	32354	6	
		<i>Adcrocuta eximia</i>	122585	7	
		<i>Chasmaporthetes kani</i>	83802	8	
		<i>Felis</i> sp.	5696	9	
	Proboscidea	Gomphotheriidae	Gomphotheriidae gen. et sp. indet.	2329010 *	10
	Perissodactyla	Equidae	<i>Hipparion licenti</i>	129147 *	11
<i>Hipparion hippidiodus</i>			155171	12	
<i>Hipparion platyodus</i>			151127	13	
<i>Hipparion pater</i>			169708	14	

Continued

Order	Family	Species	Weight (g)	Rank
Artiodactyla	Chalicotheriidae	<i>Hesperotherium</i> sp.	469459 *	15
		<i>Ancylotherium</i> sp.	1797143 *	16
	Rhinocerotidae	<i>Shansirhinus ringstroemi</i>	2601720	17
	Cervidae	<i>Cervavitus novorossiae</i>	43320	18
	Giraffidae	<i>Palaeotragus microdon</i>	462529	19
		<i>Samotherium</i> sp.	1029299	20
	Bovidae	<i>Gazella blacki</i>	23777 *	21
		<i>Sinotragus</i> sp.	255354 *	22
		<i>Capricornis</i> sp.	132252	23

Appendix 7 Longdan fauna

Order	Family	Species	Weight (g)	Rank		
Primates	Cercopithecidae	<i>Macca</i> cf. <i>M. anderssoni</i>	26930	1		
		<i>Paradolichopithecus gansuensis</i>	40002	2		
Lagomorpha	Leporidae	<i>Sericolagus brachypus</i>	423	3		
Rodentia	Sciuridae	<i>Aepyosciurus orientalis</i>	286	4		
		<i>Marmota parva</i>	754	5		
	Castoridae	<i>Castor anderssoni</i>	27686	6		
	Siphneidae	<i>Myospalax</i> sp.	780	7		
	Arvicolidae	<i>Mimomys</i> cf. <i>gansunicus</i>	102	8		
	Cricetidae	<i>Bahomys</i> sp.	120	9		
Carnivora	Canidae	<i>Vulpes chikushmanensis</i>	6410	10		
		<i>Canis teilhardi</i>	82388	11		
		<i>Canis longdanensis</i>	79325	12		
		<i>Canis brevicephalus</i>	153207	13		
		<i>Sinicuon</i> cf. <i>dubius</i>	66633	14		
		Ursidae	<i>Protarctos yinanensis</i>	52841	15	
		Mustelidae	<i>Eirictis robusta</i>	17118	16	
			<i>Meles teilhardi</i>	13054	17	
		Hyaenidae	<i>Chasmaporthetes progressus</i>	92204	18	
			<i>Pachycrocuta licenti</i>	130601	19	
			<i>Crocuta honanensis</i>	78232	20	
			Felidae	<i>Homotherium crenatidens</i>	175072	21
				<i>Megantereon nihowanensis</i>	64903	22
				<i>Sivapanthera linxiaensis</i>	55417	23
	<i>Panthera palaeosinensis</i>	57375		24		
	<i>Felis teilhardi</i>	9581	25			
	<i>Lynx shansius</i>	12860	26			
	Proboscidea	Elephantidae	Elephantidae gen. et sp. indet.	3994735 *	27	
	Hyracoidea	Procaviidae	<i>Postschizotherium</i> sp.	320645	28	
	Perissodactyla	Equidae	<i>Hipparion sinense</i>	262032	29	
<i>Equus eisenmannae</i>			682112	30		
Artiodactyla	Chalicotheriidae	<i>Hesperotherium</i> sp.	577099	31		
	Rhinocerotidae	<i>Coelodonta nihowanensis</i>	3007620	32		
	Suidae	<i>Sus</i> sp.	140916	33		
	Cervidae	<i>Nipponicervus longdanensis</i>	121966 *	34		
	Bovidae	<i>Gazella</i> cf. <i>G. blacki</i>	23777 *	35		
		<i>Budorcas</i> sp.	225116	36		
		<i>Leptobos brevicornis</i>	304320	37		
		<i>Hemibos gracilis</i>	267465 *	38		