

## Early Paleogene stratigraphic sequences, mammalian evolution and its response to environmental changes in Erlian Basin, Inner Mongolia, China

WANG YuanQing<sup>1\*</sup>, MENG Jin<sup>2</sup>, Christopher K. BEARD<sup>3</sup>, LI Qian<sup>1</sup>, NI XiJun<sup>1</sup>, Daniel L. GEBO<sup>4</sup>, BAI Bin<sup>1</sup>, JIN Xun<sup>1</sup> & LI Ping<sup>1</sup>

<sup>1</sup> *Laboratory of Evolutionary Systematics of Vertebrates, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing 100044, China;*

<sup>2</sup> *Division of Paleontology, American Museum of Natural History, New York NY 10024, USA;*

<sup>3</sup> *Section of Vertebrate Paleontology, Carnegie Museum of Natural History, 4400 Forbes Avenue, Pittsburgh, PA 15213, USA;*

<sup>4</sup> *Department of Anthropology, Northern Illinois University, DeKalb, IL 60115, USA*

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Paleogene strata in the Huheboerhe area, Erlian Basin, Inner Mongolia, China have been subdivided into three lithological units: the Nomogen Formation, the Arshanto Formation, and the Irдин Manha Formation. At least 12 mammal-bearing horizons have been recognized in these formations, of which 4 in the Nomogen Formation, 6 in the Arshanto Formation, and 2 in the Irдин Manha Formation. Recent investigation proved that the “Houldjin Formation” recognized in this area by the Central Asiatic Expeditions (CAE) of the American Museum of Natural History in the 1920s is actually the Irдин Manha Formation, while the “Irдин Manha Formation” of CAE is the Arshanto Formation. A recent paleomagnetic study suggests that the upper part of the Nomogen Formation is early Eocene in age and the Arshanto Formation is mainly early Eocene rather than middle Eocene as previously thought. The Gashatan, Bumbanian, and Arshantan land mammal ages are correlated respectively to the Thanetian, the early Ypresian, and the middle Ypresian through earliest Lutetian of the Geological Time Scale. These land mammal ages are also correlated with the late Tiffanian through Clarkforkian, the early Wasatchian, and the middle-late Wasatchian and most of the Bridgerian of the North American Land Mammal Ages. During the early Paleogene, the mammalian history of the Erlian Basin was dominated by the appearance of new mammalian families and the replacement of a variety of genera and species, corresponding to the gradual climatic changes during this time period. The abrupt emergence of several modern mammalian orders at the beginning of the Eocene is probably related to extreme climatic warming in relation to the Paleocene-Eocene Thermal Maximum.

### Erlian Basin, Paleogene, mammal, faunal turnover, biochronology, environmental response

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The Mongolian Plateau is one of the most important regions in Paleogene vertebrate paleontological and stratigraphical research in the world. Since the investigation of the CAE of

the American Museum of Natural History in the 1920s, a number of mammalian localities have been discovered and many specimens have been collected from these localities [1]. Paleogene Asian Land Mammal Ages (ALMAs) were primarily based on the mammalian faunas from this region [1, 2]. Those land mammal ages form the framework of

\*Corresponding author (email: wangyuanqing@ivpp.ac.cn)

Asian mammalian biochronology and are considered the age references in Paleogene studies of eastern Asia as well as having been widely adopted both in the regional and intercontinental correlation of terrestrial Paleogene. They are also commonly referred to in studies considering faunal turnovers and the paleobiogeography of Paleogene mammals [3–7]. However, the lack of an independent age constraint for these Paleogene ALMAs not only affects intercontinental biostratigraphic correlations, but hampers our understanding of the evolutionary history of major mammalian groups.

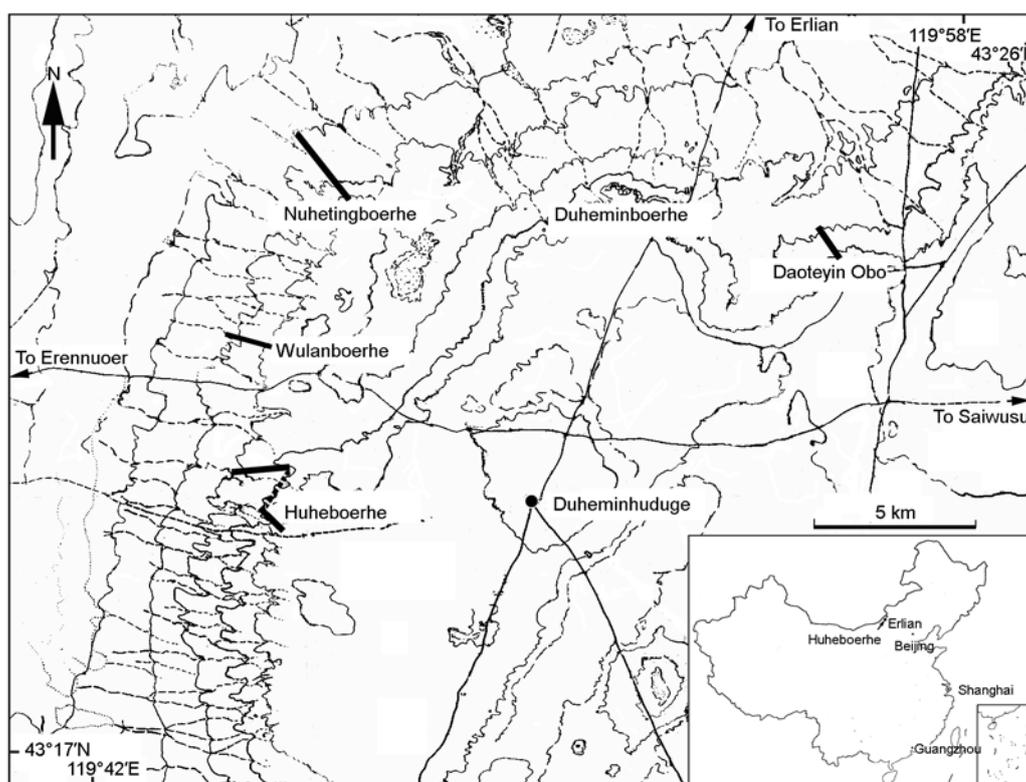
The Paleogene strata with rich fossil mammals [1, 8] are well exposed in central Inner Mongolia, China, especially in the Erlian Basin [9]. A number of Paleogene lithologic units were named in this area and several ALMAs are based on local mammalian faunas [2, 7, 10, 11]. The Erlian Basin thus bears importantly on Asian Paleogene mammalian biostratigraphy and biochronology. However, the great lateral variation of lithology and partial exposure of outcrops at the sites where the lithologic units were named have resulted in the misinterpretation of the lithostratigraphic divisions and their correlations. These geological problems have resulted in a mixture of faunal compositions and have not been resolved to date [12–15]. From 2004 through 2007, a comprehensive investigation in the eastern part of the Erlian Basin clarified a number of long-standing problems in lithostratigraphy and biostratigraphy [16] and improved the

biostratigraphic sequence in this area. This information, along with a paleomagnetic study [17], strongly enhanced mammalian biochronology in the Erlian Basin.

## 1 Geological settings

The Erlian Basin is located in the central Inner Mongolia and close to the China-Mongolia border (Figure 1). The Paleogene deposits are well exposed in the basin. In its eastern part, exposures are mainly strata of lower Paleogene, including 3 formations: the Nomogen Formation, the Arshanto Formation, and the Irdin Manha Formation [14, 16, 18].

The Nomogen Formation was named at a section at Hailiutu (=Haliut) of Nomogen, Siziwang Qi, Inner Mongolia. It consists of sandstone, muddy sandstone, and sandy mudstone [18, 19]. Both the Arshanto Formation and the Irdin Manha Formation were named at the Irdin Manha escarpment, about 30 km southeast of the Erlian city. All the deposits exposed at the section were originally referred to the Irdin Manha Formation [20]. In 1924, the red mudstone and siltstone at the lower part of the section were separated from the upper part and tentatively called the Arshanto Formation, after the name of the Arshanto Obo about 11 km away northeast [21]. Later, the red mudstone and siltstone at the lower part of the section were unambiguously separated as the Arshanto Formation [22]. The Irdin Manha Formation



**Figure 1** Sketch map showing the location of sections in the Huheboerhe area, Erlian Basin, Inner Mongolia. Modified from Meng et al. [16].

was thus restricted to the white sandy mudstone, sandstone, and conglomerates at the upper part of the section.

The age of the Nomogen Formation has been considered for a long time to be limited to the Paleocene [10, 19, 23, 24]. In the Bayan Ulan area, the age of the “Bayan Ulan Formation” was reported to be Early Eocene, but the fossil mammals listed from this “formation” are typical Paleocene forms [18]. A later study suggested that the “Bayan Ulan Formation” was probably a lithofacies variation of the Nomogen Formation and its age should be Paleocene [25]. The Arshanto Formation was considered to be Middle Eocene [10] or Early-Middle Eocene [7, 11] in age, while the Irdin Manha Formation was of Middle Eocene age [7, 8, 10, 11]. The Lower Eocene in the Erlian Basin was not recognized until the typical Mongolian Early Eocene mammals, such as *Gomphos elkema*, were found in the upper part of the Nomogen Formation at Wulanboerhe [16].

In the Huheboerhe area, roughly the Camp Margetts and adjacent area of CAE, four sections were measured. They are located at Daoteyin Obo, Nuhetingboerhe, Wulanboerhe, and Huheboerhe, respectively (Figure 1). A composite section, based on both the Nuhetingboerhe and Huheboerhe sections, represents all Paleogene strata exposed in the area (Figure 2). Its total thickness is 82.5 m. Two unconformities demarcate the strata into 3 parts: the Nomogen Formation (37.5 m thick), the Arshanto Formation (35.2 m), and the Irdin Manha Formation (9.8 m) from the bottom up [16]. The composite section is described as follows:

#### Irdin Manha Formation

18. Grayish white sandy conglomerates with poorly sorted and rounded, dark-colored debris, yielding *Lophialetes expeditus* and *Protitan* sp. On the top of the mesa, or the Gobi plain, are sandstone and conglomerates consisting of particles of quartz that are better sorted and rounded. 4.2 m

17. Gray muddy sandstone and coarse sandstone containing lumps of reddish mudstone from underlying beds and some white nodules; thin-bedded yellowish green sandy mudstone and sandstone, intercalated with lenses of conglomerate and reddish sandy mudstone. The contact surface with the underlying beds is distinctively uneven. This bed is richly fossiliferous, including *Tarkops mckennai*, *Propterodon morisi*, *Harpagolestes leei*, *Andrewsarchus mongoliensis*, *Lophialetes expeditus*, *Deperetella* sp., *Gomphos shevyrevae*, *Tamquammys* sp., *Asiomys* sp., Cricetidae, Yuomyidae, and Lagomorpha. 5.6 m

----- Disconformity (upper hiatus) -----

#### Arshanto Formation

16. Variegated (earthy or reddish) sandy mudstone and siltstone, containing *Schlosseria magister*. 4.9 m

15. Grayish green, variegated sandy siltstone and fine sandstone, with uneven contact with the underlying beds, containing nodules of mudstone from underlying beds and yielding *Schlosseria magister*, *Gobiotherium mirificum*, *Fostercooperia confluens*, *Tamquammys* sp., Yuomyidae. 7.7 m

14. Light brownish siltstone or mudstone, also with black stain on the surface. The contact surface with the underlying

beds is uneven, but does not look like a significant depositional hiatus. Some levels are sandier and the top 30 cm of the beds are more reddish. Fossils from this bed include *Schlosseria magister* and *Teleolophus* sp. 2.1 m

13. Earthy, muddy siltstone intercalated with sandy lenses with *Schlosseria magister*, *Tamquammys* sp., and rodents of Yuomyidae. 8.1 m

12. Reddish sandy mudstone, with black stain and manganic nodules. Rich in *Schlosseria magister* and also yielding *Sinosinopa sinensis*, *Archetypomys erlianensis*, *Erlianomys combinatus*, *Tamquammys wilsoni*, *Advenimus burkei*, Apternodontidae, and Lagomorpha. 2.7 m

11. Variegated, primarily grayish green, siltstone interbedded with fine sandstone and mudstone. Some bone fragments and petrified wood are usually from the lower grayish green beds. 4.4 m

10. Fluvial sandstone, coarse sandstone with small debris and purplish mudstone with cross-bedding, producing *Archetypomys erlianensis*, *Erlianomys combinatus*, *Advenimus burkei*, *Tamquammys wilsoni*, Paramyidae, Apternodontidae, *Dawsonolagus antiquus*, *Gobiotherium mirificum*, *Metacoryphodon luminis*, *Litolophus gobiensis*, *Schlosseria magister*, *Teleolophus* sp., *Hyrachyus* sp. and *Mesonyx üqbulakensis*. 5.3 m

----- Disconformity (lower hiatus) -----

#### Nomogen Formation

9. Reddish sandy mudstone with white large and irregular calcareous nodules at the basal beds of 20–30 cm. The beds become more variegated (brownish red, grayish green) and sandy in upper parts, with weathered surface being earthy brown. Fossils from this bed include *Gomphos elkema*, *Baataromomys ulaanus*, *Anatolostylops zhii*, *Pataacops parvus*, Lophialetidae gen. et sp. nov., Ctenodactyloidea gen. et sp. nov. and Lagomorpha. A pair of fragmentary lower jaws of *Uintatherium* sp. was collected from the upper part of the strata. The basal beds rich in *Gomphos elkema* are called *Gomphos*-bearing beds. 7 m

8. Brownish red sandy mudstone with grayish green nodules, black stain patches and manganese nodules. The beds become more reddish upward. 6.2 m

7. Earthy brown and red muddy sandstone, weathering surface light brown, containing calcareous and sandy nodules, some of which are of elongated “fish-dropping” shape, and others are irregular. 5–10 cm thick, unstable lenses with white nodules outcropping on tops of small hills. Fossil mammals include *Lambdopsalis bulla* and *Pastoralodon lacustris*. 8.6 m

6. Variegated muddy sandstone and coarse sandstone. 2.7 m

5. Brownish red sandy mudstone with nodules 2–20 mm in diameter, dominated by small ones, which grade into variegated sandy mudstone and fine sandstone with pebbles. 2.8 m

4. Grayish white and green fine sandstone, with horizontal bedding. The lower beds contain white calcareous nodules ranging from 5–40 mm in diameter and many segments of petrified woods. The beds become sandy mudstone and more variegated (grayish brown, green) upward. 1.7 m

3. Variegated (earthy yellow, light reddish) sandy mudstone, with nodules of mudstone and petrified wood, rich in fossil mammals including *Lambdopsalis bulla*, *Prionessus lucifer*, *Bayanulanius tenuis*, *Tribosphenomys minutus*, *Eomyulus*

*borealis*, *Prodinoceras xinjiangensis* and *Palaeostylops iturus*. 3.4 m

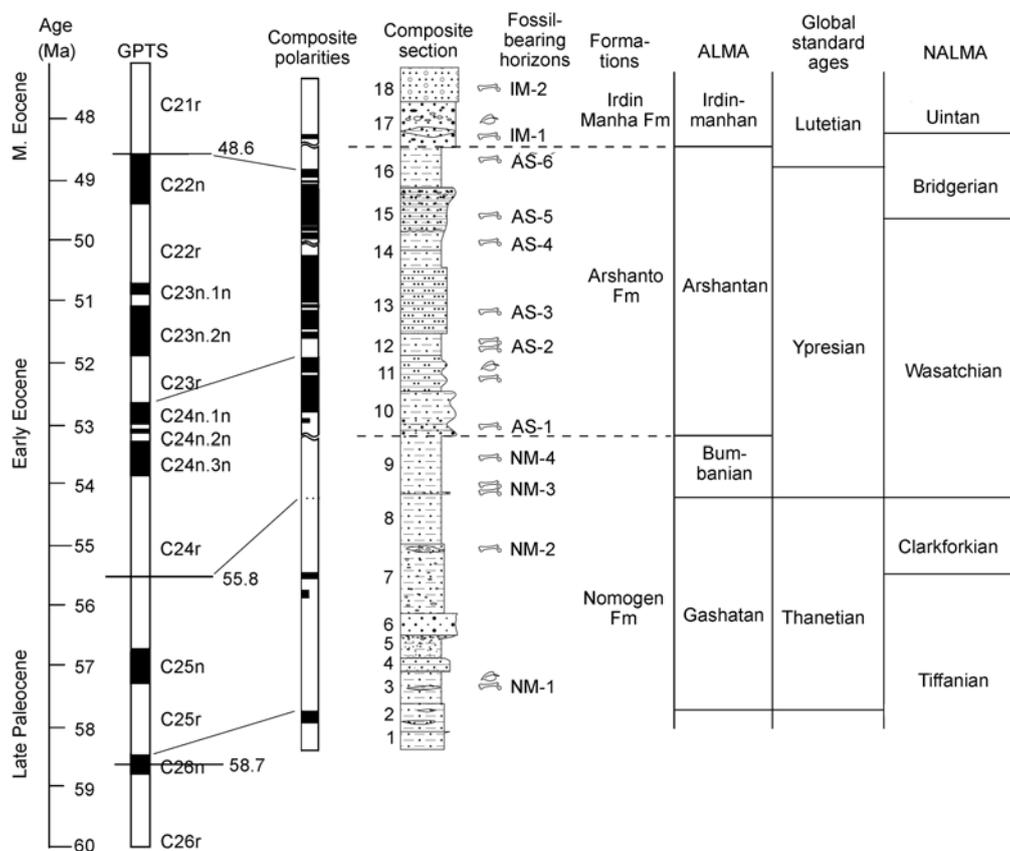
2. Brownish red muddy sandstone, soft and containing small nodules, no bedding structure, intercalated with yellowish green sandstone lens and siltstone with fine bedding; weathered surface coffee-colored. 2.9 m

1. Pale grayish green sandy clay, structureless, containing small debris of rock, capped by a layer of 5–10 cm thick hard sandstone. 2.2 m

Base of the formation is not exposed.

In general, the Nomogen Formation consists of red mudstone, silty mudstone, and intercalated sandstone. The Arshanto Formation has coarse sandstone with gravels at the base, and primarily muddy siltstone upwards, whereas the Irdin Manha Formation mainly consists of coarse sandstone with pebbles. Our extensive fieldwork and careful laboratory comparison to the CAE field notes have ascertained the location of the major fossil sites near Camp Margetts. Camp Margetts is located somewhere near Duheminboerhe. The site called 6 miles (9.6 km) west of Camp Margetts is nowadays Nuhetingboerhe, while the site named 10 miles (16 km) west of Camp Margetts is Huheboerhe. 7 miles (11 km) at 235° of Camp Margetts and 7 miles (11 km) west of Camp Margetts are respectively Wulanboerhe and a site north of Wulanboerhe. Lithological comparison with the

type sections, incorporated with fossil evidence, shows that the so-called “Houldjin Formation” of CAE in the Camp Margetts and its adjacent area is actually the Irdin Manha Formation, and the “Irdin Manha Formation” is indeed the Arshanto Formation. This idea was proposed previously, but several misinterpretations exist in the literature relating to these localities and horizons. Camp Margetts was considered to be located at Huheboerhe, and the sites southwest and west of it were thought to be in the Bayan Ulan area [14]. This was pointed out to be wrong by Meng [12] in 1990 who considered Camp Margetts at Duheminboerhe. In more recent publications, Wulanboerhe has been misinterpreted as Huheboerhe, while the grayish white coarse sandstone with gravels (basal Arshanto Formation) there was considered as the “Irdin Manha Formation” [26, 27]. More recently, due to the misunderstanding of the sketch of a section at 7 miles west of Camp Margetts in Granger’s field notes of 1930 to be that of 7 miles at 235° of Camp Margetts, the “Irdin Manha Formation” of the CAE in Camp Margetts and its adjacent area (i.e., the Huheboerhe area) was interpreted to “belong to the Arshanto and/or Nomogen formations” [16]. However, examination of our new data and the field notes of the CAE [28] clarifies that no fossils thought from the “Irdin Manha Formation” in this area by the CAE were collected from the Nomogen Formation.



**Figure 2** Paleogene stratigraphy, paleomagnetic polarities, mammalian horizons and their correlation in the eastern Erlian Basin. Paleomagnetic data is from ref. [17] and the section was modified from the ref. [16].

## 2 Horizons of fossil mammals

Many beds of the lower Paleogene in the Erlian Basin are fossiliferous. Previous collectors, however, often lumped all fossils from a long stratigraphic sequence into a single fauna [1, 8, 13, 14]. In addition, due to errors in stratigraphic correlation, the composition of adjacent faunas of different ages was mixed. During our field investigations, fossils were systematically collected with detailed stratigraphic data. Twelve mammal-bearing horizons were recognized in the Paleogene of the Huheboerhe area, including 4 in the Nomogen Formation, 6 in the Arshanto Formation, and 2 in the Irdin Manha Formation. These horizons are labeled in ascending order as NM-1 to NM-4, AS-1 to AS-6, and IM-1 to IM-2 (Figure 2). While many specimens are still under study, those that have been reported or identified are listed in each horizon. The bed that contains the fossils in each horizon is denoted at the end, with the number corresponding to those in the description of the composite section and in Figure 2.

IM-2: Perissodactyl *Lophialetes expeditus* and *Protitan* sp. (18).

IM-1: The primate *Tarkops mckennai* [29], the creodont *Propterodon morrisoni*, the mesonychid *Harpagolestes leei* and *Andrewsarchus mongoliensis*, the perissodactyl *Lophialetes expeditus* and *Deperetella* sp., the glires *Gomphos shevyrevae* [30], the rodent *Tamquammys* sp., *Asiomys* sp., Cricetidae, and Yuomyidae, and lagomorph (17).

AS-6: The perissodactyl *Schlosseria magister* (16).

AS-5: The perissodactyl *Schlosseria magister* and *Fostercooperia confluens*, the dinoceratan *Gobiatherium mirificum*, and the rodent *Tamquammys* sp. and Yuomyidae (15).

AS-4: The perissodactyl *Schlosseria magister* and *Teleolophus* sp. (14).

AS-3: The perissodactyl *Schlosseria magister*, and the rodent *Tamquammys* sp. and Yuomyidae (13).

AS-2: The perissodactyl *Schlosseria magister* [31], the lagomorph *Dawsonolagus antiquus*, the rodent *Archetypomys erlianensis* [32], *Erlianomys combinatus* [33], *Tamquammys wilsoni* and *Advenimus burkei*, and insectivore *Sinosinopa sinensis* and Apternodontidae (12).

AS-1: The rodent *Archetypomys erlianensis* [32], *Erlianomys combinatus* [33], *Tamquammys wilsoni*, *Advenimus burkei* and Paramyidae, the lagomorphs *Dawsonolagus antiquus* [34], an apternodontid insectivore, the perissodactyl *Litolophus gobiensis* [35], *Schlosseria magister*, *Teleolophus* sp. and *Hyrachyus* sp., the dinoceratan *Gobiatherium mirificum* [36], the pantodont *Metacoryphodon luminis*, and the mesonychid *Mesonyx üqbulakensis* (10).

NM-4: The glires *Gomphos elkema*, the dinoceratan *Uinatherium* sp. [36], the perissodactyl *Pataecops parvus*, and a ctenodactyloid rodent (upper part of 9).

NM-3: The glires *Gomphos elkema* [27], the primate

*Baataromomys ulaanus* [37], the arctostylopid *Anatolestylops zhaii* [38], the mesonychid *Dissacus* sp., the perissodactyl *Pataecops parvus* and a new species of Lophialetidae [39], a new ctenodactyloid rodent, and a lagomorph (lower part of 9).

NM-2: The pantodont *Pastoralodon lacustris* and the multituberculate *Lambdopsalis bulla* (uppermost of 7).

NM-1: The multituberculate *Lambdopsalis bulla* and *Prionessus lucifer*, the arctostylopid *Palaeostylops iturus*, the dinoceratan *Prodinoceras xinjiangensis*, the insectivore *Bayanulanius tenuis*, the pseudictopid *Pseudictops lophiodon*, and the glires *Tribosphenomys minutes* (3).

In addition to the above listed fossil mammals, fossils that found from the “Irdin Manha Formation” by the CAE in the Huheboerhe area are actually from the Arshanto Formation, including the mesonychid *Mongolonyx dolichognathus* [40], the creodont *Sarkastodon mongoliensis* [41], the perissodactyl *Metatelmatherium cristatum* [42], *Helaletes fissus* [43]. Fossils originally thought to be from the “Houldjin Formation” are mainly from the Irdin Manha Formation.

Moreover, fossil assemblages of the Nomogen Formation in both the Bayan Ulan area and the Subeng area [25, 44–48] are generally correlative to the NM-1.

Biostratigraphically, the Paleocene-Eocene (P-E) boundary in the Huheboerhe area of the Erlian Basin is best placed between NM-2 and NM-3 [49], which is consistent with the paleomagnetic data [17]. However, failing to obtain any carbon isotope evidence hampered a precise determination of the P-E boundary in the Huheboerhe area. Nevertheless, biostratigraphic correlation to the Lingcha area of the Hengyang Basin, Hunan Province provided additional evidence for the boundary identification. Several species from the Lingcha Formation in the Lingcha area are comparable to those of Bumbanian in the Nemegt Basin of Mongolia and are thought to be contemporaneous. Similarities of the NM-3 fossils to those of the Bumbanian support a biostratigraphic correlation with the Bumbanian beds in the Nemegt Basin. In addition, mammal-bearing beds of the Lingcha Formation are also lithologically rich in calcareous nodules, similar to the *Gomphos*-bearing beds [49]. Paleomagnetic and carbon isotope studies show that the Lingcha mammal-bearing beds occur within Chron C24r of the Geomagnetic Polarity Timescale (GPTS) and the interval of the carbon isotope excursion, so that the Early Eocene age of the Lingcha fauna is constrained [3, 50]. With all data at hand, we propose to place the P-E boundary in the Huheboerhe area at the base of the horizon NM-3.

## 3 Mammalian biochronology

Mammalian biochronological studies in the Cenozoic of North America have a wide influence around the world. Since the proposal of the North American Land Mammal

Ages [51], related studies have made great progress in both theoretical and practical aspects [52, 53]. Synthetic studies on fossil mammals, biostratigraphy, paleomagnetism, radiometric dating, and chemostratigraphy have improved the Cenozoic land mammal age system, and further made the entire system well correlated to the Geological Time Scale [54–57] and better associated chronologically with the global events in deep geological history [58]. The Asian Paleogene land mammal age system has been generally completed [7] after many years' improvement [1, 2, 8, 10, 59], and widely adopted [4]. The Paleogene in the Huheboerhe area of the Erlian Basin, Inner Mongolia relates to 4 Asian land mammal ages: Gashatan, Bumbanian, Arshantan, and Irdinmanhan.

The Gashatan was derived from the mammalian fauna of the Member I of the Gashato Formation in the Ulan-Nur Basin, while the Bumbanian was based on the mammal fauna from the Bumban Member of the Naran-Bulak Formation in Nemget Basin, Mongolia [2].

Fossil mammals from both the NM-1 and NM-2 horizons are typical late Paleocene Gashatan forms and all genera and species are only known from the equivalent strata in both China and Mongolia [8, 23–25, 44, 60]. *Gomphos elkema* from both the NM-3 and NM-4 horizons is a typical mammal species of the Mongolian Early Eocene Bumbanian [27, 61]. The euprimates *Baataromomys ulaanus* from the NM-3 is very similar to "*Teilhardina*" *brandti* of Wasatchian (Wa-0) [62] and both are thought to be congeneric [37]. The available fossil evidence suggests that both the NM-1 and NM-2 horizons in the Huheboerhe area belong to the Gashatan age and both the NM-3 and NM-4 horizons to the Bumbanian age.

The Arshantan and Irdinmanhan were respectively proposed on the basis of mammalian faunas from the Arshanto and Irdin Manha formations in the eastern Erlian Basin [2]. Fossil mammals found in the Arshanto and Irdin Manha formations are thus members of the Arshantan and Irdinmanhan mammalian faunas (Figure 2).

The Asian Paleogene land mammal ages have been used for nearly 30 years, but they lack age constraints. Early paleomagnetic work did not focus on the age constraints of related land mammal ages [3, 26, 63, 64]. In recent years, paleomagnetic works aiming at age constraints for Paleocene land mammal ages have been conducted in several basins in southern China [65, 66]. The time intervals for other Paleogene land mammal ages were mainly based on intercontinental biostratigraphic correlations with North American Paleogene [4, 7, 10, 11]. Because no samples could be used for radiometric dating in the Huheboerhe area, paleomagnetic study became the only useful approach in the age calibration of the related land mammal ages. With the recent paleomagnetic result in the Huheboerhe area [17], the time range for the related land mammal ages can be deduced with some precision.

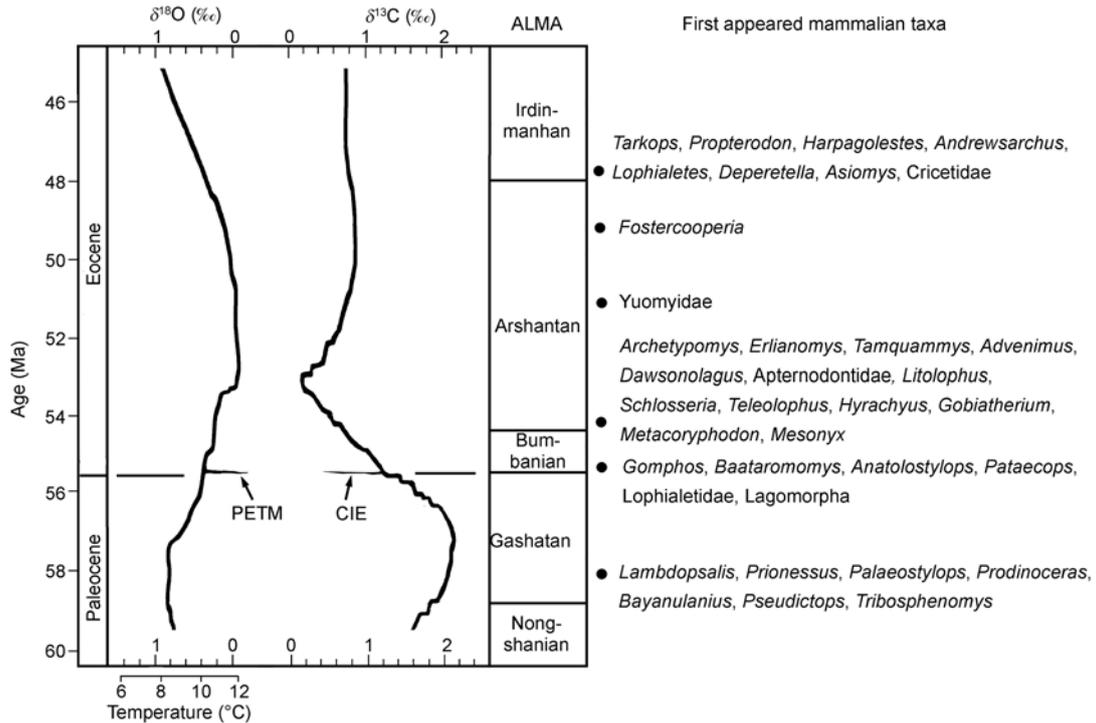
Paleomagnetic result in both the Nuhetingboerhe and the

Huheboerhe sections shows that the Paleogene in the Huheboerhe area recorded 5 normal polarity and 6 reversed polarity intervals, correlated to Chron C26r–C21r of the GPTS [17]. Currently, the Paleocene Nongshanian-Gashatan boundary has not been precisely determined due to a poor section of deposits at this boundary level. However, the paleomagnetic study in both the Chijiang Basin, Jiangxi and the Nanxiong Basin, Guangdong proves that the Nongshanian strata are mainly within Chron C26r [65, 66], while the paleomagnetic result in the Huheboerhe area indicates that the lower horizon containing the Gashatan mammals (NM-1) is in the lower part of the Chron C25r [17]. The Nongshanian-Gashatan boundary can be provisionally put at the base of Chron C26n. Given this consideration, the Gashatan land mammal age ranges from 58.8 through 55.8 Ma, corresponding to the Chron C26n to the lower part of C24r. The time interval of the Bumbanian land mammal age is from 55.8 to 54.8 Ma, equivalent to the middle part of the Chron C24r. The Arshantan land mammal age is from 54.8 through 47.6 Ma, correlating with the upper part of the Chron C24r to the Chron C21r. The upper limitation for the Irdin Manha Formation is not truncated in the Huheboerhe area, therefore, only the lower boundary (i.e., the Arshantan-Irdinmanhan boundary) can be determined within the upper part of the Chron C21r (Figure 2).

Based on these results, the related Asian land mammal ages can be correlated to the Geological Time Scale and to North American Land Mammal Ages. In chronological order, the Gashatan land mammal age is roughly equivalent to the Thanetian age, the Bumbanian land mammal age is correlative to the early Ypresian age, and the Arshantan land mammal age is correlative to the middle-late Ypresian and the earliest Lutetian. Biochronologically, the Gashatan correlates with the late Tiffanian through the Clarkforkian, the Bumbanian is equivalent to the early Wasatchian, and the Arshantan is equivalent to the middle-late Wasatchian and most of the Bridgerian (Figure 2).

#### 4 Mammalian evolution and its response to environmental change

The oxygen isotope record in the ocean deposits shows that the surface temperature of the ocean generally rose from the late Late Paleocene to the early Eocene climatic optimum. During this time period, a rapid climatic change, the Paleocene-Eocene Thermal Maximum (PETM), occurred with an association of the negative carbon isotope excursion (CIE). After the Early Eocene Climatic Optimum, the ocean temperature decreased gradually, and eventually resulted in the global cooling at the Eocene/Oligocene boundary [67]. Paleomagnetic calibrations provide evidence for indirectly correlating the land mammal ages related to the Paleogene in the Huheboerhe area to that of the ocean oxygen and carbon isotope curves (Figure 3).



**Figure 3** Correlation of mammalian events in the Huheboerhe area, Erlian Basin to the global environmental change. The curves of oxygen and carbon isotope are redrawn after the ref. [68]. The dots (•) indicate the position in the section of the first appearance of some mammalian families or genera.

The fossil mammal record in the Huheboerhe area reflects the general trends in early Paleogene mammalian evolution (Figure 3). During the Paleocene Gashatan land mammal age, the mammalian fauna was dominated by the archaic groups (e.g., pantodonts, dinoceratans, arctostyloids, and multituberculates), and associated with rare ancestral forms of modern mammalian groups such as the primitive glires—the ancestor of Rodentia. In the Early Eocene Bumbanian land mammal age, a number of ordinal groups of mammals appeared including perissodactyls, euprimates, rodents, and lagomorphs. Meanwhile, the archaic groups underwent generic and specific changes (e.g., pantodonts, dinoceratans, and arctostyloids) or regionally disappearance (e.g., multituberculates). In general, the archaic groups are distinctly minor components in the faunal compositions and decreased in overall number of species [7]. It is worth mentioning that the hyracodontid, *Pataecops parvus*, from the Bumbanian, is so far the earliest known record of rhinocerotoids. *Pataecops* coexisted with a new form of lophialetid tapiroids. Both forms are previously unknown in the deposits of equivalent age around the world. Considering the fact that the representatives of chalicotheroids (Mongolia), equids (North America) and isctolophids (Asia, North America, and Europe) have been found in contemporaneous deposits, it is clear that the perissodactyls began to diversify at the beginning of the Eocene and all major lineages appeared, which established the basis for their flourish in the whole Eocene epoch. Following the distinct turnover at the P-E boundary, members of the ar-

chaic mammalian groups further decreased, and the history of modern mammals is characterized by the replacement of genera and species. The appearance of new perissodactyl and rodent forms, including deperetellids, hyrachids, and brontotheriids of the Perissodactyla and archetypomyids, myodonts, yuomyids and cricetids of the Rodentia is especially relevant and both orders became the most diversified groups among Eocene mammals. These trends in mammalian evolution are coincident with the fossil records in other regions [7].

Mammalian evolution in the early Paleogene, as suggested by the fossil records in the eastern Erlian Basin and other regions, appears in a pattern likely responding to global environmental change. From the late Paleocene to the early Middle Eocene, the global temperature experienced mostly a gradual change. A gradual succession and transition dominated mammalian history. In contrast, the PETM obviously corresponds to the jumping pattern for mammalian evolution. During the PETM, the average global temperature increased by about 5°C in a relatively short time [68] corresponding to a significant turnover in the land mammal faunas. This time of change resulted in the appearance of several mammalian orders that reshaped mammalian faunas with modern features observed today.

## 5 Conclusion

Our recent field and laboratory work have made several

accomplishments:

(1) We have corrected errors in the stratigraphic subdivision and correlations and clarified the composition of certain mammalian faunas. We confirmed that the “Houldjin Formation” of the CAE in Camp Margetts and its adjacent area is actually the Irdin Manha Formation, while the “Irdin Manha Formation” of the CAE is in fact the Arshanto Formation. The mammalian composition of the related Arshantan and Irdinmanhan faunas were reorganized accordingly.

(2) We recognized 12 mammal-bearing horizons in the Paleogene in the Huheboerhe area, including 4 in the Nomogen Formation (NM-1 to NM-4), 6 in the Arshanto Formation (AS-1 to AS-6), and 2 in the Irdin Manha Formation (IM-1 and IM-2).

(3) We provide far better chronological data for several formations including the time ranges of related land mammal ages. We confirm that the upper part of the Nomogen Formation is early Eocene in age. The Arshanto Formation is mostly early Eocene rather than middle Eocene. The Gashatan, Bumbanian, and Arshantan land mammal ages are correlated respectively to the Thanetian, the early Ypresian, and the middle Ypresian through the earliest Lutetian of the Geological Time Scale. These land mammal ages are also correlated to the late Tiffanian through Clarkforkian, the early Wasatchian, and the middle-late Wasatchian and majority of the Bridgerian of the North American Land Mammal Ages.

(4) New fossil evidence from the Huheboerhe area shows that the appearance of new mammalian families and the replacement of genera and species were primary events in the early Paleogene mammalian evolution. The PETM is likely the major environmental factor that affected the appearance of mammalian faunas with modern aspects.

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