

Paleogene integrative stratigraphy and timescale of China

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Abstract The Paleogene is the first period after the Mesozoic Mass Extinction. Mammals become the dominant group in the terrestrial ecosystem with a rapid radiation, and Asia has been considered to be the origin place of several mammalian groups. The Paleogene System consists mostly of terrestrial deposits in Asia, especially in East Asia. A well-established regional chronostratigraphic framework is the foundation for understanding both the Paleogene geologic history and evolutionary history of Asia and their relationships. The Paleogene is subdivided into the Paleocene, Eocene and Oligocene in the International Chronostratigraphic Chart. Based on the land mammal ages, the Chinese terrestrial Paleogene can be subdivided into 11 stages: the Shanghuan, Nongshanian and Bayanulanian stages of the Paleocene, the Lingchan, Arshantan, Irдинmanhan, Sharamuronian, Ulangochuian and Baiyinian stages of the Eocene, and the Ulantatalian and Tabenbulukian stages of the Oligocene. These stages have distinctive paleontological characters, with special significance of fossil mammals, which provide a reliable practical basis. The bases of the Shanghuan, Lingchan, and Ulantatalian stages are coincident respectively with those of the Paleocene, Eocene and Oligocene. The ages for their bases are determined as 66.0, 56.0 and 33.9 Ma, respectively, following that for the corresponding series in the International Chronostratigraphic Chart. For other stages, estimated ages are provided based on available paleomagnetic results.

Keywords Paleogene, Correlation, Biostratigraphy, Magnetostratigraphy, Chronostratigraphy

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1. Introduction

Paleogene is the first period of the Cenozoic Era and one of the key intervals in the Earth history. After the disappearance of the terrestrial dinosaurs and pterosaurs as well as the marine ichthyosaurs and ammonites at the end-Cretaceous Mass Extinction, Paleogene faunas emerged with a great number of new taxa. Studies on the collision of Indian subcontinent with Eurasia, climatic changes, and their relationships with the Paleogene biological events have

received a great and extensive attention (Prothero and Berggren, 1992; Aubry et al., 1998; Chen et al., 2014a, 2016; Gehler et al., 2016; Gingerich, 2016; Ding et al., 2017; Hu et al., 2017; Ingalls et al., 2017; Wang, 2017).

Paleogene was first used by the German geologist C. F. Naumann in 1866, including Eocene and Oligocene then (Berggren, 1998). However, early in 1759, the Italian geologist G. Arduino proposed Tertiary to represent the strata currently recognized as the Paleogene and Neogene (Head et al., 2008). Since 1976, the International Commission on Stratigraphy has subdivided the Cenozoic Erathem into Paleogene, Neogene and Quaternary systems. In 1987, the

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Subcommission on Neogene Stratigraphy decided that the term Tertiary would no longer be used in the International Stratigraphic Chart, and the Paleogene and Neogene are used as the system-level units. Some subsequently issued stratigraphic charts abandoned the term Tertiary and used Paleogene and Neogene instead (e.g. Cowie and Bassett, 1989; Remane, 2000), but some stratigraphic charts or geological timescales still retained the Tertiary (e.g. Harland et al., 1990; Berggren et al., 1995; Aubry et al., 2005). The Tertiary, the Lower (Early) Tertiary, and the Upper (Late) Tertiary have been used in China, until December, 1999 when the Tertiary Group of the National Commission on Stratigraphy of China (NCSC) decided to discard Tertiary and to use the Paleogene and Neogene (Zhang and Li, 2000).

The subdivision of the Paleogene into the Paleocene, Eocene and Oligocene, and further into 9 stages, was confirmed by the Subcommission on Paleogene Stratigraphy at the International Geological Congress at Washington D.C., USA in 1989 (Jenkins and Luterbacher, 1992). Except for the Bartonian and Priabonian, the Global Boundary Stratotype Sections and Points (GSSPs) for other stages have been determined, including Danian (El Kef, Tunisia, ratified in 1991; Molina et al., 2006), Selandian and Thanetian (Zumaia, Spain, ratified in 2008; Schmitz et al., 2011) of the Paleocene, Ypresian (Dababiya, Luxor, Egypt, ratified in 2003; Aubry et al., 2007) and Lutetian (Gorronatxe, Basque Country, Spain, ratified in 2011; Molina et al., 2011) of the Eocene, and Rupelian (Massignan, Ancona, Italy, ratified in 1992; Premoli Silva and Jenkins, 1993) and Chattian (Monte Cagnero, Urbania, Italy, ratified in 2016; Coccioni et al., 2018).

All the aforementioned GSSPs are located in sections of marine deposits. The ratified GSSPs for the bases of the stages were defined by marine biotic succession, especially the calcareous nannoplanktons and planktonic foraminifera, except the base of Ypresian (also the base of the Eocene) (Luterbacher et al., 2004; Vandenberghe et al., 2012). The Chinese Paleogene is mainly composed of continental deposits, whereas the marine deposits are restrictedly distributed in Taiwan, southern Tibet and southwestern part of the Tarim Basin (Li, 1984). Great difficulties exist in correlation of wide distributed terrestrial Paleogene in China to the global marine standard, which requires the establishment of a regional Paleogene chronostratigraphic system based on continental deposits.

2. Brief review of Chinese Paleogene chronostratigraphical study

The chronostratigraphy of the Phanerozoic Eonothem is generally based on their biostratigraphical results. The extinction of large land reptiles, represented by non-avian di-

nosaurus, at the end of the Mesozoic Era provided huge ecological space for the radiation of mammals in the beginning of the Cenozoic, which resulted in the dominance of mammals in the terrestrial ecosystems. Fossil mammals have played an important role in the Cenozoic biostratigraphical studies.

In the early studies of Chinese Paleogene, the pioneer work of the Central Asiatic Expeditions of the American Museum of Natural History (CAE) in the Erlian Basin, Nei Mongol (Inner Mongolia), China has a great and lasting effect. The Expeditions discovered a large number of fossil specimens and recognized a series of lithostratigraphic units. Followed the principle of North American Land Mammal Ages (Wood et al., 1941; Woodburne, 1987), Romer (1966) proposed some related Asian Paleogene land mammal ages on the bases of mammalian faunas from different stratigraphic levels recognized by the CAE, which has formed the foundation for further Asian Paleogene chronostratigraphical study (Wang et al., 2012). Most of the Asian Paleogene land mammal ages proposed by Romer (1966) were derived from the Paleogene mammal faunas found in the Erlian Basin, Nei Mongol, including Ulanbulakian, Arshantan, Irдинmanhan, Sharamuronian, Ulangochuian, and Houldjinian (Figure 1).

In the 1960s–1970s, significant progresses were made in the study of Chinese Paleogene stratigraphy and correlations (South China “Redbeds” Research Group, 1977), which were included in *The Mesozoic and Cenozoic Red Beds of South China* edited by the Institute of Vertebrate Paleontology and Paleoanthropology and Nanjing Institute of Geology and Palaeontology (1979). When they summarized the Chinese Paleogene mammals, Li and Ting (1983) proposed several new Chinese land mammal ages, i.e. Shanghuan, Nongshanian, Bayanulanian, Lingchan, and Tabenbulukian. Later, Tong (1989) and Tong and Huang (1991, see also Tong et al., 1995) proposed Naduan and Ulantatalian, respectively. Wang (1997a, 1997b) revised the age of the related land mammal ages and included both Ulangochuian and Houldjinian in the late Eocene, following the revised base age of the Oligocene and the correlation of North American continental deposits with the global time scale. By then, the framework of Chinese Paleogene mammalian chronology has been generally established (Figure 1). These land mammal ages have been often used in the discussion of intercontinental biostratigraphical correlation and mammalian dispersals (e.g. Archibald et al., 1987; Beard and Dawson, 1999; Lofgren et al., 2004; Clyde et al., 2008, 2010). Of them, the Shanghuan, Nongshanian, Arshantan, Irдинmanhan, Sharamuronian, Ulangochuian, and Tabenbulukian ages have been adopted as the Asian Paleogene Land Mammal Ages in the Geologic Time Scales (Luterbacher et al., 2004; Vandenberghe et al., 2012; Figure 1).

Fossil mammals have played an important role in the biostratigraphic subdivision, correlation and age determina-

Period	Epoch	Romer (1966)	Li and Ting (1983)	Tong et al. (1995)	Wang (1997b)	Wang et al. (2007)	This paper (2018)	ALMA [*] Luterbacher (2004)	
Paleogene	Oligocene	Hsandagolian	Tabenbulukian	Tabenbulukian					
		Houldjinian	Houldjinian	Ulantatalian	Tabenbulukian	Tabenbulukian	Tabenbulukian	Tabenbulukian	
		Ulangochuian	Ulangochuian	Ulangochuian	Hsandagolian	Ulantatalian	Ulantatalian	Hsandagolian	
	Eocene	Sharamurunian, Irдинmanhan	Sharamurunian	Naduan	Houldjinian	Ulangochuian	Ulangochuian	Baiyinian	Ergilian
				Sharamurunian	Ulangochuian	Naduan	Naduan	Ulangochuian	Ulangochuian
		Arshantan	Arshantan	Irдинmanhan	Sharamurunian	Sharamurunian	Sharamurunian	Sharamurunian	Sharamurunian
				Arshantan	Irдинmanhan	Irдинmanhan	Irдинmanhan	Irдинmanhan	Irдинmanhan
		Ulanbulakian	Lingchan	Lingchan	Lingchan	Lingchan	Lingchan	Lingchan	Bumbanian
	Paleocene	Gashatan	Bayanulanian						
			Nongshanian	Nongshanian	Nongshanian	Nongshanian	Gashatan	Bayanulanian	Gashatan
			Shanghuan	Shanghuan	Shanghuan	Shanghuan	Nongshanian	Nongshanian	Nongshanian

Figure 1 History of subdivision of the Chinese Paleogene Mammal Ages. * ALMA, Asian Land Mammal Ages.

tion of the Paleogene. In December of 1999, the NCSC agreed to set up the sequence of Chinese local terrestrial “stages” on the bases of mammalian turnover together with other biotic and abiotic features (Zhang and Li, 2000). Followed this suggestion, Zhang and Li (2000) introduced a possible solution of the Chinese Paleogene chronostratigraphic subdivision, which consists of Shanghuan and Nongshanian stages of the Paleocene, Wutuan, Arshantan, Irдинmanhan, Sharamurunian and Ulangochuian stages of the Eocene, and Wulanbulagean and Tabenbulukian stages of the Oligocene. Such a suggestion is somehow different from what Zhang et al. (2000) proposed (Figure 2). Later in 2002, the subdivision of the Chinese Paleogene was revised as Shanghuan and Chijiangan of the Paleocene, Lingchan, Lushian, Yuanquan and Caijiachongian of the Eocene, and Wulanbulagean and Tabenbulukian of the Oligocene (National Commission on Stratigraphy of China, 2002). This subdivision was further modified when the NCSC issued The Stratigraphic Chart of China (2014). The modified subdivision is composed of Shanghuan and Chijiangan of the Paleocene, Lingchan, Arshantan, Irдинmanhan, Yuanquan and Caijiachongian of the Eocene, and Wulanbulagean and Tabenbulukian of the Oligocene (Zhang et al., 2015; Figure 2).

3. Revision of the terrestrial Paleogene chronostratigraphy of China

Given the proposal of the NCSC in 1999 (Zhang and Li, 2000), it is proper that the Paleogene land mammal ages are considered as the foundation for establishment of the Chinese Paleogene local stages. However, several stages in the Stratigraphic Chart of China (2014) have different names from the Chinese land mammal ages that have been accepted as the Asian Paleogene Land Mammal Ages, e.g. the Chijiangan, Yuanquan, and Caijiachongian (Luterbacher et al., 2004; Vandenberghe et al., 2012). Meanwhile, some problems have been revealed by the related studies. It is thus necessary to revise and clarify the Paleogene terrestrial chronostratigraphic frame of China.

3.1 Paleogene land mammal ages of China

The current biochronological subdivision of the Chinese Paleogene includes 11 land mammal ages: the Shanghuan, Nongshanian and Gashatan of the Paleocene; the Lingchan, Arshantan, Irдинmanhan, Sharamurunian, Naduan and Ulangochuian of the Eocene; and the Ulantatalian and Tabenbulukian of the Oligocene (Wang et al., 2007; Figure 1). Most of these ages are adopted in the subdivisional scheme

System	Series	Zhang and Li (2000)	Zhang et al. (2000)	NCSC* (2002)	NCSC (2014)	This study (2018)
Paleogene	Oligocene	Tabenbulukian	Tabenbulukian	Tabenbulukian	Tabenbulukian	Tabenbulukian
		Wulanbulagean	Hsandagolian	Wulanbulagean	Wulanbulagean	Ulantatalian
	Eocene	Ulangochuan	Naduan	Caijiachongian	Caijiachongian	Baiyinian Ulangochuan
		Sharamurunian	Sharamurunian	Yuanquan	Yuanquan	Sharamurunian
		Irdinmanhan	Irdinmanhan	Lushian	Irdinmanhan	Irdinmanhan
		Arshantan	Arshantan		Arshantan	Arshantan
		Wutuan	Lingchan	Lingchan	Lingchan	Lingchan
		Paleocene	Nongshanian	Nongshanian	Chijiangian	Chijiangian
	Shanghuan		Shanghuan	Shanghuan	Shanghuan	Shanghuan

Figure 2 History of subdivision of the Paleogene chronostratigraphy in China. * NCSC refers to the National Commission on Stratigraphy of China.

of the current paper, following their definition of [Tong et al. \(1995\)](#), [Wang \(1997a\)](#), [Ting \(1998\)](#), and [Wang et al. \(2007\)](#). The explanation and clarification of a few ages are provided in the following sections.

3.1.1 *Gashatan vs. Bayanulanian*

[Tong et al. \(1995\)](#) subdivided the Paleocene into 2 land mammal ages in China, the Shanghuan and the Nongshanian, and included the fossil mammals from the Nomogen Formation of Nei Mongol Autonomous Region and the Taizicun Formation of Xijiang Uigur Autonomous Region in the Nongshanian. However, these fossil mammals as a whole are clearly different from those from the typical Nongshanian faunas in southern China; instead, they are very close to those from the Gashatan strata of Mongolia ([Wang et al., 1998](#)). The corresponding fauna in southern China is represented by the fossil mammals collected from the Shuangtasi Formation of Xuancheng and Chizhou (formerly as Guichi), Anhui Province and the Tujinshan Formation of Mingguang (formerly as Jiashan), Anhui Province ([Huang and Chen, 1997](#); [Huang and Zheng, 1997](#); [Wang et al., 1998](#); [Huang, 2003](#)). It is reliable to subdivide the Chinese Paleocene into 3 land mammal ages. In the following studies, most researchers maintained the Gashatan as the last land mammal

age for the Chinese Paleocene ([Meng and McKenna, 1998](#); [Meng et al., 1998](#); [Ting, 1998](#); [Wang et al., 1998](#); [Bowen et al., 2002](#); [Clyde et al., 2008, 2010](#); [Ting et al., 2011](#)). Considering the requirement for establishing the Paleogene chronostratigraphic sequence of China, a new name different from the Gashatan should be used for the land mammal age.

Li and Ting (1983) proposed a mammal age Bayanulanian based on the Bayan Ulan fauna from the Nomogen Formation at Bayan Ulan (=“Bayan Ulan Formation” of [Jiang, 1983](#)), Sunid Youqi, Nei Mongol, and considered it as being Paleocene/Eocene transitional. Fossil mammals of this fauna were also frequently found from the Nomogen Formation at other sites, and many of them are typical forms of the Gashatan land mammal age ([Meng et al., 1998](#)). Therefore, it is reasonable to replace the Gashatan with the Bayanulanian in the Chinese Paleogene land mammal age sequence. Accordingly, the Bayanulanian Stage should be added into the Paleogene chronostratigraphic sequence of China.

3.1.2 *Naduan*

Based on the mammalian fauna found from the Nadu Formation of the Baise Basin of Guangxi Zhuang Autonomous Region, [Tong \(1989\)](#) proposed the Naduan land mammal age and inserted it between the Sharamurunian and Ulango-

chuan in the Paleogene land mammal age sequence of China. Recent investigation shows that the strata yielding the Sharamurunian and Ulangochuanian mammalian faunas in the Erlian Basin, Nei Mongol are generally continuous, and it is less probable to have a significant gap between the two faunas. In the Baise Basin, the assemblage of fossil mammals from the Dongjun Formation below the Nadu Formation is comparable with those of Irдинmanhan land mammal age. There seems no sufficient stratigraphical data that support a separate Naduan land mammal age between the Sharamurunian and Ulangochuanian. During the Eocene, the mainland China is mostly in the same biogeographic province, but a narrow zone, with mammals preferring moist and forested habitats, exists along the eastern and southern coastal region of China, which covering the Baise Basin of Guangxi (Qiu and Li, 2005). The difference between fossil mammals from the Nadu Formation and those of contemporaneous fauna of North China is probably caused by the different habitats. Fossil mammals of the Nadu Formation generally suggested a Sharamurunian age (Tang et al., 1974). It is clear that the opinion considering Naduan as a Chinese Paleogene land mammal age lacks adequate evidence.

3.1.3 *Ulangochuanian and Baiyinian*

Following the advance of the study on the Eocene/Oligocene boundary and the result of correlation between the terrestrial deposits and the global standard, Wang (1997b) included the faunas of both the Ulangochuanian and Houldjinian into late Eocene. By merging the Houldjinian into the Ulangochuanian (Tong et al., 1995), the Ulangochuanian became the latest land mammal age in the Eocene of China (Wang et al., 2007). Recent investigation in the Erlian Basin, Nei Mongol, reveals that the deposits between those with typical Ulangochuanian and early Oligocene mammal faunas respectively produce the fossil mammals correlative to the Mongolian Ergilian fauna. Both the Ulangochuanian and Ergilian have been included in the Asian Paleogene Land Mammal Ages, and the Ergilian is considered to be the latest one of the Eocene (Luterbacher et al., 2004; Vandenberghe et al., 2012). To keep the definition of Ulangochuanian consistent in both Chinese and Asian Paleogene land mammal age sequences, it is proper to propose a new land mammal age for the mammalian fauna of China equivalent to the Mongolian Ergilian.

Wang (1997b) suggested maintaining the Houldjinian as the latest Eocene land mammal age. However, the fossil mammals reported from the classic Houldjin site in the Erlian Basin, Nei Mongol are poorly preserved, and recent investigation at the classic site shows that the reported Houldjin fauna is represented by a mixed assemblage due to rework. In addition, the exposures of the Houldjin deposits are relatively isolated without clear relationship to other Paleogene deposits, and no equivalent strata could be confirmed at other Paleogene localities in the Erlian Basin

(Wang et al., 2012). It is thus improper to maintain the Houldjinian as the latest Eocene land mammal age in the Paleogene land mammal age sequence of China.

The deposits containing the mammalian fauna between the typical Ulangochuanian and early Oligocene ones have a relatively wide distribution in the Erlian Basin, Nei Mongol, and are well exposed near the location of Baiyin Obo Sumu government. The land mammal age represented by the fauna between the Ulangochuanian and early Oligocene age is here named Baiyinian after the Baiyin Obo Sumu.

3.1.4 *Ulantatalian*

Tong and Huang proposed in 1991 the Ulantatalian land mammal age on the basis of the mammalian fauna found at Ulantatal, Alax Zuoqi, Nei Mongol, and considered it to be middle Oligocene in age (Tong et al., 1995). After amendment of the previous early Oligocene mammalian faunas into late Eocene (Wang, 1997a), Wang (1997a) used Hsandagolian, proposed by Romer (1966), to represent the Asian early Oligocene land mammal age, due to her consideration of the Ulantatalian covering only the latest early Oligocene. In recent years, related work at Ulantatal indicates that the Ulantatal mammalian fauna comes from several horizons, which can be correlative to the Mongolian Hsandagolian fauna (Zhang et al., 2016; pers. comm.). Considering the requirement for establishing the Paleogene chronostratigraphic sequence of China, the Ulantatalian is used in this paper as the early Oligocene representative in the Chinese Paleogene land mammal age sequence.

3.2 Subdivision of Paleogene Chronostratigraphy in China

To summarize the above discussion, the Chinese Paleogene Period and System can be subdivided into 11 land mammal ages and corresponding local stages, including the Shanghuan, Nongshanian and Bayanulanian of the Paleocene, the Lingchan, Arshantan, Irдинmanhan, Sharamurunian, Ulangochuanian and Baiyinian of the Eocene, and the Ulantatalian and Tabenbulukian of the Oligocene (Figures 1 and 2).

Compared with the Stratigraphic Chart of China (2014), the modifications of the subdivision include: (1) The Chijiangian is removed and replaced by the Nongshanian and Bayanulanian. This change is based on two reasons. First, the corresponding Nongshanian land mammal age has been widely accepted before the proposal of the Chijiangian Stage, and thus, the Nongshanian Stage should have the priority over the Chijiangian Stage. Secondly, the subdivision of Paleocene Period into two land mammal ages is not compatible with the evolutionary stages of Paleocene mammals in China, and inconsistent with the Asian land mammal age sequence already accepted internationally. (2) The Yuanquan and Caijiachongian stages are replaced by the

Sharamurunian and Ulangochuian stages, respectively. The main reasons for such change are as follows. Both the Sharamurunian and Ulangochuian stages should have the priority over the Yuanquan and Caijiachongian stages, because the Sharamurunian and Ulangochuian land mammal ages were proposed earlier. In addition, the Sharamurunian and Ulangochuian land mammal ages have been widely accepted as part of the Asian Land Mammal Age sequence. The establishment of the stages on both mammal ages will be greatly convenient in discussion of related stratigraphic issues. (3) A new stage, the Baiyinian Stage, is proposed to represent the existence of the strata between those containing the typical Ulangochuian and early Oligocene mammal faunas. The new stage is considered to be correlative to the Mongolian Ergilian deposits, which would keep the definition of the Ulangochuian land mammal age consistent in both Chinese and Asian land mammal age sequences. (4) The Wulanbulagean Stage is replaced with the Ulantatalian Stage, because the latter has priority due to its earlier proposal. Moreover, the Ulantatal fauna is much better known than that from the Wulanbulage Formation in the scientific community. Using the Ulantatalian Stage will be helpful in the scientific exchange.

The above-mentioned changes not only reflect the recent advances of the Paleogene research in China and embody the regional features of Chinese Paleogene as well. The revised chronostratigraphic subdivision of Chinese Paleogene will be used in interregional Paleogene correlation with convenience.

4. The base and biostratigraphic features of stages

According to the “International Stratigraphic Guide”, the Series should be generally worldwide recognizable (Salvador, 1994). Regarding to the base of Chinese Paleogene regional stages, some should refer to the Global Stratotype Sections and Points (GSSPs), if the stages have bases consistent with those of certain series and even of system and Erathem, whereas the others could be determined on the evolutionary history of regional faunas to express the regional characteristics.

The Chinese Paleogene stages were proposed after the land mammal ages that were subdivided on the basis of the faunal turnover of Paleogene mammals. This chapter will introduce the bases of each stages and related fossil groups with special reference to the fossil mammals.

4.1 Shanghuan Stage

4.1.1 The base of Shanghuan Stage

The base of the Shanghuan is considered correlative to the

base of the Paleocene Series, and those of the Paleogene System and the Cenozoic Erathem as well. It should also be synchronous with the base of the Danian Stage of the global standard. The GSSP for the base of the Danian Stage is located at the section near El Kef, Tunisia (Molina et al., 2006). Since 2012, the International Chronostratigraphic Chart has taken 66.0 Ma as the numerical age for the base of the Danian (Vandenberghé et al., 2012). Therefore, the base age of the Shanghuan Stage should be also set at 66.0 Ma.

The Datang Section (also called the Ejingling–Nilongkeng Section, i.e. the upper part of the Yangmeikeng–Nilongkeng Section) in the Nanxiong Basin of Guangdong is a fairly documented section related to the Cretaceous/Paleogene boundary, but the position of the boundary at the section is in dispute (see Tong et al., 2002, 2013; Zhao et al., 2017). Two major arguments for the boundary are based on fossil mammals together with other evidence (Tong et al., 2002, 2013) and on palynological evidence (Erben et al., 1995; Zhao et al., 2017). The palynological boundary is about 80–100 m below the mammalian boundary (Tong et al., 2013). The paleomagnetic result of the Datang Section published by Erben et al. (1995) showed that the transition of polarity chrons C30n and C29r is located between 49 and 57 m, which is consistent with the result of another paleomagnetic study (Clyde et al., 2010). According to the paleomagnetic results, the palynological boundary is close to the bottom of chron C29r, inconsistent with the Geological Time Scales in which the boundary is located in the middle-upper part of the C29r. In contrast, the mammalian boundary is located in the middle-upper part of the C29r and accompanied by a transient negative excursion of carbon isotope (Clyde et al., 2010), corresponding to the carbon isotopic excursion at the Cretaceous/Paleogene boundary (Molina et al., 2006). In addition, the SHRIMP U-Pb zircon dating of the tuff sample confirmed the base of the overlying Nongshan Formation falls into the chron C26r (Tong et al., 2013), indirectly supporting the mammalian boundary in the middle-upper part of chron C29r. In the case of impossibility of precisely determining the Cretaceous/Paleogene boundary in the terrestrial deposits of China, it is reliable and acceptable to use the mammalian boundary as the alternative for the base of the Shanghuan Stage.

4.1.2 Fossil mammals

Fossil mammals of the latest Cretaceous in China are extremely rare. All the groups of the Shanghuan mammals are new at the ordinal level. The fossils of Anagalida and Miotonida have a distribution strictly limited in Asia, whereas the oldest and most primitive forms of the Pantodonta, Tiltodontia and Mesonychia appeared in the Shanghuan land mammal age (Wang et al., 2007). Except for a few species, almost all the mammalian species reported from the Shanghuan deposits have not been recorded in other land

mammal ages.

The Shanghuan Stage is characterized by containing rich fossils of *Bemalambda*, which has been found in all the Shanghuan deposits that producing fossil mammals (Wang et al., 1998). The family Bemalambdidae is only known from the Shanghuan (Wang et al., 2007). It is noteworthy that fossil *Bemalambda* did not appear at the bottom of the Shanghuan Stage (Wang Y Q et al., 2016). Fossil mammals from the lowermost Shanghuan level are *Carnilestes palaeoasiaticus* from the Nanxiong Basin, Guangdong (Wang and Zhai, 1995; Tong et al., 2013) and *Astigale wanensis* and *Benaius qianshuiensis* from the Qianshan Basin, Anhui (Zhang and Tong, 1981; Wang and Jin, 2004). In addition to *Carnilestes*, *Astigale* and *Benaius*, unique Shanghuan mammals include *Hypsilolambda*, *Linnania*, *Zhujegale*, *Stenanagale*, *Wanogale*, *Diacronus*, *Anictops*, *Paranictops*, *Cartictops*, *Wania*, *Anchilestes*, *Pappictidops*, *Hukoutherium*, *Meiostylodon*, *Plethorodon*, *Lofochaius*, and *Pro-sarcodon*. These fossils can be regarded as indicative of the Shanghuan age.

4.1.3 Other fossils

Different kinds of fossils other than mammals have been reported from the Datang Section of the Nanxiong Basin.

(1) Charophytes. Fossil charophytes from the Shanghuan Stage belong to *Grovesichara changzhouensis*-*Latochara curtula* assemblage (Wang et al., 1979). From the Datang Section, the charophyte species mainly include: *Charites sadleri*, *C. styliovalis*, *C. oblonga*, *Gobichara desena*, *Grovesichara changzhouensis*, *Peckichara varians*, *P. longa*, *P. zhijiangensis*, *Croftiella* cf. *steniformis*, *Neochara sinuolata*, *N. huananensis*, *Stephanochara kiangsuensis*, *S. brevivalis*, *S. cuneiformis*, *S. huangjianensis*, *S. funingensis*, *S. micrococca*, *S. hukouensis*, *Stephanochara wanzhuangensis*, *Rhabdochara jiangduensis*, *Latochara curtula*, *L. cylindrica* (Huang, 1988). The assemblage is characterized by the appearance of many forms with tubercles common on side walls or with cinquefoil on the top, which are mainly found in the Paleogene deposits (Huang, 1988).

(2) Ostracods. Fossil ostracods from the Shanghuan Stage belong to *Porpocypris-Parailocypris-Cypridea*, including *Ilyocypris subhuangqiaoensis*, *Parailocypris taizhouensis*, *Cypridea* (*Cypridea*) *xindianensis*, *C. (Pseudocypridina) subtera*, *Cyprois depressa*, *Porpocypris orbiculata* (He, 1979; Yang, 1979; Zhang, 1988).

(3) Nonmarine gastropods. Fossil nonmarine gastropods from the Shanghuan Stage belong to *Ptychochilus bellus-Agallospira multispiralis* assemblage, mainly land snails and freshwater prosobranchians. The dominant species include *Ptychochilus bellus*, *Shanghuspira costata*, *Parhydrobia* sp., *Palaeostrobilops* sp., *Nystia luminosa*, *Incrella? incerta*, *Agallospira multispiralis*, *Zhengjiangospira dignata*, *Hydrobia datangensis*, *Grandipatula? deformis*, *Charydrobia*

cf. *lubrica*, *Fluminicola guangdongensis*, etc. (Yü, 1977; Yü et al., 1990).

(4) Conchostracans. Fossil conchostracans are fairly rare in the deposits bearing fossil mammals. Only fragmentarily preserved *Fushunograptia* cf. *changzhouensis* has been reported from the Shanghu Formation in the Nanxiong Basin (Chen, 1986). The Xinzhuangcun Formation (formerly known as the first member of the Buxin Formation), correlative to the Shanghu Formation based on fossil mammals (Wang and Zhang, 1997), has been reported to produce *Nanhaiestheria sanshuiensis* and *Paraleptestheria menglaensis* (Shen and Zhang, 1979; Zhang and Lin, 2000).

(5) Sporo-pollen. The sporo-pollen assemblage of the Shanghu Formation in the Nanxiong Basin is dominated by the angiosperm pollen (84.12%), especially the porate pollen grains mainly of *Ulmipollenites*, *Ulmoideipites*, *Alnipollenites* and *Pterocaryapollenites*. The tricolpate and tricolporate pollen are mainly represented by *Quercoidites* and *Cupuliferoipollenites*, respectively in the assemblage. The gymnosperm pollen (12.10%) are mainly of *Taxodiaceapollenites*. The fern spores (3.4%) are represented by *Schizaeoisporites*, *Pterisisporites* and *Lygodiumsporites* (Li, 1989).

4.2 Nongshanian Stage

4.2.1 The base of Nongshanian Stage

The base of the Nongshanian Stage corresponds to the boundary of the Shanghuan and Nongshanian land mammal ages. The deposits known to produce the Nongshanian mammals mainly include the Nongshan Formation of the Nanxiong Basin, Guangdong, the Chijiang Formation of the Chijiang Basin, Jiangxi, and the upper part of the Upper Member of the Wanghudun Formation through the Doumu Formation of the Qianshan Basin, Anhui (Wang et al., 1998). According to the fossil horizons in different basins, *Dilambda zhuguikengensis*, *Harpyodus decorus*, *Eosigale gujingensis*, *Qipania yui* and *Altilambda yujingensis* are from the lowermost mammal-bearing beds in the Nongshanian Stage, close to the bottom of the stage, and can be used to define the base of the Nongshanian Stage.

Paleomagnetic result has shown that the transition of chrons C27n and C26r occurred between the strata respectively containing the Shanghuan and Nongshanian mammals, which is roughly coincident with the boundaries of the Shanghu/Nongshan formations in the Nanxiong Basin and of the Shizikou/Chijiang formations in the Chijiang Basin (Clyde et al., 2008, 2010), which can be used to help define the base of the Nongshanian Stage. If the transition of chrons C27n and C26r is accepted as the base of the Nongshanian, the numerical age for the base of the stage would be 62.22 Ma (Ogg, 2012).

4.2.2 Fossil mammals

Fossil mammals from the Nongshanian are still dominated by the archaic forms, but the proportion of archaic forms decreases in comparison with the Shanghuan mammals. Mixodontia, Arctostyloidea and Pastoralodontidae first appeared in the Nongshanian land mammal age (Wang et al., 2007).

Mammalian genera known only from the Nongshanian include Asiostylops, Sinostylops, Allostylops, Eosigale, Qipania, Haltictops, Allictops, Mina, Heomys, Interogale, Simplodon, Altilambda, Wanolestes, Ernánodon, Petrolemur, Minchenella, Yuelophus, Radinskya, Pseudanisonchus, Jiangxia, Ganolophus, Ganungulatum, and Yuesthonyx.

4.2.3 Other fossil

(1) Charophytes. Fossil charophytes from the Nongshanian Stage belong to *Peckichara longa-Obtusochara elliptica* assemblage, represented by *Peckichara coronata*, *P. longa*, *P. zhijiangensis*, *P. subsphaerica*, *Grovesichara changzhouensis* (Wang et al., 1979).

(2) Ostracods. Fossil ostracods from the Nongshanian Stage belong to *Sinocypris-Eucypris* assemblage (He, 1979). Species known from the Nongshan Formation include *Eucypris hukouensis*, *E. hengyangensis*, *E. repanda*, *E. stagnalis*, *E. fuscata*, *Sinocypris arca*, *S. excelsa*, *S. funingensis*, *S. subfuningensis*, *S. ovata*, *S. reticularis*, *Parailocypris changzhouensis*, *Cyprinotus libitus*, *Procypris peculiaris* (Guan, 1979; He, 1979; Zhang, 1988).

(3) Nonmarine gastropods. Fossil nonmarine gastropods from the Nongshanian Stage belong to *Polycirsus gracilicostata-Nanxiongospira uniptychia* assemblage, mainly including *Polycirsus gracilicostata*, *Renistoma regularium*, *R. anomphalum*, *Cirsomphalus laevigatus*, *Amnicola zhenjiangensis*, *Bithynia* aff. *lordostoma*, *Nanxiongospira uniptychia*, *N. nobilis*, *Opeas guangdongensis*, *Pupoides zhenjiangensis* (Yü, 1977; Yü et al., 1990).

(4) Conchostracans. Only *Paraleptestheria menglaensis* has been reported from the Nongshan Formation in the Nanxiong Basin, Guangdong (Chen and Shen, 1980).

(5) Sporo-pollen. The sporo-pollen assemblage of the Shanghu Formation in the Nanxiong Basin is dominated by the angiosperm pollen (70.2%), especially the tricolporate pollen. The angiosperm pollen are mainly consists represented by *Rhoipites*, *Rutaceipollis*, *Boehlensipollis*, *Pentapollenites*, *Lonicerapollis*, *Myrtaceidites*, *Santalumidites*, *Zonorapollis*, *Cupuliferoipollenites*, *Rhamnacidites*, *Callistopollenites*, *Tricolporopollenites* and *Retitricolporites*. The gymnosperm pollen (only 6.87%) is mainly of *Ephedripites*, *Parcisporites*, *Taxodiaceapollenites*, *Podocarpiidites*, *Sciadopityspollenites*. The fern spores (22.9%) are mainly of *Pterisiporites*, *Zlivisporis* and *Lygodiumsporites* (Li, 1983).

4.3 Bayanulanian Stage

4.3.1 The base of Bayanulanian Stage

In the Erlian Basin, Nei Mongol, fossil mammals of the Bayanulanian land mammal age have been found from two horizons in the lower part of the Nomogen Formation (Meng et al., 1998, 2007; Wang et al., 2010), mainly from the lower horizon. Incorporation of the data from the Bayanulanian fossil sites in the Erlian Basin, all the species have been recorded from the lower horizon. Species common in the fauna include *Prionessus lucifer*, *Lambdopsalis bulla*, *Sphenopsalis nobilis*, *Pseudictops lophiodon*, *Eomylus borealis*, *Dissacus serratus*, *Gashatostylops macrodon*, *Palaeostylops iturus*, *Pastoralodon lacustris*, *Prodinoceras turfanensis*, *P. xinjiangensis*, *Sarcodon minor*, *Bayanulanius tenuis*, and *Tribosphenomys minutus*. Theoretically, these fossils can be used to define the base of the Bayanulanian Stage. However, the relatively restricted distribution of most species or lacks of strong evidence supporting their synchronous appearance in different basins hampered the application of such definition.

Paleomagnetic results have shown that the strata bearing the Nongshanian mammals fall into chron C26r (Clyde et al., 2008, 2010) and the lower fossil horizon of the Bayanulanian in chron C25r (Bowen et al., 2005; Sun et al., 2009). Two polarity transitions for C26r/C26n and C26n/C25r thus exist between the deposits bearing fossil mammals of the Nongshanian and Bayanulanian. Referring the Selandian/Thanetian boundary in the Geological Time Scale at the transition of C26r/C26n (Vandenberghe et al., 2012), it is proposed here to adopt the C26r/C26n transition as the base of the Bayanulanian Stage with a numerical age of 59.2 Ma (Ogg, 2012).

4.3.2 Fossil mammals

Compared with the Nongshanian mammals, the Bayanulanian mammals are not greatly changed at the family level in composition. Dinocerata, Alagomyidae, Hyaenodontidae and Coryphodontidae first appeared in the Bayanulanian land mammal age (Wang et al., 2007).

The mammalian fauna of the Bayanulanian land mammal age is distinctive (Meng et al., 1998, 2007). Mammalian genera common in the Bayanulanian sites and strictly limited in the Bayanulanian land mammal age include *Lambdopsalis*, *Prionessus*, *Sphenopsalis*, *Palaeostylops*, *Wanostylops*, *Bayanulanius*, *Sarcodon*, *Pseudictops*, *Prolimnocyon*, *Eomylus*, *Tribosphenomys*, *Subengius*, *Pastoralodon*, *Prodinoceras*, *Tienschaniophus* and *Sinonyx*.

4.3.3 Other fossils

(1) Charophytes. The lower part of the Nomogen Formation is rich in fossil charophytes, dominated by the small-sized late Paleocene forms, mainly including *Gobichara deserta*,

G. tenera, *Nemegtichara prima*, *N. secunda*, *N. quarta*, *Peckichara lefeldi*, *Raskyaechara erlianensis*, *R. chinensis*, *Grambastichara bailanteensis*, *G. amanwusuenis*, *G. xilinensis*, *Stephanochara gobica*, *Harrisichara jiningensis*, *Retusochara pseudogobica*, *Krassavinella daiqingshanensis* (Liu, 1988).

(2) Ostracods. Fossil ostracods from the Bayanulanian Stage belong to *Homoecypris-Limnocythere-Ilyocypris-Cyprois* assemblage, including mainly *Homoecypris vulgaris*, *Limnocythere nemegtensis*, *Ilyocypris multinoda*, *Cyprois subengensis*, *Metacypris bituberculata*, *Candona* sp., *Cypris dccaryi*, *Eucypris cf. profunda* and less *Candoniella* sp., *Talicypridea glabella* (Zhao, 1985).

Relatively abundant fossil charophytes have also been found from the contemporaneous Limuping Formation and were referred to *Cypris henanensis-Cyprois reniformis-Limnocythere honggangensis* assemblage, comprising 15 species of 7 genera and characterized by the dominance of *Cypris henanensis* and *Limnocythere honggangensis* (Zhang and Li, 2010).

(3) Nonmarine gastropods. No fossil gastropods have been reported from the Nomogen Formation, but the middle part of the Shuangtasi Formation, correlative to the lower Nomogen Formation, has yielded rich gastropods, mainly including *Theodoxus xuanchengensis*, *Bithynia loxostoma*, *Pupoides (Ischnopupoides) antiquus*, *Enuroplax? luosigangensis*, *Prionolabium polyptychium*, *Xuanchengospira flexilabrosa*, *Archaeozonites luosigangensis*, *Anhuispira granulifera*, *Giffordius antiquus*, *Multiscapta raris*, *Ganselloides latus*, *Undatornatus peregrinus*, *Crenatilibiellus profundus* (Yü et al., 1982).

(4) Sporo-pollen. Fossil spores and pollen have not been reported from the Nomogen Formation. Based on the fossil mammals, the mammal-bearing Shuangtasi Formation in Xuancheng Basin, Anhui can be correlated with the Nomogen Formation (Paleocene part) (Huang and Zheng, 1997; Wang et al., 1998). Relatively rich fossil pollen and spores have been found from the middle part of the Shuangtasi Formation, composing an angiosperm-dominated (53.2–67.2%) assemblage. The most abundant tricolporate pollen mainly include *Lonicerapollis*, *Pentapollenites*, *Rhoipites*, *Rutaceoipollis*, *Santalumidites*, *Sapindaceidites*, *Boehlensipollis*, *Syncolporites*, *Symlocoipollenites*, *Cupuliferopollenites* and *Faguspollenites*. The less abundant tricolporate pollen includes *Quercoidites*, *Fraxinoipollenites*, *Ilexpollenites*, *Salixipollenites*, *Labitricolpites* and *Tricolpites*. Gymnosperm pollen (18.8–32.3%) are mainly coniferal saccate pollen, including *Pinuspollenites*, *Abietinaepollenites*, *Cedripites*, *Podocarpidites*, *Keteleeriaepollenites*, *Parcisporites*. The fern spores (11.5–16.4%) include *Pterisisporites*, *Polypodiaceoisporites*, *Verrutraspora*, *Deltoidospora*, *Lygodiumsporites*, *Schizaeoisporites*, *Toroiporis*, *Lygodioisporites*, *Zlivisporis* and

Corrugatisporites (Li, 2005).

Fossils other than the above mentioned groups in the Bayanulanian have not been reported from the type and correlative sections.

4.4 Lingchan Stage

4.4.1 The base of Lingchan Stage

The Lingchan Stage is the first stage in the Eocene Series. It has the same base as the series. Ratified by the IUGS in 2003, the GSSP for the base of the Eocene Series, defined by the carbon isotope excursion, is located at 1.58 m above the base of Section DBH in the Dababiya Quarry, on the east bank of the Nile River, about 35 km south of Luxor, Egypt (Aubry et al., 2007). Its age is 56.0 Ma (Vandenberghé et al., 2012).

Several Paleogene sections of China have been reported to display the carbon isotope excursions related to the Paleocene/Eocene boundary (Bowen et al., 2002; Zhu et al., 2010; Chen et al., 2014a). However, such studies on some sections focused on the Paleocene-Eocene Thermal Maximum (PETM) event (Zhu et al., 2010; Chen et al., 2014a, 2014b, 2016), which hampered the incorporation of the result into the chronostratigraphic sequence.

Fossil mammals from the Lingcha Formation in the Hengyang Basin, Hunan have been considered as a representative of the early Early Eocene. It has been revealed that the fossil-bearing beds are related to the carbon isotope excursion and the earliest Eocene in age (Figure 3; Bowen et al., 2002; Ting et al., 2003; Wang et al., 2011).

In the Nuhejingboerhe Section of the Erlian Basin, Nei Mongol, both the highest late Paleocene mammal-bearing bed (NM-2) and the lowest early Eocene mammal bed (NM-3) are in the Nomogen Formation and chron C24r, with only 7m difference in thickness. Biostratigraphic study shows that mammals from NM-3 are the earliest Eocene in age (Meng et al., 2007; Wang et al., 2010, 2011). It was suggested the NM-3 occurred in the PETM by currently undertaking carbon isotope study of colleagues from the Institute of Geology and Geophysics, Chinese Academy of Sciences (Wang Xu, pers. comm.), which will precisely mark the Paleocene/Eocene boundary in the section. Fossils from the Lingcha Formation and the upper part of the Nomogen Formation can be considered as the indicator for the early Eocene age.

4.4.2 Fossil mammals

Possibly related to the PETM event, the archaic forms greatly decreased in the mammalian fauna of the Lingchan land mammal age. Some modern mammalian groups, such as Perissodactyla, Artiodactyla and Primates, first appeared in the Lingchan (Wang et al., 2007).

Most fossil mammals found at the Lingchan localities are new forms. Relatively common and representative forms include *Hsiangolestes*, *Hapalodectes hetangensis*, *Matuti-*

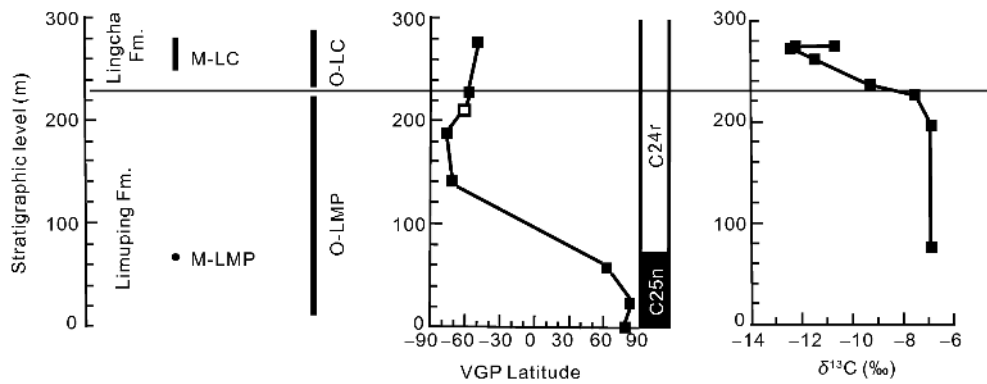


Figure 3 Paleomagnetic and carbon isotope data and the distribution of fossil mammal and ostracod assemblages at the Tianzhifen-Jixianwan section, Hengyang Basin, Hunan (Wang et al., 2011). M-LC, Mammal-bearing horizon in the Lingcha Formation; M-LMP, Mammal-bearing horizon in the Limuping Formation; O-LC, Ostracod assemblage of the Lingcha Formation; O-LMP, Ostracod assemblage of the Limuping Formation.

nia, *Rhombomylus*, *Gomphos elkema*, *Anatolostylops*, *Heterocoryphodon*, *Asiocoryphodon*, *Changlelestes*, *Cocomys*, *Advenimus hupeiensis*, *Teilhardina asiatica*, *Archicebus achilles*, *Orientalophus*, *Minchenoletes*, *Homogalax wutuensis* and *Pataecops parvus*.

4.4.3 Other fossils

(1) Charophytes. No fossil charophytes have been reported from the Lingcha Formation in the Hengyang Basin, Hunan and the upper part of the Nomogen Formation in the Erlian Basin, Nei Mongol. Biostratigraphic correlation based on fossil mammals and ostracods shows that the Huayong Formation in the Sanshui Basin, Guangdong is the Lingchan in age and correlative to Lingcha Formation and the upper part of the Nomogen Formation (Wang et al., 2011). Fossil charophytes from the Huayong Formation belong to *Hornichara huachongensis*-*Amblyochara taixianensis* assemblage, mainly consisting of *Hornichara huachongensis*, *H. jintanensis*, *Amblyochara taixianensis*, plus less amount of *Charites nanhaiensis*, *Croftiella shangbaiensis*, *Raskyachara xinghuensis* etc. (Huang and Zhang, 1984). Fossil charophytes from the contemporaneous Yuhuangding Formation in the Liguangqiao Basin are dominated by the species of *Amblyochara*, *Grovesichara*, *Obtusochara*, including *Amblyochara taixianensis*, *Grovesichara changzhouensis*, *Obtusochara subcylindrica*, *O. jianglingensis*, *Gyrogona qianjiangica*, *Charites columinaria*, *Stephanochara* cf. *compta*, *Sphaerochara rugulosa* (Ge, 1994).

(2) Ostracods. Fossil ostracods from the Lingcha Formation were referred to *Limnocythere irregularis*-*Cypris favosa*-*Ilyocypris gaoyouensis* assemblage by Zhang and Li (2010). Major forms composing the assemblage include *Cypris favosa*, *C. echinata*, *Heterocypris dongyuemiaoensis*, *Candona xiaotangensis*, *Candoniella peculiaris*, *C. minima*, *C. longa*, *Ilyocypris hengyangensis*, *I. cornae*, *I. gaoyouensis*, *I. jintanensis*, *Cypris circularis*, *Limnocythere irregularis* and *L. spinisalata* (Zhang and Li, 2010).

(3) Nonmarine gastropods. No fossil gastropods have been

reported from the Lingcha Formation in the Hengyang Basin, Hunan and the upper part of the Nomogen Formation in the Erlian Basin, Nei Mongol. A few fragmentarily preserved gastropods have been found in the Huayong Formation of the Sanshui Basin, which mainly include *Ammicola?* sp., *Physa* sp., *Gyraulus* sp., *Australorbis* sp., *Pupoides* sp., *Discostrobilops?* sp., *Nanhaispira eversilabia*, *Palaeoxestina?* sp. (Yü and Zhang, 1982).

(4) Sporo-pollen. No fossil spores and pollen have been reported from the Lingcha Formation in the Hengyang Basin, Hunan and the upper part of the Nomogen Formation in the Erlian Basin, Nei Mongol. The Dainan Formation of the Subei Basin, Jiangsu has been considered to be correlative of the Lingcha Formation based on the fossil evidence (Zhang et al., 2000; Zhang and Li, 2010). Fossil spores and pollen from the Dainan Formation belong to *Ulmipollenites*-*Inaperturopollenites*-*Pterisisporites* assemblage, known from the first and second members of the Dainan Formation. This assemblage is dominated by angiosperm pollen, rich in small-grained triporate pollen, mainly including *Ulmoideipites tricosiatus*, *Ulmipollenites minor*, *Ulrnideipites krempii*, *Momipites*, *Ostryoipollenites*, *Betulaepollenites plicoules*, *Alnipollenites*, *Paraalnipollenites* and *Engelhardtoulites*. The gymnosperm pollen are mainly of *Inaperturopollenites*, *Taxodiaceapollenites*, *Abietinaepollenites*, *Pinuspollenites*, *Podocarpulites* and *Parcisporites*. The fern spores have a low proportion (11.25%), mainly including *Pterisporites* and *Lygodiumsporites* (Zhang and Qian, 1992).

Fossils other than the above mentioned groups in the Bayanulanian have not been reported from the type and correlative sections.

4.5 Arshantan Stage

4.5.1 The base of Arshantan Stage

Fossil mammals of the Arshantan land mammal age are notably different from those of the earlier Lingchan. It is

fairly reliable to determine the age based on fossil mammals. However, it is difficult to precisely define the base of the Arshantan Stage by using fossil mammals; this is because there is no well-exposed and continuous section that contains the transition with rich fossils. Six mammal-bearing horizons have been recognized in the Arshanto Formation in the Huheboerhe area, the Erlian Basin, Nei Mongol (Meng et al., 2007). Fossil mammals found from the lowest horizon are possibly qualified for defining the base of the Arshantan Stage, such as *Gobiatherium mirificum*, *Schlosseria magister*, *Litolophus gobiensis*, *Dawsonolagus antiquus*, *Eudinoceras mongoliensis*, *Erlianomys combinatus*, *Archetypomys erlianensis*, etc. (Wang et al., 2010).

At the Nuhetingboerhe Section, a disconformity exists between the Arshanto Formation and the underlying Nomogen Formation (Meng et al., 2007). Paleomagnetic result showed that both the upper part of the Nomogen Formation and the basal Arshanto Formation are in the reversed-polarity zone, which was originally interpreted as a single chron C24r (Sun et al., 2009). The boundary between the Nomogen and Arshanto formations was thus put near the top of chron C24r (Wang et al., 2010). Jiang et al. (2014) reported the paleomagnetic result of the Xijiadian Section in the Liguangqiao Basin, which indicates that a late Lingchan mammal-bearing horizon of the Yuhuangding Formation is situated in chron C24n. Such result excludes the possibility that the Arshantan base is in chron C24r but suggest the base could be in chron C23r instead. Referring to the Geological Time Scale, the numerical age for the base of the Arshantan Stage is estimated as about 52 Ma.

4.5.2 Fossil mammals

The archaic mammalian forms further decreased in proportion in the Arshantan land mammal age. Both the Mixodontia and Arctostylopida disappeared, whereas the large archaic ungulates, such as Coryphodontidae and Dinocerata, still persisted. Among the extant mammalian groups, the Perissodactyla significantly diversified and are dominant in the fauna. Most newly appeared families are of Perissodactyla. The perissodactyl families, Lophialetidae and Deperetellidae greatly flourished in the Arshantan (Wang et al., 2007), while the primitive paraceratheriid perissodactyle first appeared (Wang H B et al., 2016).

Incorporation of the data from the Arshantan faunas, mammals reported from the Arshantan land mammal age include *Mesonyx obtusidens*, *M. nuhetingensis*, *M. uqbula-kensis*, *Mongolonyx dolichognathus*, *Gobiatherium mirificum*, *Archaeoryctes borealis*, *Sinosinopa sinensis*, *Pantolambdodon fortis*, *P. minor*, *Breviodon minutus*, *Pappaceras confluens*, *P. meiomenus*, *Heptodon minimus*, *Homogalax reliquius*, *Hyrachyus crista*, *H. eximius*, *H. neimongoliensis*, *Schlosseria magister*, *Teleolophus medius*, *T. rectus*, *Telmatherium cristatum*, *Litolophus gobiensis*,

Archetypomys erlianensis, *Erlianomys combinatus*, *Advenimus burkei*, *A. ulungurensis*, *Tamquammys wilsoni*, *T. robustus*, *Simplicimys bellus*, *Dawsonolagus antiquus*, *Eudinoceras mongoliensis*. Most of them have their first appearance in the Arshantan land mammal age. Mammalian taxa, common and limited in the Arshantan, include *Mesonyx*, *Mongolonyx*, *Gobiatherium*, *Schlosseria*, *Pappaceras*, *Litolophus*, *Erlianomys*, *Advenimus ulungurensis*, *Dawsonolagus*.

4.5.3 Other fossils

The study on the Arshantan fossils other than mammals was relatively insufficient in the classic localities. Due to the long-standing problem in the stratigraphic subdivision in the Erlian Basin, fossil charophytes and ostracods of the Arshantan, Irдинmanhan and Sharamurunian land mammal ages were combined to form their own assemblage (Zhao, 1985; Liu, 1988), which makes it impossible in applying to the precise correlation.

Mammalian biostratigraphic correlation has shown that the Dacangfang Formation in the Liguangqiao Basin and the Üqbulak Formation of the Dzungaria Basin, Xijiang are referable to the Arshantan Stage (Tong, 1989; Tong et al., 1995). Fossil charophytes were mentioned in the description of the Üqbulak Formation (Wei and Tong, 1992), but have not been formally reported.

Fossil charophytes from the Dacangfang Formation are not diverse and contain only the small-sized forms, mainly including *Gyrogona qianjiangica*, *Obtusochara jianglingensis*, *Sphaerochara rugulosa*, *Charites minutissima*. They form *Obtusochara jianglingensis*-*Gyrogona qianjiangica* assemblage (Ge, 1994) and can be temporally considered as the representatives of the Arshantan Stage.

Fossils of the related groups have been probably reported from the Arshantan deposits in some other basins bearing no fossil mammals, but it is impossible to correlate them to the current mammal-based stratigraphic sequence. To avoid further confusion and misunderstanding, inclusion of them in the chronostratigraphic sequence awaits more detailed work in the future.

4.6 Irдинmanhan Stage

4.6.1 The base of Irдинmanhan Stage

Long-standing problem in the subdivision and correlation of the Irдин Manha and Arshanto formations caused the mixture of mammalian faunas and further affected significantly the discussion on related issues (Meng et al., 2007; Wang et al., 2012). Recent investigations in the Erlian Basin have clarified the stratigraphic relationship of the Arshanto and Irдин Manha formations (Meng et al., 2007), based on which the compositions of mammalian faunas from the Arshantan and Irдинmanhan land mammal ages were revised (Wang et al.,

2010).

Most fossil mammals from the Irдинmanhan land mammal age are clear indicators for the age because of their significant difference from the earlier Arshantan mammals. Confined to the exposures and the depositional condition of the related strata, difficulties still remain in determining precisely the base of the Irдинmanhan Stage. Some mammalian species found in relatively lower horizon might be qualified for defining the base, which include *Miacis lushiensis*, *Harpagolestes orientalis*, *Andrewsarchus mongoliensis*, *Chungchienia sichuanica*, *Propterodon morrisoni*, *P. shipigouensis*, *Gobiohyus pressidens*, *G. robustus*, *G. orientalis*, *Forstercooperia totadentata*, *Lophialetes expeditus*, *Protitan grangeri*, *Desmatotherium mongoliense*, *Paracolodon fissus*, *Rostriamynodon grangeri*, *Asiomys dawsoni*, *Yuomys huheboerhensis*, *Orientocylindrodon liguanqiaoensis*, *Palasiomys conulus*, *Pappocricetodon antiquus*, *P. neimongolensis*, *Tamquammys fractus*, *Mimolagus aurorae*, *Strenulagus shipigouensis*, *S. solaris*, *Erenlagus anielae*, *Tarkops mckennai*, etc.

Magnetostratigraphic study has not provided confident constraint on the base of the Irдинmanhan Stage. Sun et al. (2009) reported the paleomagnetic result for the Huheboerhe Section of the Erlian Basin, and interpreted the reversed-polarity zone across the boundary of the Arshanto/Irдин Manha formations as chron C21r. Due to the reason mentioned above (see Arshantan Stage, 4.5 in this paper), such calibration should be reconsidered. Referring to the unpublished preliminary paleomagnetic result of a different section, it is more reliable to interpret the reversed-polarity zone as chron C20r, which is consistent with the correlation of the Asian Irдинmanhan to the North American Uintan (Tong et al., 1995; Wang et al., 2007). According to the position of the boundary in the reversed polarity zone, its age is estimated to be close to 45 Ma. Recently, a report of paleomagnetic result on a drill core section proposed an age of 51–34 Ma for the Irдин Manha Formation (Tao et al., 2017), covering the upper Lower Eocene through Upper Eocene. The result is obviously conflict with the results of biostratigraphic and other paleomagnetic studies on the surface sections.

4.6.2 Fossil mammals

Archaic mammals further decreased in the Irдинmanhan land mammal age, with the disappearance of condylarthrans in the mammalian faunas of China. In the Perissodactyla, the Deperetellidae and Lophialetidae still flourished, while the Brontotheriidae, Amynodontidae and Hyracodontidae initiated a rapid radiation. The Rodentia has greater diversity with the first appearance of the Cricetidae and the Zapodidae. The Helohyidae of the Artiodactyla first appeared (Wang et al., 2007).

The Irдинmanhan Stage is rich in fossil mammals with a

great number of species being reported. Among them, taxa restricted to and common in the Irдинmanhan with relatively significant biostratigraphic value include *Miacis lushiensis*, *Harpagolestes*, *Andrewsarchus mongoliensis*, *Chungchienia*, *Propterodon*, *Gobiohyus*, *Forstercooperia*, *Lophialetes*, *Deperetella*, *Protitan*, *Desmatotherium mongoliense*, *Paracolodon fissus*, *Asiomys*, *Yuomys huheboerhensis*, *Pappocricetodon neimongolensis*, *Tamquammys fractus*, *Mimolagus aurorae*, *Strenulagus*, *Lushilagus*, *Erenlagus*, *Eosimias sinensis* and *Tarkops mckennai*, etc.

4.6.3 Other fossils

The study on the Irдинmanhan fossils other than mammals was relatively insufficient in the classic localities. Few related studies in the Erlian Basin combined the fossil charophytes and ostracods of the Arshantan, Irдинmanhan and Sharamurunian land mammal ages to form their own assemblage (Zhao, 1985; Liu, 1988), which makes it impossible in applying to the precise correlation.

Mammalian biostratigraphic correlation has shown that the Hetaoyuan Formation in the Liguangqiao Basin is referable to the Irдинmanhan Stage (Tong, 1989; Tong et al., 1995). Fossil charophytes and ostracods from the formation can be taken as representatives of their own groups in the Irдинmanhan Stage.

(1) Charophytes. Fossil charophytes from the Hetaoyuan Formation are dominated by *Amblyochara*, *Grovesichara* and *Obtusochara*, including *Amblyochara taixianensis*, *Grovesichara changzhouensis*, *Obtusochara subcylindrica*, *O. jianglingensis*, *Gyrogona qianjiangica*, *Charites columinaria*, *Stephanochara cf. compta*, *Sphaerochara rugulosa* (Ge, 1994).

(2) Ostracods. Fossil ostracods from the Hetaoyuan Formation mainly include *Candona abrupta*, *C. reticulata*, *Candoniella* sp., *Cyprois* sp., *Pseudoecypris* sp., *Darwinula* sp., *Ecypris* sp., *Cyprinotus?* sp. (Guan, 1984).

Aptychus fossils of the gastropod *Mirolaminatus validus* was reported from the Hetaoyuan Formation (Guan, 1984).

4.7 Sharamurunian Stage

4.7.1 The base of Sharamurunian Stage

The Sharamurunian mammals are distinctly different from those of the Irдинmanhan at the family level (Wang et al., 2007). Some species from the relatively lower horizon might be qualified for defining the base of the Sharamurunian Stage, such as *Gobiolagus tolmachovi*, *G. aliwusuensis*, *G. lii*, *Archaeomeryx optatus*, *Prohyracodon meridionale* and *Propterodon tongi*, etc. Preliminary paleomagnetic result in the Erlian Basin shows that the base of the Sharamurunian is located in the lower part of chron C19r, with an estimated age of 42 Ma.

4.7.2 Fossil mammals

In the Sharamuronian mammals, archaic form like Dinocerata disappeared. The Anthracotheriidae of the Artiodactyla greatly diversified, while the Ruminantia appeared and began to differentiate. The oldest representative of the Suidae appeared on the earth (Liu, 2001). The Perissodactyla is still a dominant group in land mammals. The Amynodontidae became the most diversified group, whereas the Deperetellidae and Lophialetidae declined. Rodents of the Eomyidae first appeared, while the Tamquammyidae reduced (Wang et al., 2007).

A number of mammalian species have been reported from the Sharamuronian land mammal age. Taxa common in different sites and restricted to the Sharamuronian mainly include *Pterodon*, *Allosminthus diconjugatus*, *A. unconjugatus*, *Pappocricetodon rencunensis*, *P. schaubi*, *Protataromys mianchiensis*, *P. yuanquensis*, *Raricricetodon zhongtiaensis*, *Yuomys cavioides*, *Hoanghoni*, *Eosimias centennicus*, *Rencunius*, *Gobiolagus tolmachovi*, *G. aliwusuensis*, *G. lii*, *Anthracokeryx sinensis*, *Archaeomeryx*, *Deperetella cristata*, *Caenolophus*, *Prohyracodon*, *Sianodon*, *Sharamynodon*, *Huananodon*, *Juxia sharamurunensis*, *Eomoropus* and *Rhinotitan*, etc.

4.7.3 Other fossils

The study on the Sharamuronian fossils other than mammals was very limited in the classic localities. Few related studies in the Erlian Basin combined the fossil charophytes and ostracods of the Sharamuronian with those of the Arshantan and Irдинmanhan to form their own assemblage (Zhao, 1985; Liu, 1988), which makes it impossible in applying to the precise correlation.

Mammalian biostratigraphic correlation has shown that the Nadu Formation in the Baise Basin, Guangxi is referable to the Sharamuronian Stage (see discussion above). The results of related studies on the fossils other than mammals from the Nadu Formation are summarized below as representatives of the Sharamuronian Stage.

(1) Charophytes. Fossil charophytes were reported from the lower part of the Nadu Formation, and were referred to *Obtusochara elliptica-Rhabdochara isgyonensis* assemblage. Major taxa include *Obtusochara elliptica*, *Rhabdochara kisgyonensis*, *R. copica*, *R. colida*, *R. stockmansis*, *Stephanochara kenliensis* and *Gyrogona qianjiangica* (Liu and Yuan, 2002).

(2) Ostracods. When they reported the fossil charophytes of the Nadu Formation, Liu and Yuan (2002) mentioned the occurrence of fossil ostracod fauna from the upper part of the formation, mainly consisting of *Cyprinotus guangxiensis*, *Chinocythere obliqua*, *C. boseensis*, *Candona boseensis*, etc.

(3) Nonmarine gastropods. Fossil gastropods from the Nadu Formation were referred to *Kwangsispira accelerata-Sinoplanorbis sinensis* assemblage, commonly consisting of

Kwangsispira accelerata, *K. grabau*, *Paracampeloma ovata*, *P. paucilineata*, *Tulotomoides kwangsiensis*, *Sinoplanorbis sinensis*, and *Hippeutis luminosa*, etc. (Yü, 1977). More recently, Hu (1991) recognized two gastropod assemblages in the Nadu Formation: (1) *Crassitaia guangxiensis-Tulotomoides nodosocarinata* assemblage is from the basal part of the formation, and mainly includes *Taia? boseensis*, *Crassitaia guangxiensis*, *Tulotomoides nodosocarinata*, *Pachydrobia guangxiensis*, *Semisulcospira napoensis*, “Melanin” *turrita*, etc. (2) *Kwangsispira accelerata-Sinoplanorbis sinensis* assemblage from the upper part of the formation mainly consists of *Kwangsispira accelerata*, *Paracampeloma paucilineata*, *Pachydrobia guangxiensis*, *Tulotomoides kwangsiensis*, *Sinoplanorbis sinensis*, *Hippeutis luminosa*, *Napospira spinula*, *Margarya guangxiensis*, *Semisulcospira napoensis*, *Gangetia rissoides*, “Ngetia” *scala*, *Stenothyra ovata*, etc. Yü’s (1977) gastropod assemblage corresponds to the second (upper) one of Hu’s assemblages (1991).

(4) Bivalves. Fossil bivalves from the Nadu Formation were referred to two assemblages (Hu, 1991). (i) *Napoconcha suborbicularis* assemblage from the lower part of the formation mainly comprises *Napoconcha elliptica*, *N. suborbicularis*, *N. inflata*, *Margaritifera emarginata*, *Unio crassus*, *Acuticosta subimmutata* and *Betekeia cf. perdeclivis*, etc. (ii) *Cuneopsis heudei* assemblage from the middle part of the formation mainly contains *Cuneopsis*, *Acristaria*, *Acuticosta* and *Rectidens rumatraensis*, etc.

(5) Sporo-pollen. Relatively more studies have been done on fossil spores and pollen from the Nadu Formation. Wu (1981) briefly reported the fossil spores and pollen of the formation. Later on, Yang (1994), Liu and Yang (1999), and Tong et al. (2001) restudied the fossil spores and pollen of the formation respectively. They all recognized four sporo-pollen assemblages or zones and reached the generally same result. Four sporo-pollen assemblages proposed by Liu and Yang (1999) are as follows in ascending order: (i) *Polypodiaceae-Pinuspollenites* assemblage from the lower member of the formation is dominated by spores of *Polypodiaceae* (27–91%, average at 35%). The most common forms are *Polypodiisporites*, *Polypodiaceasporites* and *Extrapunctatosporis*. The average proportion of angiosperm pollen in the assemblage is 40%. The most abundant form is *Quercoidites microhenrici*, and pollen of *Quercoidites minutus*, *Ulmipollenites* and *Ulmoideipites* is common as well. For gymnosperm pollen, only *Pinuspollenites* is common in the assemblage. (ii) *Quercoidites-Ulmipollenites* assemblage from the lower part of the Middle Member of the formation is dominated by angiosperm pollen (89–99%). The rich pollen of *Quercoidites* and *Ulmipollenites* is commonly with that of *Liquidambarpollenites*, *Caryapollenites*, *Juglanspollenites*, *Momipites*, *Persicarioipollis*, *Retimultiporopollenites* and *Randiapollis*. Both *Pinuspollenites* and

Taxodiaceapollenites are relatively common gymnosperm forms in the assemblage. The number of fern spores reduced greatly, with a little spores of *Polypodiaceasporites*, *Polypodiaceoisporites* and *Polypodiisporites*. (iii) *Alnipollenites-Tricolporopollenites* assemblage from the upper part of the Middle Member of the formation is still dominated by angiosperm pollen, but the dominant forms changed obviously. *Quercoidites* retained the dominance, whereas *Alnipollenites* replaced *Ulmipollenites* becoming a dominant form. *Florschuetzia trilobata*, *Verrutricolporites pachydermus* and *Tricolporopollenites bosepachydermus* are common in the assemblage. Gymnosperm pollen is similar to that in the second assemblage, while the number of spores increased slightly. (iv) *Pinuspollenites-Quercoidites* assemblage from the Upper Member of the formation is still dominated by angiosperm pollen. *Quercoidites* retained high proportion in the assemblage. The proportion of *Cupuliferoideaepollenites* and *Tricolpites* pollen increased, whereas pollen of *Alnipollenites* is rare in most samples, and pollen of *Florschuetzia trilobata*, *Verrutricolporites pachydermus* and *Tricolporopollenites bosepachydermus* nearly disappeared. The gymnosperm pollen increased distinctively, mainly including *Pinuspollenites*, *Abietinaepollenites*, *Keteleeria* and *Cedripites*.

(6) Dinoflagellates. Fossil dinoflagellates from the Nadu Formation were referred into four assemblages. They are in ascending order: (i) *Bosea-Leiosphaeridia-Granodiscus* assemblage consists mainly of *Bosea granulata*, *Leiosphaeridia* sp. and *Granodiscus granulatus*. (ii) *Rugosphaera-Granodiscus* assemblage is dominated by *Rugosphaera*, represented by *Rugosphaera corrugis* and *R. micirugis*, together with *Granodiscus granulatus*. (iii) *Granodiscus-Leiosphaeridia-Bosea* assemblage is dominated by *Granodiscus* and *Leiosphaeridia*. Major forms include *Leiosphaeridia taxodiforma*, *Granodiscus granulatus*, *G. caperatus*, *G. staplinii* and *Bosea granulata*. (iv) *Pediastrum-Leiosphaeridia-Granodiscus* assemblage consists mainly of *Pediastrum boryanum*, *P. simplex* var. *deltoidea*, *P. duplex*, *Leiosphaeridia hyalina*, *L.* sp. and *Granodiscus granulatus* (He and Qian, 1979).

4.8 Ulangochuan Stage

4.8.1 The base of Ulangochuan Stage

At the type locality in the Erlian Basin, the Ulan Gochu Formation, only 18.3 m thick, overlies conformably on the Shara Murun Formation (Wang et al., 2012). Fossil mammals from the Ulan Gochu Formation are potentially qualified for defining the base of the Ulangochuan Stage. They include *Anagale gobiensis*, *Mongolestes hadrodens*, *Ardynomys olsoni*, *Gobiomys neimongolensis*, *Gobiolagus andrewsi*, *Desmatolagus vetustus*, *Teleolophus magnus*, *Juxia shoui*, *Nasamplus progressus*, *Titanodectes ingens*, *Embo-*

lotherium grangeri, *Hulgana ertinia*.

Preliminary paleomagnetic result shows that the base of the Ulangochuan can be correlated to chron C18n.2n, with an estimated age at 39.9 Ma.

4.8.2 Fossil mammals

In the Erlian Basin, the Ulangochuan mammals was mixed by specimens collected from different levels due to the improper correlation within the basin. To clarify the faunal composition, the listed Ulangochuan mammals of the Erlian Basin are here restricted to those from the Ulan Gochu Formation at the type section and its reconfirmed equivalent deposits. Inclusion of fossil mammals from the other basins is based on the biostratigraphic correlation.

Of the reported Ulangochuan mammals, taxa restricted to the Ulangochuan land mammal age mainly include *Anagale*, *Mongolestes*, *Guangxilemur*, *Heothema chengbiensis*, *Huananodon hypsodonta*, *Brachyhyops neimongolensis*, *Odoi-choerus uniconus*, *Ardynomys olsoni*, *Gobiomys neimongolensis*, *Gobiolagus andrewsi*, *Desmatolagus vetustus*, *Teleolophus magnus*, *Juxia shoui*, *Titanodectes ingens*, *Embolotherium grangeri*, and *Hulgana ertinia*, etc. It is worthy to note two mammal species, *Mimolagus rodens* and *Anagalopsis kansuensis*, described by Bohlin (1951) from Shanmacheng (Shih-her-ma-ch'eng) in the Jiuxi Basin, Gansu. They were controversially considered to be found in the Huoshaogou Formation (Liang et al., 1992) or the lower part of the higher Baiyanghe Formation (Zhai and Cai, 1984). Different opinions about their age include the Paleogene (Early Tertiary), the early Oligocene and the late Eocene (see Zhang and Wang, 2016). After the field investigation, Zhang and Wang (2016) confirmed that they came from the lower part (Shanmacheng Member) of the Huoshaogou Formation, about 40 m above the formation base. Calibration with the paleomagnetic result of the section (Dai et al., 2005), the fossil-bearing bed falls into chron C18n (~39–40 Ma) (Zhang and Wang, 2016), which suggest a correlation to the Ulangochuan Stage.

4.8.3 Other fossils

No fossils other than mammals have been reported from the type locality of the Ulan Gochu Formation. Mammalian biostratigraphic correlation has shown that the Caijiachong Formation of Qujing, Yunan is referable to the Ulangochuan Stage (Wang, 1997a). However, the Ulangochuan land mammal age currently used in the Chinese Paleogene land mammal age sequence is equivalent to both the Ulangochuan and Ergilian Asian land mammal ages (Tong et al., 1995; Wang et al., 2007; Vandenbergh et al., 2012). For the sake of convenience in the international scientific exchange, the Baiyinian land mammal age is proposed as the equivalence of the Ergilian in the Chinese Paleogene land mammal age sequence. It is thus possible that part of the mammals

from the Caijiachong Formation is referable to the Baiyinian land mammal age.

When they reported the section of the Caijiachong Formation, Wang and Zhang (1983) listed fossil charophytes and gastropods from the middle and upper fossil-bearing horizons. The gastropods from both horizons are the same in taxonomy, including *Bithynia (Pseudommericia)? largicirca*, *B. (P.)? parvobliquus* and *Assiminca pressoopercula*. The charophytes were formally reported by Liu (1989), but she failed to distinguish the horizons. The charophyte flora was dominated by *Maedlerisphaera qujingensis* (nearly 45%), and the other major forms include *Rhabdochara copica*, *R. stockmansii*, *R. raibocarpa*, *Amblyochara regularis*, *A. subeiensis*, *Sphaerochara rugulosa* f. *elliptica*, *Harrisichara yunlongensis* and *H. vasiformis*.

4.9 Baiyinian Stage

4.9.1 The base of Baiyinian Stage

The Baiyinian mammals have only been reported from a few sites. Fossil mammals from the basal part of the Xianao-gangdai Formation can be used in defining the base of the Baiyinian Stage. They include *Entelodon gobiensis*, *Schizotherium avitum*, *Embolotherium andrewsi*, *Zaisanamynodon borisovi*, *Gigantamynodon giganteus*, *Urtinotherium intermedium*, *Parabrontops gobiensis*, *Ardynia praecox* and *Proeggyssodon qiui*, etc.

Preliminary paleomagnetic result shows that the base of the Baiyinian can be correlated to the top of chron C17n.1n, with an estimated age at 37.2 Ma.

4.9.2 Fossil mammals

Fossil mammals reportedly restricted to the Baiyinian Stage include *Bothriodon chowi*, *Embolotherium andrewsi*, *Zaisanamynodon borisovi*, *Gigantamynodon giganteus*, *Urtinotherium intermedium*, *Parabrontops gobiensis*, *Ardynia praecox*, *Proeggyssodon*, *Guangnanodon*, *Heosminthus primiveris*, *H. nomogenesis*, *Sinosminthus inapertus*, *Allosminthus ernos* and *A. majusculus*.

4.9.3 Other fossils

Only charophytes were reported from the Baiyinian Stage in the Erlian Basin. They were collected from the Xianao-gangdai Formation and not rich, including *Maedlerisphaera shalamulunensis*, *Sphaerochara parvula*, *S. minor*, *Krassavinella lagenalis*, *Gyrogona qianjiangica* (Liu, 1988).

4.10 Ulantatalian Stage

4.10.1 The base of Ulantatalian Stage

The Ulantatalian Stage is the first stage of the Oligocene, and its base is thus consistent with that of the Oligocene Series. It has been formally decided to put the base of the Oligocene

Series (i.e. the base of the Rupelian Stage) close to the top of chron C13r, with a numerical age of 33.9 Ma (Vandenberghe et al., 2012).

According to the currently available biostratigraphic data, the Eocene/Oligocene boundary, i.e. the base of the Ulantatalian Stage, is probably located in the upper part of the Xianao-gangdai Formation at the Erden Obo Section, Sizi-wang Qi, Nei Mongol, which is a set of reddish muddy siltstones or silty mudstones. The composition of rodent fauna has changed obviously across the boundary (Li Q et al., 2016, 2017). Preliminary paleomagnetic result also supports to place the boundary in the upper part of the Xianao-gangdai Formation.

Currently on-going studies at Ulantatal, Alax Zuoqi (Zhang et al., 2016) and Balagong, Hangjin Qi, Nei Mongol, have indicated that the Eocene/Oligocene boundary probably existed at both sites. The Caijiachong fauna previously thought to be the early Oligocene has been confirmed as the late Eocene in age, but recent discovery shows the possible existence of the lower Oligocene above the strata bearing the Caijiachong fauna in Qujing, Yunnan (Maridet and Ni, 2013; Li L Z et al., 2017).

A number of mammalian taxa have been reported from the Ulantatalian land mammal age, with many restricted to the age. Some of the taxa occurred at the lower horizon of the section could be used to define the base of the Ulantatalian Stage. They include: *Eumeryx culminus*, *Praetragulus gobiae*, *Desmatolagus pusillus*, *D. youngi*, *Didymoconus colgatei*, *Hyaenodon neimongoliensis*, *Palaeoscaptor acridens*, *Selenomys mimicus*, *Eucricetodon asiaticus*, *E. meridionalis*, *Bagacricetodon tongi*, *Anomoemys lohicolus*, *Coelodontomys asiaticus*, *Cyclomylyus lohensis*, *Tsaganomys altaicus*, *Ageitonomys neimongolensis*, *Karakoromys decessus*, *Paracricetops virgatoincisus*, *Cricetops dormitor*, *Bohlinosminthus parvulus*.

4.10.2 Fossil mammals

To date, a number of mammalian forms have been reported from the Ulantatalian Stage. Taxa restricted to the Ulantatalian include *Eumeryx culminus*, *Praetragulus gobiae*, *Desmatolagus pusillus*, *D. youngi*, *Ordolagus teilhardi*, *Hyaenodon neimongoliensis*, *Palaeoscaptor acridens*, *Eomys orientalis*, *Selenomys*, *Eucricetodon asiaticus*, *E. meridionalis*, *Bagacricetodon tongi*, *Plesiodipus wangae*, *Witenia yolua*, *Pseudocricetops matthewi*, *Anomoemys lohicolus*, *Litodontomys huangheensis*, *Euryodontomys exiguus*, *Coelodontomys asiaticus*, *Cyclomylyus lohensis*, *Tsaganomys altaicus*, *Ageitonomys neimongolensis*, *Tataromys sigmodon*, *Karakoromys decessus*, *Paracricetops virgatoincisus*, *Cricetops dormitor*, *Propalaeocastor irtyshensis*, *Bohlinosminthus parvulus*, *Yunnanadapis folivorus*, *Y. imperator*, *Laomaki yunnanensis*, *Gatanthropus micros*, *Bahinia banyueae*, and *Oligotarsius rarus*.

No fossils other than mammals have been reported from the classic and unequivocal Ulanatalian deposits, the related data await for further investigation in the future.

4.11 Tabenbulukian Stage

4.11.1 The base of Tabenbulukian Stage

The Tabenbulukian land mammal age was proposed on the basis of the Yandantu fauna (also called Tabenbuluk fauna) of the Tabenbuluk area (also called Danghe area) (Li and Ting, 1983; Wang et al., 2008). Fossil mammal taxa common in many contemporaneous localities can define the base of the Tabenbulukian Stage. They include *Sinologomys major*, *S. kansuensis*, *Yindirtemys grangeri*, *Y. ambiguus*, *Y. suni*, *Plesiosminthus asiaecentralis*, *P. tangingoli*, *P. parvulus*, *Tataromys parvus*, *T. plicidens*, *Distylomys qianlishanensis*, *Tachyoryctoides kokonorensis*, and *T. obrutschewi*.

The strata bearing the Yandantu fauna was disputedly considered as the Baiyanghe Formation or the Huoshaogou Formation (see Wang et al., 2003). It was confirmed later that the fossil-bearing bed has no relations to the true Huoshaogou and Baiyanghe formations and was named the Paoniuquan Formation (Wang et al., 2003). The early Oligocene mammals were also found from the Paoniuquan Formation in the same area, but at a different section from that bearing the Yandantu fauna (Wang et al., 2003), which do not greatly help in determining the base of Tabenbulukian Stage.

Both the early Oligocene Nanpiping fauna and the late Oligocene Xiagou fauna were found from the lower part of the Xianshuihe Formation in the Lanzhou Basin, Gansu (Qiu et al., 1997), but the paleomagnetic study did not provide a confident age (Yue et al., 2001). Preliminary result and observation has shown that the undertaking investigation at Ulanatal in Alax Zuoqi (Zhang et al., 2016) and Balagong in Hangjin Qi, Nei Mongol will probably provide a resolution to this issue.

According to the recent progress made in the Great Lake Valley of Mongolia that is relevant to this issue, the boundary between the Tabenbulukian and the earlier Hsandangolian mammalian faunas is located in the middle of chron C8n.2n with an age of 25.5 Ma (Daxner-Höck et al., 2017). This age can be temporally used as for the base of the Tabenbulukian Stage in Chinese Oligocene.

4.11.2 Fossil mammals

Known mammalian taxa restricted to the Tabenbulukian Stage include *Amphechinus rectus*, *A. minimus*, *Sinologomys major*, *S. kansuensis*, *S. gracilis*, *Sayimys obliquidens*, *Yindirtemys grangeri*, *Y. ambiguus*, *Y. deflexus*, *Plesiosminthus asiaecentralis*, *P. tangingoli*, *P. parvulus*, *Heterosminthus lanzhouensis*, *Tataromys parvus*, *T. plicidens*, *T. minor*, *Distylomys qianlishanensis*, *Dzungariotherium orgosense*, and *Paraceratherium yagouense*.

No fossils other than mammals have been reported from the classic and unequivocal Ulanatalian deposits, the related data awaits for the investigation in the future.

5. Correlation of Paleogene at major localities in China

Stratigraphic correlation must be on the basis of reliable evidence of various respects. Biostratigraphic evidence has played an important role in such correlation. This section will focus on the strata that have well-developed deposits with detailed and reliable stratigraphic records, and can be calibrated with the Chinese Paleogene chronostratigraphic sequence (Figure 4). The strata will not be discussed, if their subdivision and age are in dispute, and/or if they cannot be reliably calibrated based on the currently available data.

5.1 Terrestrial Paleogene

5.1.1 Shanghuan Stage

The Shanghuan Stage is corresponding to paleomagnetic polarity chron C27n through the middle-upper part of chron C29r, and lasted from 66 Ma to 62.22 Ma. It spans most part of the Danian Stage (Vandenbergh et al., 2012).

The most prominent characteristic of fossil mammals from the Shanghuan Stage is the dominance of archaic groups and endemic Asian forms. The pantodont *Bemalambda* occurred in the Shanghuan Stage in all the Paleocene basins with contemporaneous deposits, from the Sanshui Basin of Guangdong to the Shimen and Luonan basins of Shaanxi (Wang Y Q et al., 1998, 2016). Based on mammalian biostratigraphic correlation, the following strata can be referred to the Shanghuan Stage: The Shanghuan Formation of the Nanxiong Basin and the Xinzhuangcun Formation of the Sanshui Basin, Guangdong; the Shizikou Formation of the Chijiang Basin, Jiangxi; the Zaoshi Formation of the Chaling Basin, Hunan; the Lower Member to the lower Upper Member of the Wanghudun Formation of the Qianshan Basin, Anhui; the Gaoyugou Formation of the Tantou Basin, Henan; the Juanling Formation of the Shanyang Basin and the Fangou Formation of the Shimen Basin, Shaanxi. Such a correlation was supported by the fossil records of other groups, such as ostracods (Zhang, 1988). Studies on fossil charophytes, ostracods, and spore-pollen suggest a correlation of the Member I of the Funing Formation of the Subei Basin, Jiangsu to the Shanghuan Stage (He, 1979; Wang et al., 1979; Yang, 1979; Li, 1989). The correlation of both the Shizikou Formation and the Juanling Formation to the Shanghuan Stage was supported by paleomagnetic studies (Xue et al., 1994; Clyde et al., 2008, 2010). Carbon isotopic results confirmed that the normal polarity in the upper part of the Shanghuan Stage is corresponding to chron C27n (Clyde

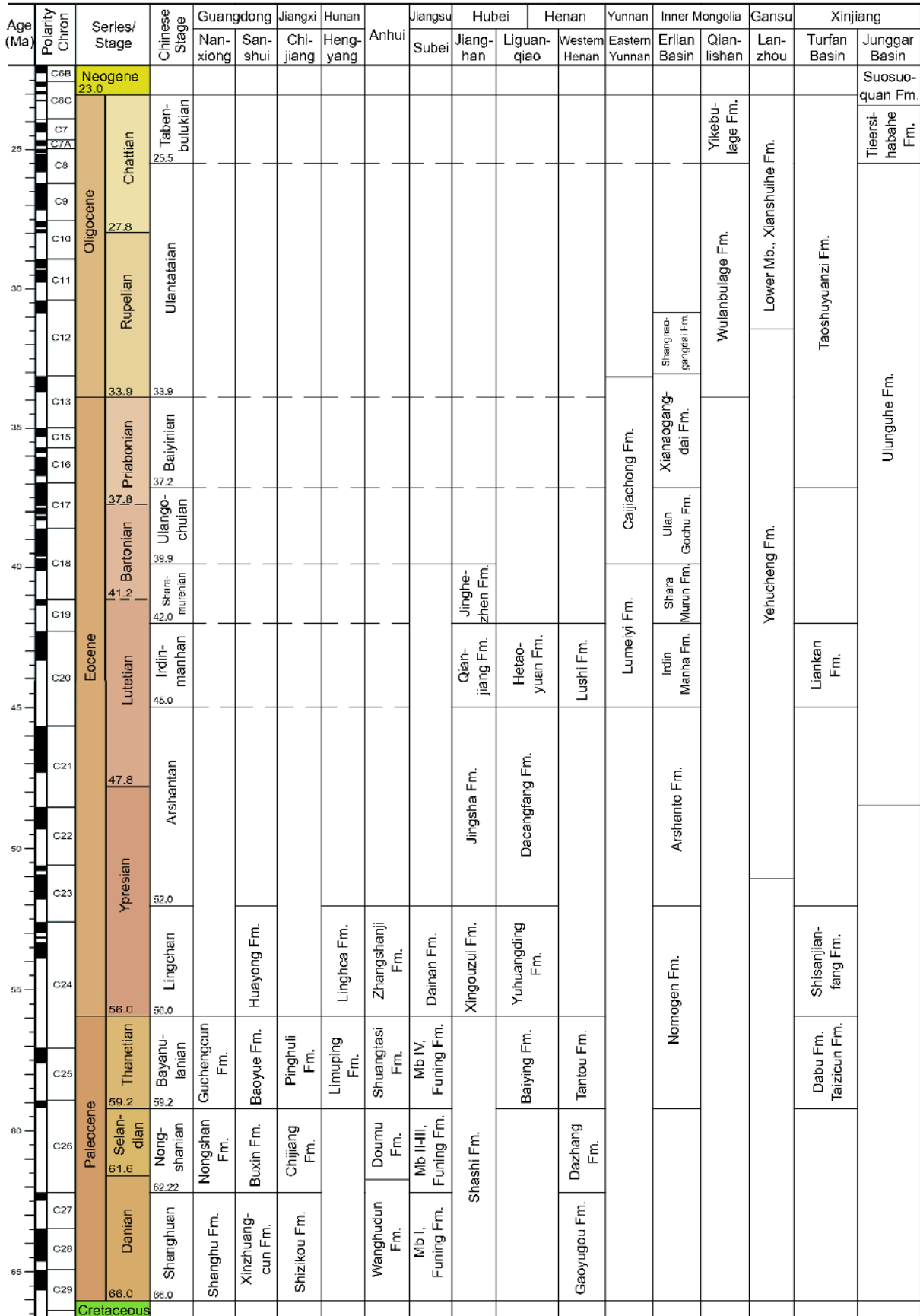


Figure 4 Correlation of Chinese terrestrial Paleogene at some localities.

et al., 2008).

5.1.2 Nongshanian Stage

The Nongshanian Stage is corresponding to the whole chron C26r of the paleomagnetic polarity timescale, and lasts from 62.22 to 59.2 Ma. The stage can be correlated to the top of the Danian Stage and the Selandian Stage (Vandenbergh et al., 2012).

Based on mammalian biostratigraphic correlation, the following strata can be referred to the Nongshanian Stage: the Nongshanian Formation of the Nanxiong Basin, the Chijiang Formation of the Chijiang Basin, and the top of the Wanghudun Formation and the Doumu Formation of the Qianshan Basin (Wang Y Q et al., 1998, 2016). Studies on fossil charophytes, gastropods and ostracods suggest a correlation of the Member II–III of the Funing Formation of the Subei Basin, Jiangsu to the Nongshanian Stage (Yü, 1977; He, 1979; Li, 1983; Zhang, 1988). Meanwhile, studies on fossil charophytes and ostracods also provided evidence for a correlation of the Buxin Formation of the Sanshui Basin to the Nongshanian Stage (Li, 1983; Zhang, 1988). The correlation of the base of the Chijiang Formation with the base of the Nongshan Formation was further supported by paleomagnetic studies (Clyde et al., 2008, 2010).

5.1.3 Bayanulanian Stage

The Bayanulanian Stage is corresponding to chron C26n through the lower part of C24r of the paleomagnetic polarity timescale, and spans from 59.2 to 56 Ma. It can be correlated to the Thanetian Stage (Vandenbergh et al., 2012).

Based on mammalian biostratigraphic correlation, the following strata can be referred to the Bayanulanian Stage: The lower part of the Nomogen Formation of the Erlian Basin, Nei Mongol; the Tujinshan Formation of Mingguang, Anhui; the Shuangtasi Formation of Xuancheng and Chizhou, Anhui; the Limuping Formation of the Hengyang Basin, Hunan; the Taizicun and Dabu formations of Turfan Basin, Xinjiang (Wang et al., 1998). Studies on fossil gastropods and ostracods suggest a correlation of the Member IV of the Funing Formation of the Subei Basin, Jiangsu, the Shuangtasi Formation of Anhui, and the Baoyue Formation of the Sanshui Basin, Guangdong to the Bayanulanian Stage (Yü, 1977; Yü and Zhang, 1982; Zhang and Li, 2010).

5.1.4 Lingchan Stage

The Lingchan Stage is corresponding to the upper part of chron C24r to the lower part of C23r of the paleomagnetic polarity timescale, and lasted from 56 to ~52 Ma. The stage can be correlated to the lower part of the Ypresian Stage (Vandenbergh et al., 2012). Carbon isotope excursion recognized in several sections demarcated the base of the Lingchan Stage, i.e., the Paleocene/Eocene boundary (Böwen et al., 2002; Zhu et al., 2010).

The strata bearing the Lingchan mammals mainly include the Lingcha Formation of the Hengyang Basin, Hunan, the Wutu Formation of Changle, Shandong, the Yuhuangding Formation of the Liguangqiao Basin, the Huayong Formation of the Sanshui Basin, Guangdong, and the upper part of the Nomogen Formation of the Erlian Basin, Nei Mongol. The whole Yuhuangding Formation was previously considered to be the early Eocene in age. However, the result of geochemical study showed that the carbon isotope excursion representing the Paleocene/Eocene boundary occurred in the lower-middle part of the Yuhuangding Formation (Zhu et al., 2010), which suggests a late Paleocene age and correlative to the Bayanulanian Stage for the lower part of the formation. Such result is coincident with the study on fossil charophytes (Ge, 1994).

Studies on fossil charophytes, gastropods and ostracods suggest a correlation of the Huayong Formation of the Sanshui Basin, Guangdong, and the Dainan Formation of the Subei Basin, Jiangsu with the Lingchan Stage (Ge, 1994; Zhang and Li, 2010).

5.1.5 Arshantan Stage

The Arshantan Stage is roughly corresponding to the lower part of C23r through the lower part of chron C20r of the paleomagnetic polarity timescale, and lasts from ~52 to ~45 Ma, which can be correlated to the upper part of the Ypresian Stage and the lower part of the Lutetian Stage (Vandenbergh et al., 2012). Determination of the base of the Arshantan Stage is based on the combined paleomagnetic result of different sections.

Currently, the mammal-bearing strata referable to the Arshantan Stage include the Arshanto Formation of the Erlian Basin, Nei Mongol, and the Dacangfang Formation of the Liguangqiao Basin. Ge (1994) considered that the charophyte taxa from the Dacangfang Formation were also present in the Hanshou Formation of the Dongting Basin, Hunan, the Member IV of the Shahejie Formation in the coastal area of the Bohai Sea, and the Sanduo Formation of the Subei Basin, Jiangsu, which suggest that these formations are referable to the Arshantan Stage.

5.1.6 Irдинmanhan Stage

The Irдинmanhan Stage is roughly corresponding to the lower part of C20r through the lower part of chron C19r of the paleomagnetic polarity timescale, and lasts from ~45 to ~42 Ma. It can be correlated to the middle-upper part of the Lutetian Stage (Vandenbergh et al., 2012). In the Erlian Basin, sections containing the base of the Irдинmanhan Stage are not well-developed, and no better section has been documented in other contemporaneous basins, a better age determination for the base of the stage thus awaits the finding of better sections, and further work.

Based on the mammalian biostratigraphic correlation, the

Hetaoyuan Formation of the Liguangqiao Basin, the lower part of the Lumeiyi Formation of Lunan, Yunnan, and the Lushi Formation of the Lushi Basin, Henan are referable to the Irindinmanhan Stage.

5.1.7 *Sharamurunian Stage*

The Sharamurunian Stage is roughly corresponding to the middle-upper part of C19r to the middle of chron C17r of the paleomagnetic polarity timescale, and lasts from ~42 to ~38.4 Ma, which can be correlated to the top of the Lutetian Stage and the lower-middle part of the Bartonian Stage (Vandenbergh et al., 2012). Horizontal variation of the deposits containing the base of the Sharamurunian Stage in the Erlian Basin is significant, a better boundary section is therefore necessary to improve the base determination of the stage.

Based on the mammalian biostratigraphic correlation, the Nadu Formation of the Baise Basin, Guangxi and the upper part of the Lumeiyi Formation of Lunan, Yunnan are referable to the Sharamurunian Stage.

5.1.8 *Ulangochuian Stage*

The Ulangochuian Stage is roughly corresponding to the middle part of C17r to near the top of chron C17n.1n of the paleomagnetic polarity timescale, and lasts from ~38.4 to ~37.2 Ma. It can be correlated to the top of the Bartonian Stage and the basal part of the Priabonian Stage (Vandenbergh et al., 2012).

Based on the mammalian biostratigraphic correlation, the Chaganbulage Formation of the Haosibuierdu Basin, Nei Mongol and the lower part of the Caijiachong Formation of Qujing, Yunnan are referable to the Ulangochuian Stage.

5.1.9 *Baiyinian Stage*

The Baiyinian Stage is corresponding to near the top of chron C17n.1n to the top of chron C13r of the paleomagnetic polarity timescale, and lasts from ~37.2 to 33.9 Ma. The stage can be correlated to most part of the Priabonian Stage (Vandenbergh et al., 2012).

Based on the mammalian biostratigraphic correlation, the upper part of the Caijiachong Formation of Qujing, Yunnan may be referable to the Baiyinian Stage.

5.1.10 *Ulantatalian Stage*

The Ulantatalian Stage is corresponding to the top of chron C13r to the middle of chron C8n of the paleomagnetic polarity timescale, and lasts from 33.9 to 25.6 Ma. It can be correlated to the Rupelian Stage and the lower part of the Chattian Stage (Vandenbergh et al., 2012).

Based on the mammalian biostratigraphic correlation, the upper part of the Xianaogangdai Formation and the Shangnaogangdai Formation of the Erlian Basin, the Wulanbulage Formation of Otag Qi, and the lower part of the Ulantatal

Formation of Alax Zuoqi, Nei Mongol, and the lower part of the Paoniuguan Formation of the Lanzhou Basin, Gansu are referable to the Ulantatalian Stage.

5.1.11 *Tabenbulukian Stage*

The Tabenbulukian Stage is corresponding to the middle of chron C8n through C6Cn.2r of the paleomagnetic polarity timescale, and lasts from 25.6 to 23.0 Ma. It can be correlated to the upper part of the Chattian Stage (Vandenbergh et al., 2012). Based on the mammalian biostratigraphic correlation, deposits referable to the Tabenbulukian Stage currently include the Yikebulage Formation of Otag Qi and Hangjin Qi, and the upper part of the Ulantatal Formation of Alax Zuoqi, Nei Mongol.

5.2 Correlation with marine deposits

The Paleogene marine deposits of China have a distribution restricted in Taiwan, southern Tibet and the Tarim Basin. All these marine deposits are rich in fossil foraminifera, and can be directly correlated with the global standard chronostratigraphic scale (Wang and He, 2018). A possible correlation of marine and terrestrial deposits in China was provided in The Stratigraphic Chart of China (2014). Due to the uncertainty of the correlation of the marine Paleogene with the Chinese chronostratigraphic system, the related issue will not be discussed in this paper.

6. Concluding remarks

In recent years, some advances have been made in Chinese Paleogene chronostratigraphy. Published achievement, mainly related to the early Paleogene, has established the general chronostratigraphic framework. The Paleocene/Eocene boundary has been precisely demarcated by using stable isotope analysis. Based on the combined results of magnetostratigraphy and mammalian biostratigraphy, the bases of stages in the Paleocene and early Eocene have been re-defined with age estimation, which provided a reliable basis for the discussion on evolutionary events and paleoenvironmental changes, and settled a timescale for inter-continental correlation.

The discovery of continuous and fossiliferous Oligocene section represented the progress on the Oligocene chronostratigraphic work. Preliminary observation of fossil mammals from the Saint Jacques area suggests that the mammal-bearing deposits represent complete Oligocene sequence with both the Eocene/Oligocene and the Oligocene/Miocene boundaries, which laid a foundation for establishing the Oligocene chronostratigraphic scheme.

Some difficulties remain in establishing the middle-late Eocene chronostratigraphic framework because of two major

reasons. One is because the discontinuous section of related interval, especially in the classic areas, could not provide enough evidence for reliable base definition of the stages. The other is that some longstanding problems of subdivision and correlation in the classic areas have not been resolved satisfactorily. Both require detailed and hard work in order to resolve the basic problems.

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