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Neogene integrative stratigraphy and timescale of China

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Abstract The widely exposed Chinese Neogene terrestrial deposits provide the best circumstance for the establishment of an accurate chronostratigraphic system of Eurasia, and the rapidly evolved mammalian fossils contribute efficiently to the division and correlation of Asian Neogene strata. A uniform Neogene biostratigraphic framework for China has already been established, with seven mammalian ages named. With a developed stratigraphic basis for the geochronologic "ages", seven chronostratigraphic "stage" have been established for the Chinese Neogene terrestrial strata, namely the Miocene Xiejian, Shanwangian, Tunggurian, Bahean, and Baodean stages, and the Pliocene Gaozhuangian and Mazegouan stages. Based on a series of research achievements, refined biostratigraphic, paleomagnetic and isotopic methods were combined and applied to continuous sections, and a Chinese Neogene chronostratigraphic sequence with accurate geological ages was established and improved in recent years. The lower boundaries of most of the stages could be correlated with those of the marine stages in the International Chronostratigraphic Chart, except the Tunggurian Stage, which is correlated with the European land mammal age. The biostratigraphic markers of the Chinese Neogene stages are usually first appearance of a single taxon, some representing regional species replacement, others indicating intercontinental migration of certain taxa. Candidate stratotype sections have been proposed for all the Chinese Neogene stages according to the principle and rule of modern stratigraphy, and other Chinese Neogene strata in different regions are comprehensively correlated.

Keywords Neogene, Stage/age, Mammal, Biostratigraphy, Chronostratigraphy, Magnetostratigraphy, China

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1. Introduction

With the leadership of the International Commission on Stratigraphy (ICS) and the unremitting efforts of stratigraphers from around the world, the domain of stratigraphy underwent rapid development during the last three decades. Benefitting from the intensive study of marine microfossils, a global standard chronostratigraphic scale was established, and the Neogene chronostratigraphy stood a highlighted development. Six of eight Neogene stages in the International Chronostratigraphic Chart have already been ratified for the lower boundaries of Global Standard Stratotype-Section and Point (GSSP), and accurate ages of the lower boundaries for the other two stages (Langhian and Burdigalian) have been defined as well. With the marine strata as standard, widespread Neogene terrestrial strata can be correlated well with the marine strata (Ogg et al., 2016).

Though the Chinese Neogene is dominated by terrestrial deposits, the chronostratigraphic study did not gain sufficient recognition until 1978; biostratigraphic study focused mainly on description of mammalian fossils, and studies of other fossils only confined to local reports. Chiu et al. (1979) re-

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viewed the Chinese Neogene mammalian faunas and first proposed an age scheme. Subsequently, a Chinese Neogene land mammalian ages framework was established and improved by later researchers (Li et al., 1984; Qiu, 1989; Qiu and Qiu, 1990, 1995; Tedford, 1995; Tong et al., 1995; Qiu et al., 1999; Deng, 2006; Qiu et al., 2013; Woodburne et al., 2013; Deng and Hou, 2014). The establishment of the Chinese Neogene stages was actively proposed since the Third Congress of the Chinese Commission on Stratigraphy in 2000. Based on the mammalian ages and following the rule of the International Stratigraphic Guide (ISG) (Salvador, 1994), the Chinese Neogene was divided into seven stages and embodied in the "Stratigraphic Chart of China" (Wang et al., 2014). The seven stages are the Miocene Xiejian, Shanwangian, Tunggurian, Bahean, and Baodean stages, and the Pliocene Gaozhuangian and Mazegouan stages.

There is no strict international standard for the division and correlation of the terrestrial stratigraphy, because the division of the terrestrial stratigraphy is based mainly on mammalian fossils, which are usually scarce, fragmentary, and endemic. On the other hand, the Chinese Neogene deposits are more suitable for the establishment of an accurate Neogene biostratigraphic sequence than those of Europe (Tedford, 1995), since the terrestrial deposits in Europe often limited, and many important faunas are unearthed from fissure-fillings. Chinese Neogene deposits are widespread and well suited for magnetostratigraphic analysis, despite the few radiometric dates available.

2. History of the Chinese Neogene chronostratigraphic studies

The Chinese Neogene deposits are widely distributed, especially in northern China. As far back as the early 19th century, paleontologists began to note mammalian fossils in the Chinese Neogene deposits. Hugh Falconer reported a few fragmentary mammalian fossils from the Zanda Basin, Tibet in 1839 and initiated Chinese Neogene mammalian studies, with the first scientific research of the Chinese vertebrate fossils (Falconer, 1868). Later, Koken (1885) named *Hipparion richthofeni* from the Neogene deposits of North China. Though lacking exact location information, the discovery of *H. richthofeni* made great sense for the age estimation. Johan Andersson's geological survey in North China (1916–1923) made brilliant achievements. Abundant mammalian fossils were collected from the *Hipparion* Red Clay, which constitute the famous "Lagrelius Collection" at Uppsala University, Sweden. Somewhat later, the collection and study of the *Platybelodon* fauna from the Middle Miocene of the Mongolian Plateau were started by the American Museum of Nature History (AMNH). Another significant collection was the Pliocene mammalian fauna from the Yushe Basin, Shanxi Province. Fossils collected by Émile Licent in the Yushe Basin in 1930s were studied by Pierre Teilhard de Chardin and others, while fossils collected for Childs Frick of New York from the Yushe Basin were stored in AMNH and their study lagged behind (Tedford et al., 2013). Other important fossil discoveries and researches in 1930s include the Early Miocene Shanwang fauna from Shandong by Young (1936a), and the Miocene mammalian faunas from the Qaidam Basin by Birger Bohlin. Teilhard de Chardin and Leroy (1942) summarized the former studies and established the Chinese Neogene stratigraphic sequence.

Neogene stratigraphic research advanced after 1949. Many new localities were discovered with great significance, including Lantian in Shaanxi, Gyirong and Bulong in Tibet, Lufeng in Yunnan, and Xiejia in Qinghai, etc. Excavations and re-studies of some classic localities, like Ertemte in Inner Mongolia and Yushe in Shanxi, were also conducted. Complementing the sequencing of the mammalian faunas, a Neogene chronostratigraphic framework also gradually developed.

Based on the mammalian fossils, Chiu et al. (1979) sequenced the Neogene deposits by lithostratigraphic formations. Later, Li et al. (1984) named seven Chinese Neogene "ages" and correlated them with the European ones. These Chinese Neogene land mammal ages are the Early Miocene Xiejian, early Middle Miocene Shanwangian, late Middle Miocene Tunggurian, Late Miocene Bahean, latest Late Miocene Baodean, Early Pliocene Jinglean, and the Late Pliocene Youhean. Qiu and Qiu (1990) adjusted the Shanwangian to late Early Miocene, merged the Bahean of North China to Baodean, assigned the Late Miocene of South China to Lufengian, and replaced the Pliocene Jinglean and Youhean by Yushean, using the Gaozhuang and Mazegou faunas to represent Early and Late Pliocene respectively. In 1999, the Chinese Commission on Stratigraphy formally erected the Pliocene Gaozhuangian and Mazegouan ages, and Deng (2006) revalidated the Bahean Age.

In the recent years, many new discoveries were made in well-exposed fossiliferous regions, such as Tongxin in Ningxia, central Inner Mongolia, northern Junggar Basin in Xinjiang, the Linxia Basin in Gansu, and so on. Magnetostratigraphic datings were done in many classic regions. Based on these datings, and following the principle that the chronostratigraphic "stage" should correspond to the geochronologic "age", a Chinese Neogene chronostratigraphic system was erected, which consists of the lower Lower Miocene Xiejian, upper Lower Miocene Shanwangian, Middle Miocene Tunggurian, lower Upper Miocene Bahean, upper Upper Miocene Baodean, Lower Pliocene Gaozhuangian, and Upper Pliocene Mazegouan stages, and the Chinese Neogene chronostratigraphic system was correlated with the geologic time scale of the International Chronostratigraphic Chart, which was established based on marine stratigraphy (Qiu et al., 2013).

3. Chinese Neogene chronostratigraphic scheme

Although the International Commission on Stratigraphy (ICS) has regarded chronostratigraphic division as the ultimate goal of stratigraphic division, and aimed to establish a standard international chronostratigraphic chart (Hedberg, 1976), the ISG 1994 (Salvador, 1994) explicitly mentioned that regional stage/age and series/epoch are perhaps always needed, and boundary-stratotype of a stage is better as a marine deposit (with the exception, for example, of the Tertiary non-marine stages based on mammalian faunas). Therefore, the ISG allows regional stage/ages based on terrestrial deposits that bear mammalian fossils. In China, the comprehensive distribution and systematic evolution of each stage′s mammals, which are regarded as the biostratigraphic base to establish the Neogene terrestrial chronostratigraphic system, have been reviewed by Qiu et al. (2013, figs. 1.2, 1.3, 1.7).

There are two viewpoints on the definition of the lower boundary of the Neogene terrestrial stages, one equates the lower boundary of the terrestrial stages with the marine stages, and the other recommends a lower boundary based on mammalian fossils. Considering that the first and last appearance of mammalian fossils is difficult to determine, and that different marine and terrestrial stage boundaries will add to complexity of the stratigraphic division, we tend to define the Neogene terrestrial stages by the standard of established marine stages, and take the mammalian fossils as auxiliary markers of boundaries. The establishment of the boundary-stratotype of terrestrial stages still follows the basic requirements of the ISG 1994: obvious marker beds that are easily recognized and tracked regionally, and with practical significances, like boundaries of bio-zones, magnetic reversals, and stratigraphic beds that can be precisely dated by isotopic or other geological dating methods.

3.1 Xiejian Stage

The Xiejian Stage is the first stage of the Chinese Lower Miocene. This stage is named after Xiejia Village, Tianjiazhai Township, Huangzhong County, Qinghai Province. The Petroleum Survey Team under the Qinghai Geological Survey named the Xiejia Formation in 1978. Li and Qiu (1980) later named the Xiejia fauna based on micromammals found from the Xiejia Formation, which is also the first discovery of the Chinese Early Miocene mammalian fauna. Li et al. (1984) first used the Xiejian Age, dated it as Early Miocene and represented it by the Xiejia fauna. The Xiejian Stage was formally proposed at the Second Congress of the Chinese Commission on Stratigraphy in 1999.

The candidate stratotype section of the Xiejian Stage is located at Chetougou gully, north of Xiejia Village. The Xiejia section is composed of four formations (from bottom to top): Mahalagou Formation, Xiejia Formation, Chetougou Formation, and Xianshuihe Formation. The Xiejia Formation conformably contacts both the Mahalagou Formation and the Chetougou Formation. The Xiejia fauna, which is mainly composed of micromammals, consists of *Sinolagomys pachygnathus* of Lagomorpha, *Cricetodon youngi*, *Parasminthus xiningensis*, *P. huangshuiensis*, *Litodonomys lajeensis*, *Yindirtemys suni*, *Y. xiningensis*, *Tachyoryctoides kokonorensis* of Rodentia, *Turpanotherium elegans* of Perissodactyla, and *Sinopalaeoceros xiejiaensis* of Artiodactyla (Qiu et al., 2013).

The Xiejian Stage correlates with the marine Aquitanian Stage of the International Chronostratigraphic Chart, and its lower boundary corresponds to C6Cn.2n (base, 23.03 Ma) (Steininger et al., 1997). However, C6Cn.2n cannot be clearly observed at the Xiejia section, and the position of this boundary might be at the continuous brownish-red massive mudstone of the lower part of the Xiejia Formation, 14 m above the bottom of the Xiejia Formation (Figure 1).

Although being the nominated locality of Xiejian Stage and perhaps containing the paleomagnetic marker of the lower boundary, the Xiejia section lacks a biostratigraphic marker for its lower boundary. The Xiejia fauna was found 20 m above the lower boundary. The Xiejian Stage contains three Neogene Mammal Units (NMU 1–3), of which the Xiejia fauna corresponds to NMU 2, while the NMU 1 is represented by the Suosuoquan fauna found to the northern Junggar Basin in Xinjiang (Qiu et al., 1999).

The Tieersihabahe section of the northern Junggar Basin in Xinjiang has simple geological tectonics, and contains abundant Late Oligocene to Early Miocene mammalian fossils, dominated by micromammals like lagomorphs, rodents, and insectivores. The Tieersihabahe Formation contains two Oligocene biozones (Tieersihabahe I and II). The lower Suosuoquan Formation contains three biozones (Suosuoquan I–III), and the age of Suosuoquan-I biozone is Late Oligocene, and Suosuoquan-II biozone is Early Miocene (Meng et al., 2006). The Tieersihabahe section is recommended as a candidate stratotype section of Xiejian Stage. This section has a continuous magnetic polarity sequence of C7n–C5E, which contains the Oligocene-Miocene boundary recognized at the base of C6Cn.2n. The boundary is above the Suosuoquan-I biozone, about 7.25 m above the bottom of the Suosuoquan Formation. The first appearance of *Democricetodon sui* (Rodentia) is chosen as the characteristic fossil of the lower boundary of Xiejian Stage. However, the Suosuoquan-II biozone that contains *D. sui* is only found from another locality about 10 km from the Tieersihabahe section (Meng et al., 2013). Therefore, the

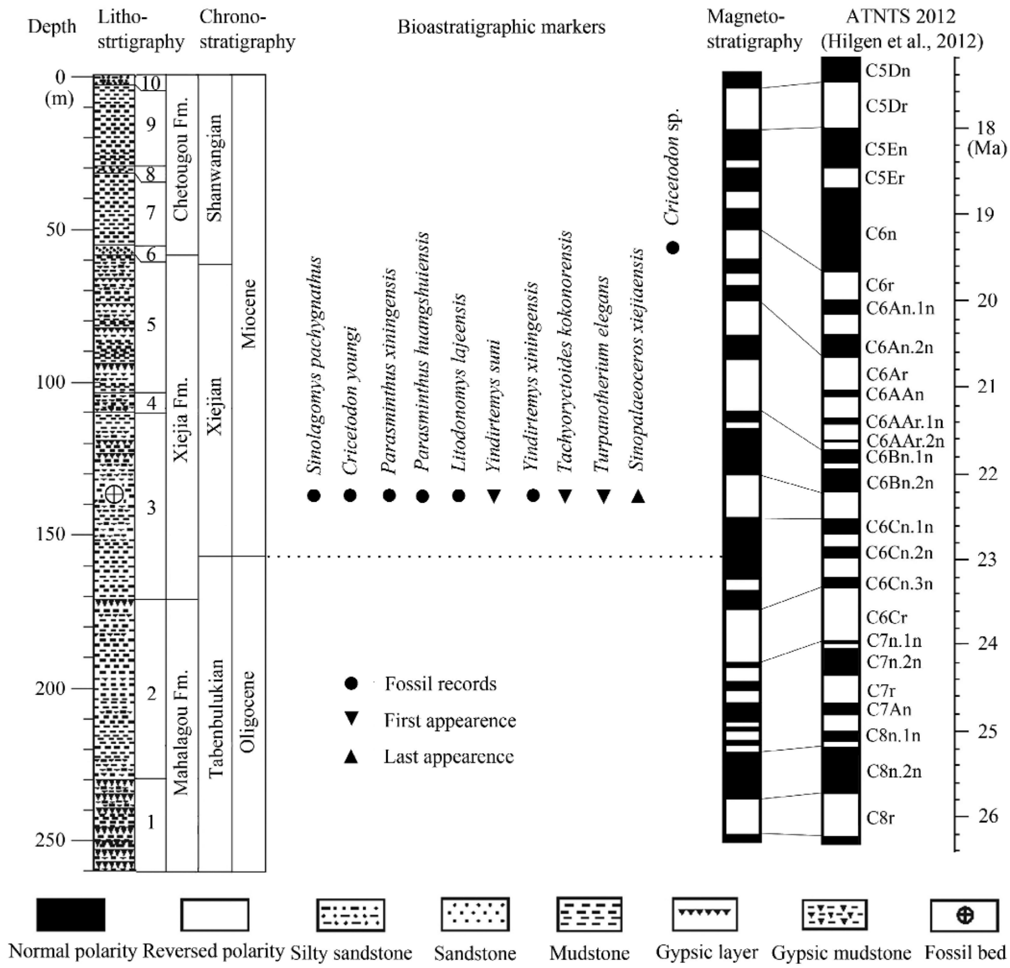


Figure 1 Comprehensive column section at Xiejia of the Xining Basin, Qinghai Province.

Tieersihabahe section also has some obvious drawbacks as the candidate stratotype section of Xiejian Stage.

The Xiejian fauna is characterized by the retention and/or extinction of the Oligocene taxa. Those common Oligocene members, like cylindrodontids, tachyoryctoidids, distylomyids, and brontotheriids are rare or became extinct during Xiejian Age; the tataromyids and some genera that flourished particularly in the Oligocene, like *Parasminthus* of Zapodidae, *Yindirtemys* of Ctenodactylidae, *Turpanotherium* of Paraceratheriidae, *Phyllotillon* of Chalicotheriidae, and *Sinopalaeoceros* of Bovidae, took their last appearance during the Xiejian Age. There are also some first-appearing Miocene components, including *Mioechinus* and *Quyania* of Insectivora, and *Sayimys*, *Ansomys*, *Sinotamias*, *Microdyromys*, *Sicista*, *Cricetodon*, *Democricetodon*, and *Protalactaga* of Rodentia (Qiu et al., 2013). Taken as a whole, the Xiejian fauna, composed mainly of advanced Oligocene taxa together with some new Miocene components, represents the turnover of an impoverished and specialized Oligocene fauna to Miocene fauna (Tong et al., 1995).

3.2 Shanwangian Stage

The Shanwangian Stage is the second stage of the Chinese Lower Miocene. The name of this stage is taken from Shanwang Village, Shanglin Township, Linqu County, Shandong Province. Young (1936a) named the Early or Middle Miocene "Shanwang Series" for the fossiliferous fluvio-lacustrine sediments overlying in the ″Qingshan Series″ (the basalt of the present Niushan Formation). Li et al. (1984) proposed the Shangwangian Age for the Shanwang fauna from the Shanwang Formation, and assigned the Sihong and Fangshan faunas from Jiangsu Province to the Shanwangian Age. The name Shanwangian Stage was formally proposed by the second Chinese Commission on Stratigraphy in 1999, its time range corresponding to the Shanwangian Age.

The main exposed area of Shanwang Basin is only about 0.3 km^2. The stratotype section for Shanwangian is situated at the Jiaoyanshan hill and Laomuqian valley, southwest of the Shanwang Basin. The Cenozoic deposits in the Shanwang Basin were divided into three formations (from bottom to top): Niushan Formation, Shanwang Formation, and Yaoshan Formation (Zheng et al., 1999). The mammalian fossils in the Shanwang Formation, especially in the diatomite deposits, are the main basis for the Neogene terrestrial stratigraphic division and correlation.

The early definition of Shanwangian Age only generally described the fauna, and did not specify the characteristic taxa of its lower boundary. The Shanwangian Age is defined to correlate to the European Orleanian Age, and the lower boundary of the latter is marked by the first appearance of *Anchitherium*. Therefore, the first appearance of *Anchitherium* is also used as the biostratigraphic marker of the lower boundary of the Shanwangian Age or Stage. The lower boundary of the Orleanian correlates with the lower boundary of the marine Burdigalian (Steininger, 1999), and the GSSP of the latter corresponds to Chron C6An (top, 20.44 Ma) (Hilgen et al., 2012), therefore, the age of the lower boundary of the Shanwangian would be 20.44 Ma. However, in the Shanwang Basin there is stratum absence between the Shanwang Formation and the underlying Niushan Formation, and the bottom age of the Shanwang Formation is 18 Ma (He et al., 2011). Therefore, the early Shanwangian and its lower boundary do not exist at the Shanwang section. The Lower Miocene deposits are also well-exposed in the Linxia Basin, Gansu Province (Deng et al., 2013) and central Inner Mongolia (Wang et al., 2009), which contain characteristic fossils of the earliest Shanwangian and are suitable for magnetic analysis, so we prefer these two areas as candidate stratotype sections for the Shanwangian Stage. *Choerolophodon guangheensis* from the Dalanggou section in Guanghe County within the Linxia Basin, which is perhaps the earliest proboscidean of China (Wang and Deng, 2011) with an paleomagnetic age of about 20 Ma, could be used as the biostratigraphic marker of the Shanwangian Stage; the Lower Aoerban fauna from the Aoerban Formation in central Inner Mongolia has a paleomagnetic age of about 20–20.3 Ma, which is very close to the lower boundary of the Shanwangian Stage, and the first appearance of *Atlantoxerus*, *Miodyromys*, *Keramidomys*, and *Ligerimys* (Qiu et al., 2013) could also be chosen as biostratigraphic markers of the lower boundary.

The evolutionary characteristics of the Shanwangian mammals are: at the family level almost all the Oligocene survivors are extinct; some modern families or subfamilies, for example, Petauristinae, Ursidae, Giraffidae and Cervidae, arise. Many new genera take their first appearance in Shanwangian, like *Mioechinus* of Insectivora, *Alloptox* of Lagomorpha, *Ansomys*, *Prodistylomys*, *Distylomys*, *Miodyromys*, *Keramidomys*, *Diatomys*, *Apeomys*, *Leptodontomys*, *Protalactaga*, and *Megacricetodon* of Rodentia, *Amphicyon*, *Phoberocyon*, *Ballusia*, *Semigenetta*, and *Pseudaelurus* of Carnivora, *Platybelodon* and *Stegolophodon* of Proboscidea, *Anchitherium*, *Anisodon*, and *Plesiaceratherium* of Perissodactyla, and *Hyotherium*, *Ligeromeryx*, *Dorcatherium*, *Sinomeryx*, and *Turcocerus* of Artiodactyla. Many genera last appear in this period, like *Amphechinus* and *Metexallerix* of Insectivora, *Prodistylomys*, *Ligerimys*, *Asianeomys*, *Plesiosminthus*, *Litodonomys*, and *Cricetodon* of Rodentia, and *Diaceratherium* of Perissodactyla (Qiu et al., 2013). To sum up, mammals enters a new evolutionary stage in Shanwangian Age; Rodentia started to be dominated by sciurids and murids; Creodonta was replaced by Carnivora; Proboscidea appeared; Perissodactyla declined, and primitive forms became extinct, only Rhinocerotidae, chalicotheres, and *Anchitherium* were common members; ruminants flourished. On the other hand, almost none of the genera of this period have modern survivors. Therefore, the Shanwangian Age is only the start of the modernization of mammals (Tong et al., 1995).

3.3 Tunggurian Stage

The Tunggurian Stage is the Middle Miocene stage of the Chinese Neogene. The name is taken from the Tunggur Tableland, 15 km southeast of Saihan Gobi Township, Sonid Left Banner, Inner Mongolia. Spock (1929), a member of the Central Asiatic Expedition (CAE) organized by the American Museum of Natural History (AMNH), established the Tunggur Formation, and the name derived from a well called Gur Tung Khara Usu. The Tunggur Formation mainly consists of fluvial deposits with a maximum thickness of nearly 80 m. This formation can be divided into two members: the upper member is well-exposed at the north and west margins of the tableland, which mainly consists of grayish-white sandstone and variegated mudstone, as well as occasional grayish marls; the lower member, which consists of uniform red or brownish-red mudstones interrupted by a fluvial sandstone, is exposed at the Tairum Nor area at the south margin of the tableland, and at the lower part of the Aletexire section of the north margin of the tableland. Both members are fossiliferous (Wang et al., 2003; Deng et al., 2007).

Li et al. (1984) established the Tunggurian Age mainly for the Tunggur fauna, generally correlating to the Astaracian of the European land mammal ages (Steininger, 1999). The second Chinese Commission on Stratigraphy formally proposed the establishment of Tunggurian Stage, with its time period incorporating the Chinese Tunggurian Age.

The candidate stratotype section for the Tunggurian Stage is located in the Tairum Nor area, southeast of the Tunggur Tableland, with a thickness of 35.6 m. The Tunggur Formation is covered by Quaternary yellow conglomerates, and the underlying contact is not visible. The stratigraphic sequence of the Tairum section is clear, from top to bottom being the upper red mudstone, the middle fluvial sandstone, and the lower red mudstone. The upper red mudstone is relatively light, more orange colored, with some repeated paleosol color bands. The lower red mudstone is dark in color and more uniform without paleosol bands.

The lower boundary of the Tunggurian Stage was considered to correspond to C5Bn.1r (base, 15 Ma), marked by the first appearance of *Alloptox gobiensis* and *Platybelodon grangeri*. This boundary is in the lower red mudstone of the Tairum section, 7.6 m below the base of the middle fluvial sandstone (Deng et al., 2007). Since this lower boundary of the Tunggurian Stage does not correlate with the marine Langhian Stage in the International Chronostratigraphic Chart, Qiu et al. (2013) replaced the lower boundary of the Tunggurian Stage to C5Cn.1n (15.97 Ma) (Hilgen et al., 2012), approximately the age of the Dingjiaergou fauna from Tongxin, Ningxia, or the Shinanu fauna from the Linxia Basin, a date consistent with the lower boundary of the Langhian Stage.

The evolutionary features of the Tunggurian mammals are: the Proboscidea began to radiate, and the ruminants started their dominance. The time interval is defined by the first appearance of Dipodidae and Hyaenidae. New-coming genera include *Sinotamias* and *Gobicricetodon* of Rodentia, *Protictitherium* and *Metailurus* of Carnivora, and *Palaeotragus*, *Euprox*, *Micromeryx*, and *Hispanomeryx* etc. of Artiodactyla. On the other hand, *Alloptox* of Lagomorpha, Ctenodactylidae and Tachyoryctoididae of Rodentia, *Pliopithecus* of Primates, *Hemicyon* of Carnivora, *Platybelodon* of Proboscidea, *Anisodon*, *Plesiaceratherium*, and *Hispanotherium* of Perissodactyla, and *Ligeromeryx*, *Stephanocemas*, and *Turcocerus* of Artiodactyla take their last appearance in this age (Tong et al., 1995; Qiu et al., 2013).

3.4 Bahean Stage

The Bahean Stage is the first Upper Miocene stage of the Chinese Neogene, named after the Bahe River running through the Lantian area, Shaanxi Province. The exposures along the Bahe River in the Lantian area provide one of the best Upper Miocene biostratigraphic sections. Liu et al. (1960) named the Bahe Formation. Li et al. (1984) established the Bahean Age, and correlated it with the Vallesian of the European Neogene land mammal ages (Steininger, 1999). The Bahean Stage corresponds to the Bahean Age.

The Bahe Formation is in unconformable contact with both the underlying Koujiacun Formation and the overlying Lantian Formation. The contact of the Bahe Formation with the underlying Koujiacun Formation could be seen at the western end of the Bailu Tableland and the western slope of the Lishan Mountain, but it is not visible at the south bank of the Bahe River. The Bahe Formation mainly consists of brownish-red mudstone and silty mudstone, and grayish-white sandstone and conglomerates. The paleomagnetic result indicates that the age of the Bahe Formation is 11–6.8 Ma (Kaakinen, 2005), therefore, the lower boundary of the Bahean Stage, which is correlated with the lower boundary of the marine Tortonian (11.63 Ma) (Hilgen et al., 2005), does not exist in the Lantian area.

The Liushu Formation in the Linxia Basin, Gansu Province, consists of uniform brownish-red mudstone. The Dashengou fauna from the lower part of the Liushu Formation is similar to the Bahean fauna, and the Guonigou fauna from the bottom of the Liushu Formation contains the earliest Late Miocene fossils. The candidate stratotype section of the Bahean Stage is located at a gully north of Guonigou Village, Nalesi Township, Dongxiang County, with well exposed strata named, from bottom to top, the lower Middle Miocene Dongxiang Formation, the upper Middle Miocene Hujialiang Formation, and the upper Miocene Liushu Formation (Deng et al., 2015).

The Guonigou fauna represents the fauna of the lowest Bahean Stage, and contains many new genera that mark its lower boundary, for example, *Dinocrocuta*, *Machairodus*, *Konobelodon*, *Hipparion*, *Nestoritherium*, *Parelasmotherium*, *Ningxiatherium*, and *Shaanxispira*, etc. The first appearance of *Hipparion* in the Palearctic terrestrial strata has long been considered as the lower boundary marker of the Upper Miocene. *Hipparion dongxiangense* of the Guonigou fauna is the smallest *Hipparion* known in China, and its strongly constricted hypocone and deep-and-wide hypocone groove are common characters of the Middle Miocene *Hipparion* of North America. The first appearance of *H. dongxiangense* is close to the base of C5r.2n (11.63 Ma) (Fang et al., 2016), which represents the earliest *Hipparion* locality in Eurasia, and it is correlated with the lower boundary of the marine Tortonian Stage (Deng et al., 2015).

Compared with the Tunggurian Stage, the mammalian fauna of the Bahean Stage represented a more modernized time: Myomorpha became the dominant Rodentia; Eomyidae and Gliridae continued to decline; Myospalacidae and Muridae appeared; Cricetinae displaced Cricetodontiae (Qiu and Li, 2016). Mustelidae, Hyaenidae, and Felidae flourished; the number of Proboscidea significantly contracted; *Hipparion* and *Chilotherium* became the dominant Perissodactyla, while Chalicotheriidae and Tapiridae had low diversity and fewer individuals; ruminants and other artiodactyls expanded. A pattern similar to that of modern mammals at high taxonomic levels formed (Tong et al., 1995). Common genera of the Tunggurian Stage were almost extinct, and plenty of new genera appeared, like *Ochotona* of Lagomorpha, *Castor*, *Lophocricetus*, *Sinozapus*, *Paralactaga*, *Dipus*, *Brachyscirtetes*, *Nannocricetus*, *Kowalskia*, *Sinocricetus*, *Microtoscoptes*, *Abudhabia*, *Prosiphneus,* and *Pararhizomys* of Rodentia, *Indarctos*, *Agriotherium*, *Sinictis*, *Parataxidea*, *Melodon*, *Eomellivora*, *Promephitis*, *Adcrocuta*, ictitheres, and *Machairodus* of Carnivora, *Prodeinotherium* and *Tetralophodon* of Proboscidea, *Pliohyrax* of Hyracoidea, *Sinohippus*, *Hipparion*, *Chilotherium*, *Shansir-*

hinus, and *Tapirus* of Perissodactyla, and *Chleuastochoerus*, *Schansitherium*, *Honanotherium*, *Cervavitus*, *Gazella*, and *Sinotragus* of Artiodactyla, together they constituted the typical Neogene *Hipparion* fauna (Qiu et al., 2013). Among these are some modern genera, for example, *Castor*, *Ochotona*, *Tapirus*, and *Gazella*, etc. The last-appearing taxa include *Mioechinus* of Insectivora, *Desmatolagus* of Lagomorpha, *Ansomys*, *Keramidomys*, *Heterosminthus*, *Protalactaga*, *Democricetodon*, *Megacricetodon*, and *Gobicricetodon* of Rodentia, and *Euprox* of Artiodactyla, etc.

3.5 Baodean Stage

The Baodean Stage is the last Miocene stage of China, named for Baode County, Shanxi Province. Licent collected abundant Late Miocene mammalian fossils in 1920 from the Qingyang area, Gansu Province. Almost at the same time, Andersson discovered the mammalian fauna from the Baode area, and Otto Zdansky started systematic excavation and collection in 1922. Pei et al. (1963) named the Baodean Stage, and they clearly assigned Zdansky's so-called "*Hipparion* Red Clay" of Baode to the Baodean Stage, but did not formally appoint the stratotype section. Li et al. (1984) correlated the Baodean Age to the Turolian Age of Europe.

The Baode Formation in the Baode area has an unconformable contact with the underlying Carboniferous limestone, and its overlying stratum is Jingle Formation. The paleomagnetic age of the Bade Formation (excluding the basal conglomerate) is determined to be 8–5.2 Ma (Yue et al., 2004); since the lower boundary of the Turolian is correlated to the base of C4r.2r (8.7 Ma) (Steininger, 1999), this boundary is not included in the Baode Formation, so this correlation scheme was abandoned.

The Baode Formation is well exposed at the Baode area and fossiliferous, containing typical Baodean taxa, like *Adcrocuta*, ictitheres, *Metailurus*, medium-sized *Hipparion*, *Chilotherium*, and *Chleuastochoerus*. The stratotype section of the Baodean Stage is situated at the south branch of the main gully south of Jijiacun Village, Yaozhuang Township, Baode County. The "*Hipparion* Red Clay" is divided into 13 layers and has a total thickness of 60 m. The lower boundary of the Baodean Stage is correlated with that of the marine Messinian Stage, within the Chron C3Br.1r (7.25 Ma) (Hilgen et al., 2000). This boundary falls within the 9th layer at the Jijiagou section, just under the fossiliferous layer, and the first appearance of *Hipparion forstenae* can be the biostratigraphic marker of the boundary. *H. forstenae*, which is widely distributed in Baode and Huoxian of Shanxi, Qin'an and Linxia of Gansu, and Gyirong and Nyalam of Tibet, is only found from the late Late Miocene (Figure 2).

The *Hipparion* fauna is the representative of the Baodean Stage, which mainly consists of medium to large sized mammals, including ictitheres, *Chilotherium*, and medium-sized *Hipparion*. Eomyidae, Aplodontidae, and Zapodidae of the micromammals continued to decline or became extinct; Dipodidae took certain progress; Circetidae and Muridae unprecedentedly flourished, with high diversity and abundance (Qiu and Li, 2016). The first-appearing taxa include *Erinaceus*, *Parasoriculus*, and *Paenelimnoecus* of Insectivora, *Alilepus* of Lagomorpha, *Dipoides*, *Myominus*, *Paralophocricetus*, *Apodemus*, *Micromys*, *Huaxiamys*, and *Orientalomys* of Rodentia, *Plesiogulo* and *Enhydriodon* of Carnivora, *Anancus*, *Sinomastodon*, *Mammut*, and *Stegodon* of Proboscidea, and *Dihoplus* of Perissodactyla. The last-appearing taxa include *Miodyromys*, *Microdyromys*, *Leptodontomys*, *Microtoscoptes*, *Abudhabia*, and *Prosiphneus* of Rodentia, *Indarctos*, *Parataxidea*, *Melodon*, *Eomellivora*, *Adcrocuta*, and *Machairodus* of Carnivora, *Sinohippus* of Perissodactyla, and *Cervavitus*, *Plesiaddax*, and *Sinotragus* of Artiodactyla (Qiu et al., 2013).

3.6 Gaozhuangian Stage

The Gaozhuangian Stage is the first Pliocene stage of China, and its name is taken from Gaozhuang Village, Yuncu Township, Yushe County, Shanxi Province. Teilhard de Chardin and Young (1933), in the first geological report of the Yushe area, revealed that the *Hipparion* fauna occurs in fluvial-lacustrine deposits besides the red clay. Qiu et al. (1987) divided the Yushe Series into 4 formations when studying the *Hipparion* fossils from the Yushe Basin, and first proposed the Gaozhuangian Stage to represent the Chinese Lower Pliocene. These four formations are, from bottom to top, the Late Miocene Mahui Formation, Early Pliocene Gaozhuang Formation, Late Pliocene Mazegou Formation, and Early Pleistocene Haiyan Formation.

The stratotype section of Gaozhuangian Stage is situated along a Taoyang-Gaozhuang-Zhaozhuang traverse in the Yushe Basin with a total thickness of 350 m. The contact of the Gaozhuang Formation with the underlying Mahui Formation and the overlying Mazegou Formation is not widely observed, but weak regional angular unconformable contacts between the Gaozhuang Formation and its underlying and overlying strata are interpreted (Tedford et al., 2013).

The Gaozhuangian Stage corresponds to both the marine Zanclean Stage of the International Chronostratigraphic Chart and the Ruscinian of the European land mammal ages (Steininger et al., 1996). The lower boundary of the Gaozhuangian Stage is correlated to Chron C3r (upper part, 5.333 Ma) (Van Couvering et al., 2000), and the exact position of this boundary is within the yellow block sandstone (near the base) of the 5th layer of the Taoyang Member at the Taoyang section (Deng et al., 2010, fig. 2). *Hipparion pater* was widely distributed in the Yushe Basin with localities of Baihai, Nihe, Damalan, Gaozhuang, Yinjiao, Sangjiagou, Ouniwa and so on, and it first appeared near the lower

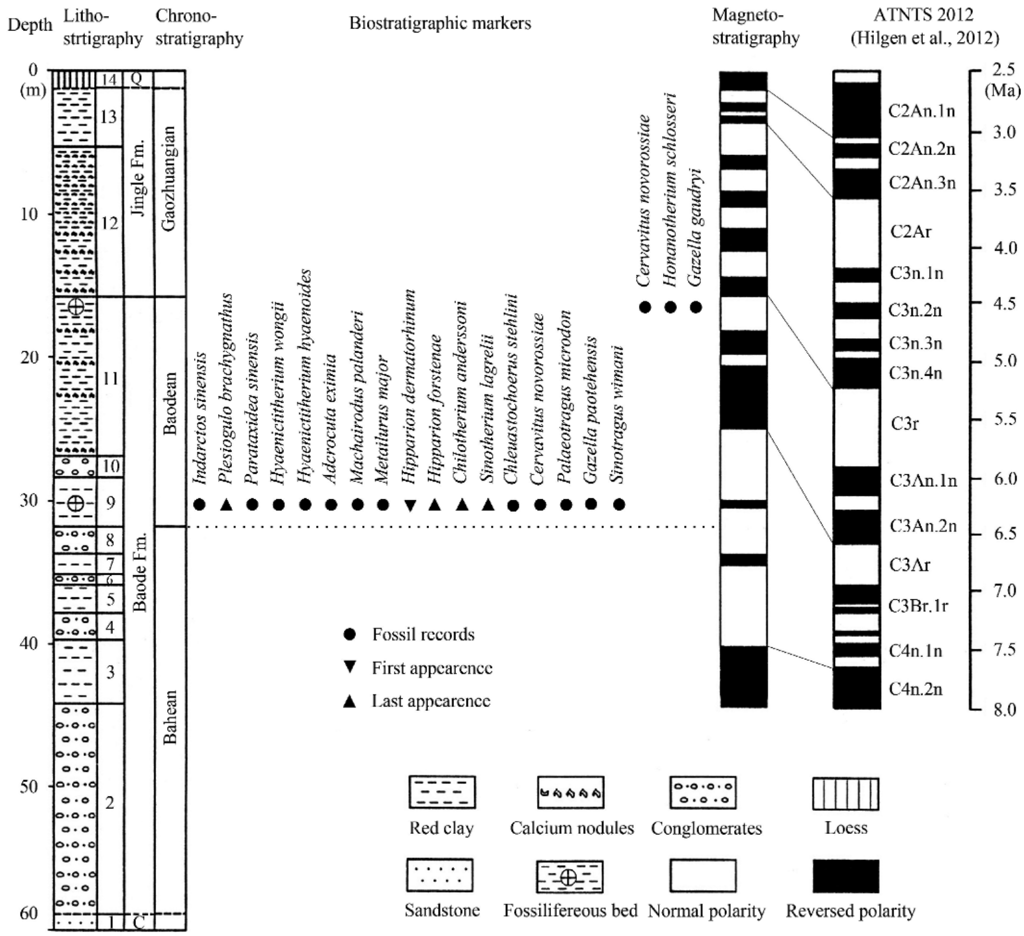


Figure 2 Comprehensive column section at Jijiagou in Baode, Shanxi.

boundary of the Gaozhuangian Stage, so it is an important biostratigraphic marker of the boundary.

The Gaozhuangian *Hipparion* fauna inherits the Baodean *Hipparion* Fauna, and reaches the primitive stage of the modern fauna. The typical macromammals of the Bodean Age, like ictitheres (*Hyaenictitherium wongii* as an exception is occasionally discovered), *Adcrocuta*, *Machairodus*, and many species of *Hipparion* disappeared, and Canidae and Camelidae migrated from North America. Except for the extinction of the Eomyidae and Aplodontidae, and the appearance of the Arvicolidae, the Gaozhuangian fauna is consistent with the Baodean fauna at the family level. Some common Baodean taxa are rare or disappeared in Gaozhuangian, and some new taxa appear (Qiu and Li, 2016). The first-appearing genera include *Desmana* and *Lunanosorex* of Insectivora, *Allocricetus*, *Allorattus*, *Chardina*, *Mesosiphneus*, *Germanomys*, and *Mimomys* (*Aratomys*) of Rodentia, *Trischizolagus* of Lagomorpha, *Nyctereutes*, *Eucyon*, *Ursus*, *Pliocrocuta*, and *Chasmaporthetes* of Carnivora, *Hipparion* (*Cremohipparion*), *Hipparion* (*Plesiohipparion*), *Proboscidipparion*, and *Coelodonta* of Perissodactyla, and *Sus*, *Paracamelus*, *Muntiacus*, *Paracervulus*, *Axis*, *Antilospira*, and *Lyrocerus* of Artiodactyla. Ictitheres and *Chilotherium* are extinct, and the last records of genera also include *Quyania*, *Parasoriculus*, and *Paenelimnoecus* of Insectivora, *Nannocricetus*, *Sinocricetus*, *Chardina*, *Lophocricetus*, *Paralophocricetus*, *Sinozapus*, and *Pararhizomys* of Rodentia, *Plesiogulo* and *Simocyon* of Carnivora, *Hipparion* (*Hipparion*) of Perissodactyla, and *Chleuastochoerus* and *Dorcadoryx* of Artiodactyla (Qiu et al., 2013).

3.7 Mazegouan Stage

The Mazegouan Stage is the second Pliocene stage of China, and the name is taken from the Mazegou gully between Zhaozhuang and Baihai villages, Yuncu Township, Yushe County, Shanxi Province. Teilhard de Chardin and Young (1930) discovered the Hefeng fauna from Hefeng in Jingle County, Shanxi Province, which records six macromammal taxa. Young (1936b) later established the Jinglean Age for the time period of the Jingle red clay and the Jingle fauna, which he considered mid-Pliocene. Li et al. (1984) argued that the exact age of the Hefeng fauna is not clear, so they only temporally chose Jinglean Age as representative of the Chinese Early Pliocene, while the Youhean Age was used to represent the Late Pliocene. Qiu and Qiu (1990) thought that the character of the Jingle fauna is not clear, so they named the Yushean Age for the whole Pliocene, and the Gaozhuang and Mazegou faunas were used as representatives of the Early and Late Pliocene respectively. The second Chinese Commission on Stratigraphy formally proposed the Gaozhuangian and Mazegouan stages for the Lower and Upper Pliocene respectively in 1999.

The stratotype section of the Mazegouan Stage is situated at the Zhaozhuang-Damalan section in the Yushe Basin, with a total thickness of 95 m. The lower Mazegou Formation is well exposed, and the upper Mazegou Formation is exposed north of Xizhou Village, about 7 km northwest of Damalan Village. The Mazegou Formation mainly consists of interbedded yellow sandstones and purplish-red mudstones in transition to mudstones, with a total thickness of about 175 m. The Mazegouan Stage is correlated with the marine Piacenzian Stage of the International Chronostratigraphic Chart, and its lower boundary is correlated to the base of Chron C2An (3.6 Ma), which is also the lower boundary of the Gauss epoch (Castradori et al., 1998). The lower boundary of the Mazegouan Stage is within the purplish-red mudstone (in the middle) of the 6th layer of the lower Mazegou Formation (Deng and Hou, 2011: fig. 3), and the Mazegou fauna is found above this boundary.

Among the micromammals of the Yushe Basin in having precise position, *Apodemus zhangwagouensis* is the one that just falls on the boundary; its predecessor *A. qiui* from the Early Pliocene is a primitive species of this lineage (Flynn et al., 1997); therefore, the first appearance of *A. zhangwagouensis* could be chosen as the lower boundary biostratigraphic marker of the Mazegouan Stage.

The Mazegou fauna contains many Gaozhuangian survivors, for example, *Agriotherium*, *Anancus*, *Hipparion* (*Plesiohipparion*), and there are also direct ancestors of many modern taxa. The first-appearing genera include *Beremendia* of Insectivora, *Ochotonoides* of Lagomorpha, *Cricetulus* of Rodentia, *Vulpes*, *Canis*, *Meles*, *Homotherium*, *Lynx*, and *Sivapanthera* of Carnivora, *Mammuthus* of Proboscidea, *Postschizotherium* of Hyracoidea, and *Sus*, *Pseudois*, *Magalovis*, and *Ovis* of Artiodactyla. The last-appearing genera include *Yanshuella* of Insectivora, *Hypolagus* and *Trischizolagus* of Lagomorpha, *Atlantoxerus*, *Pliopetaurista*, *Dipoides*, *Paralactaga*, *Kowalskia*, *Germanomys*, *Pseudomeriones*, *Huaxiamys*, *Chardina*, and *Mesosiphneus* of Rodentia, *Eucyon*, *Enhydriodon*, and *Pliocrocuta* of Carnivora, and *Lyrocerus* of Artiodactyla (Qiu et al., 2013).

4. Magnetostratigraphy and chemostratigraphy

Because radiometric dating materials are rare in the Chinese Neogene strata, high-resolution ages are used only in the Shanwang section in Linqu, Shandong to establish the stage strato-type. As a result, the most widely used chronologic scale calibration is by magnetostratigraphy in the Chinese Neogene. Detailed paleomagnetic datings have been done in many representative terrestrial Neogene sections, such as candidate strato-type sections for establishments of all stages, including the Xiejia section in Huangzhong, Qinghai (Wu et al., 2006; Dai et al., 2006; Xiao et al., 2012), the Suosuoquan section in northern Junggar Basin, Xinjiang (Zhang et al., 2007), the Tunggur section in Sonid Left Banner, central Inner Mongolia (Wang et al., 2003), the Bahe section in Lantian, Shaanxi (Kaakinen, 2005), the Guonigou section in Dongxiang, Gansu (Fang et al., 2016), the Jijiagou and Yangjiagou sections in Baode, Shanxi (Yue et al., 2004; Zhu et al., 2008), the Gaozhuang-Mazegou section in Yushe, Shanxi (Flynn et al., 1995). The paleomagnetic method can subdivide and date strata with high-resolution, but it needs at least one reliable chronologic constraint. Correspondingly, mammals which evolved rapidly, are useful in constraining the age of fossiliferous strata. Therefore, mammalian fossils and paleomagnetic datings have complementary advantages. In the past practices, however, mammalian fossils have been misused as constraints in magnetostratigraphy leading to errors in paleomagnetic datings. In conclusion, it is very important that the magnetostratigraphic method combines with fine biostratigraphic analyses (Figure 3).

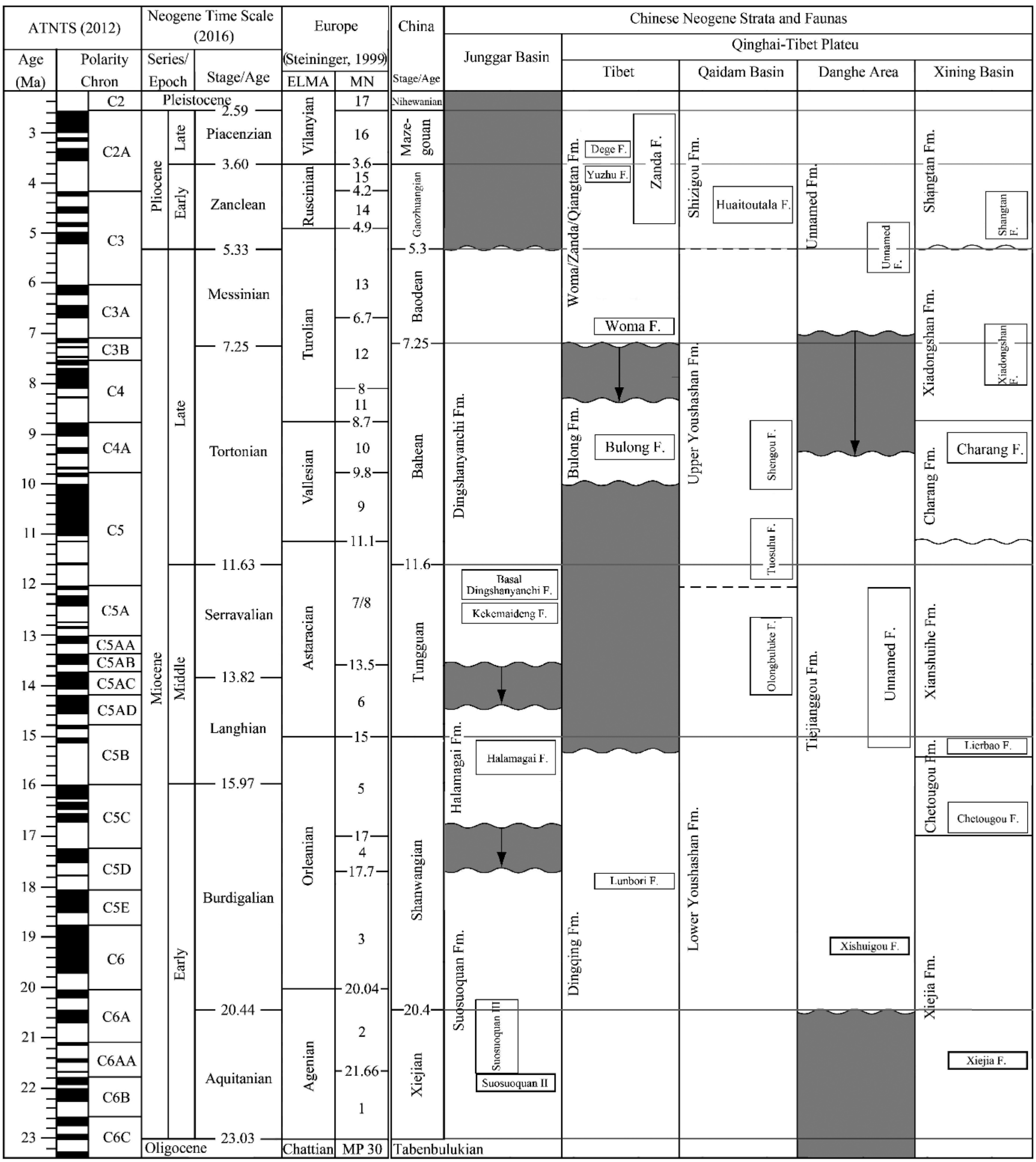
A 32 Ma sedimentary record was obtained from drilling cores in the South China Sea, covering the whole late Cenozoic, and it recoded a series of the Neogene climatic events based on stable oxygen and carbon isotope analyses and in coordination with paleomagnetic datings (Wang et al., 2003). On the other hand, deep sea drilling sections are not suitable to establish the strato-type of a chronostratigraphic unit. In the Chinese mainland, the Neogene deposits are mainly terrestrial strata. Although many sections have stable oxygen and carbon isotope analyses of paleosol carbonates and mammalian tooth enamel (Wang and Deng, 2005), their consistency is not good, and paleosol carbonates are influenced easily by diagenesis. Therefore, interpretations for the Neogene climatic and environmental changes based on isotope analyses require further improvement in resolution and accuracy.

5. Correlation framework of Chinese Neogene deposits

The Chinese Neogene deposits are mainly terrestrial, and marine deposits are only sparsely distributed. The Neogene deposit along the Central Mountain Range of Taiwan is the only Neogene marine deposit that has well-exposed and continuous strata, but are all metamorphic. Almost all the Neogene deposits on the Chinese Mainland are terrestrial deposits (Figure 3), except for the southern edge of the Tarim Basin where marine microfossils have been found (Ritts et al., 2008).

5.1 Neogene of northern China

The Chinese Neogene deposits are widely distributed in northern China, and many basins have thick, well-developed, and fossiliferous strata. The Junggar Basin and the Turpan-Hami Basin in northern Xinjiang are fluvial-lacustrine deposits consisting of coarse clastic rocks and clay accumulations. The southern Xinjiang area is dominated by terrestrial deposits, and regional sea-continent transition deposits can be found. The Qilian-Helan area mainly consists of lacus-



trine deposits and clays. The Inner Mongolia-Greater Khingan area have well-developed fluvial-lacustrine deposits, especially distributed in the Eren Basin and Xilinhot area, but the strata usually have limited thickness, and there is basalt distributed regionally. Neogene deposits are only scattered in Northeast China, and mostly fluvial, and there are also basalts of different ages and regional clays. The Neogene in North China mainly consist of fluvial or lacustrine deposits with clay accumulation, and the *Hipparion* Red Clay has particularly wide distribution in this area; there is also scattered basalt in North China (Zheng et al., 1999). There are many of complete and continuous Neogene sec-

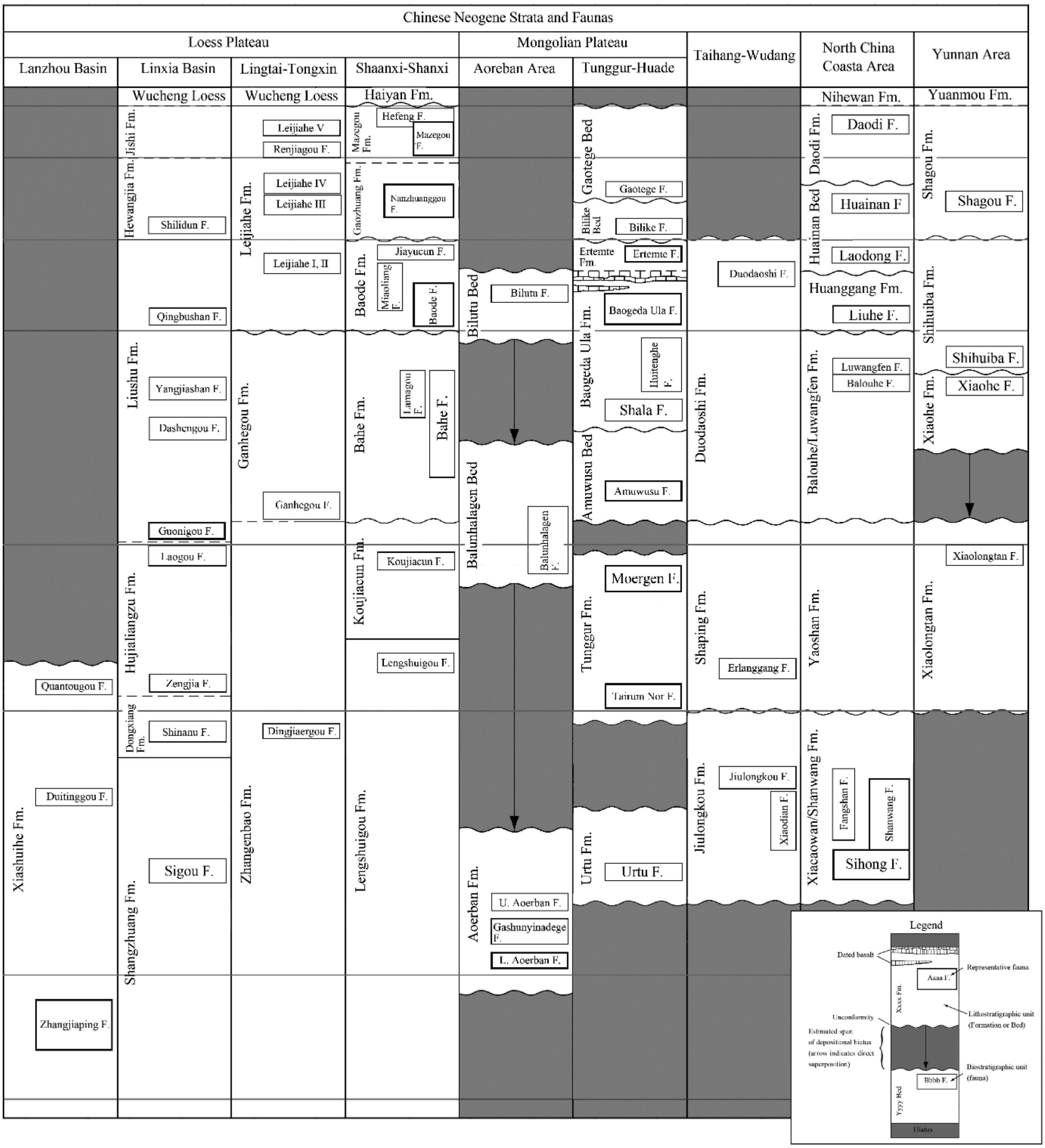


Figure 3 Correlation and division of the Chinese Neogene strata and mammalian faunas.

tions in northern China, of which the Linxia Basin is an excellent example. The Neogene deposits of the Linxia Basin are distinguished, from bottom to top, the Miocene Shangzhuang, Dongxiang, Hujialiang, and Liushu formations, and the Pliocene Hewangjia and Jishi formations.

The Xiejian Stage is distributed in the Junggar Basin of Xinjiang, the Lanzhou and Linxia basins of Gansu. The Shanwangian Stage is exposed at the Linqu-Changle area of Shandong, the Danghe, Linxia, and Lanzhou basins of Gansu, central Inner Mongolia, and the Sihong area of Jiangsu. The Tunggurian Stage can be found in the Junggar Basin of Xinjiang, the Lanzhou and Linxia basins of Gansu, the Tongxin area of Ningxia, the Lantian area of Shaanxi, and the central Inner Mongolia. The Bahean Stage is developed in the Linxia Basin, central Ningxia, the Lantian and Fugu areas of Shaanxi, central Inner Mongolia, the Xinxiang area of Henan, the Zhangqiu area of Shandong. The Baodean Stage is distributed at the Linxia Basin and the Lingtai area of Gansu, the Baode area and the Yushe Basin of Shanxi, the Lantian and Fugu areas of Shaanxi, and central Inner Mongolia. The Gaozhuangian Stage is exposed in the Linxia Basin, the Lingtai and Qinan areas of Gansu, the Yushe Basin of Shanxi, and central Inner Mongolia. The Mazegouan Stage is distributed in the Lingtai area of Gansu, the Yushe Basin and the Jingle area of Shanxi, the Weinan area of Shaanxi, the Nihewan Basin of Hebei, and the Zhoukoudian area of Beijing.

5.2 Neogene of southern China

The Neogene of southwestern China is widely distributed and represented in eastern Yunnan by mainly limnetic deposits. The Yangtze area is characterized by scattered fluvial or lacustrine deposits, and basalt is common in this area. The Nanling region has only very rare Neogene strata, which are usually fluvial deposits; the Lingnan region is dominated by fluvial deposits, and basalt is often exposed; there are also neritic or littoral deposits distributed at the Leiqiong area. The Neogene of southeastern China is mainly fluvial-lacustrine deposits and volcanic rocks, and there are marine or marine-continental transitional deposits along the coast. The Neogene of Taiwan is also neritic or marine-continental transitional deposits. There are some relatively complete and continuous Neogene sections in the Lingnan region, for example, the Miocene-Pliocene section in the Maoming Basin recognized as (from bottom to top) Huangniuling, Shangcun, Laohuling, and Gaopengling formations, but mammalian fossils are lacking, so the age of this section is questionable (Zheng et al., 1999).

The Xiejian Stage in southern China is found from western Yunnan and the Wengshao Basin of Guizhou; the Shanwangian Stage is distributed at western Yunnan and northern Jiangsu; the Tunggurian Stage is exposed at the Fangxian Basin of Hubei, and the Kaiyuan Basin of Yunnan; the Bahean Stage is developed at the Yuanmou and Lufeng basins of Yunnan; the Baodean Stage is distributed in the Jingzhou area of Hubei, the Nanjing area of Jiangsu, and the Zhaotong Basin of Yunnan; the Gaozhuangian Stage is found in the Huainan area of Anhui and the Yuanmou Basin of Yunnan; and the Mazegouan Stage is exposed in the Yuanmou Basin.

5.3 Neogene of the Tibetan Plateau

The Neogene of the Tibetan Plateau mainly consists of lacustrine or limnetic deposits and clay accumulations. The Woma Formation in the Gyirong Basin and the Zanda Formation in the Zanda Basin in southern Tibet are sandstones or mudstones; the central Tibet is coal-bearing clastic rocks or volcanic rocks interbedded with clastic rocks; the northern Tibet and the Qiangtang area are mainly volcanic rocks except the clastic rocks in Biru and Baingoin; the Qaidam Basin has continuous Neogene deposits mainly consisting of fluvial-lacustrine clasolites interbedded with regional marlstones; the Neogene deposits in the Xining Basin is also continuous fluvial or lacustrine deposits, and there are gypsum interlayers within the lower clasolites. The Qaidam Basin has relatively complete and continuous Neogene deposits of the Tibetan Plateau, with the Miocene Youshashan Formation and Pliocene Shizigou Formation as representative, but the mammalian fossils in the Qaidam Basin are rare and not continuous.

The Xiejian Stage in the Tibetan Plateau is distributed in the Xining Basin of Qinghai. The Shanwangian Stage is in the Xining Basin of Qinghai, and the Lunpola Basin of Tibet. The Tunggurian Stage is in the Qaidam and Xining basins of Qinghai. The Bahean Stage is in the Bulong Basin of Tibet, and the Qaidam and Xining basins of Qinghai. The Baodean Stage is at the Gyirong and Dati basins of Tibet, and the Xining Basin of Qinghai. The Gaozhuangian Stage is in the Kunlun Pass, Xining and Qaidam basins of Qinghai, and the Zanda Basin of Tibet; the Mazegouan Stage is in the Dege area of Sichuan, and the Zanda Basin of Tibet.

6. Conclusions and problems

The division of the Chinese Neogene strata, based on abundant mammalian fossils and multiple dating methods like biostratigraphy, magnetostratigraphy, and isotopic chronology, has resulted in the establishment of a complete chronostratigraphic scheme, which is widely accepted internationally as the core plan of the Asian area (Wang et al., 2013; Woodburne et al., 2013). Actually, ever since 2012, the chronostratigraphic scheme based on the Chinese Neogene land mammalian fossils has already been treated as the Asian standard that ranks with both the North American and the

European division plans (Gradstein et al., 2012).

The division of the Chinese Neogene strata is mainly based on land mammalian fossils. Compared with marine stratigraphy, many problems persist. The distribution of mammals is regional, and the mammalian fossils are usually rare and incomplete. Therefore, the principles, methods and procedures for the division of the terrestrial deposits are different from those of the marine deposits based on invertebrate fossils. The significance of the terrestrial deposits and mammalian fossils in the stratigraphic division is not embodied in the ISG, and there still lacks an international standard for terrestrial divisions, so that there results an independent division system for each continent.

Therefore, taking the ISG as the principle, we will continue to study and improve the Chinese Neogene chronostratigraphic scheme based on the mammalian fossils. As long as we follow the basic rule of the ISG and use correct methods and procedures, with mammalian fossils regarded as useful biostratigraphic markers, magnetostratigraphy as a primary dating method, and marine-terrestrial strata that are precisely correlated, this task will be accomplished in the near future.

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