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# Land mammal geochronology and magnetostratigraphy of mid-Tertiary deposits in the Lanzhou Basin, Gansu Province, China*

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*Key words:* Paleontology, mammals, magnetostratigraphy, tectonic uplift, Tibetan Plateau

ABSTRACT

The Lanzhou Basin is situated at the northeast slopes of the Tibetan Plateau, and its basin-fill is expected to reflect the process of uplifting of the plateau like the Siwaliks south to the Himalayas. The more than 1000 m thick Cenozoic part of the continental deposits of the basin is composed by the Xiliugou, Yehucheng and Xianshuihe Formations. They form a syncline, the axis of which stretches in SSE-NNW direction in the eastern part of the basin. The Xianshuihe Formation, which contains a rich mammalian fauna, is well dated paleontologically. More than 600 paleomagnetic samples were collected for magnetostratigraphic analysis in the Dahonggou and Xiajie sections in the western part of the basin at a mean sampling interval of 2.2 m. The polarity column which was derived from the stable part of the natural remanent magnetization of the rocks, is well defined in most parts. It contains some apparent polarity characteristics which can be linked closely to the geomagnetic polarity time scale taking paleontological key points into account. The polarity zones of the Xianshuihe Formation seem to correspond in great detail to chrons C12r – C5A with the bottom boundary of the formation placed at 31 Ma and its top around 15 Ma. The 10 normal-reversed polarity zones of the underlying Yehucheng Formation are interpreted to approach chron C22 at about 51 Ma towards the older end. This interpretation is hampered, however, by a very fragmentary fossil record and evident hiatuses. Using the paleontologic-magnetostratigraphic time frame, several obvious changes in the sedimentation environment can be recognized in the Lanzhou Basin. Their timing and character are related to the uplift of the Tibetan plateau which took place mainly after deposition of the Lanzhou red beds in the late Pliocene.

ZUSAMMENFASSUNG

Das Becken von Lanzhou liegt im Nordosten des Tibetischen Hochplateaus. Wie die Siwaliks im Süden, sollte die Beckenfüllung den Hebungsprozess des Himalayas im Norden widerspiegeln. Der känozoische Anteil der mehr als 1000 m mächtigen, kontinentalen Beckensedimente wird durch die Xiliugou-, Yehucheng- and Xianshuihe-Formationen repräsentiert. Sie bilden eine Synklinalstruktur, deren Achse im östlichen Teil des Beckens in SSE-NNW Richtung streicht. Die Xianshuihe Formation enthält eine reiche Säugetierfauna und ist paläontologisch gut datiert. Mehr als 600 orientierte Gesteinsproben mit einem mittleren Probenabstand von 2.2 m wurden in den Profilen von Dahonggou und Xiajie für eine magnetostratigraphische Analyse entnommen. Die aus dem stabilen Anteil der natürlichen remanenten Magnetisierung abgeleitete Polaritätszonierung ist gut definiert und kann mit der geomagnetischen Polaritätszeitskala korreliert werden, wenn paläontologische Schlüsselzeitmarken in Betracht gezogen werden. Danach entsprechen die Polaritätszonen der Xianshuihe-Formation den Chronen C12r – C5A, so dass für die Untergrenze der Formation ein Alter von 31 Ma und für die Obergrenze ein solches von 15 Ma anzusetzen ist. Das untere Ende der 10 Polaritätszonen der darunterliegenden Yehucheng-Formation erreicht die Chrone C22 mit einem Alter von ungefähr 51 Ma. Die letztere Interpretation ist wegen des bruchstückhaften Fossilinhalts und wegen einiger Sedimentationsunterbrüche unvollständig abgesichert. Der entwickelte Zeitrahmen impliziert mehrere Wechsel in der Sedimentationsrate im Lanzhou-Becken. Ihr Zeitpunkt und Charakter hängen mit der Hebung des Tibetischen Hochplateaus zusammen, die nach der Ablagerung der Rotsedimente des Lanzhou-Beckens im späten Pliozän stattfand.

## Introduction

The "red beds" of continental origin in the vicinity of Lanzhou, capital city of Gansu Province, were first scientifically recognized at the end of the last century (V. A. Obruchev, 1892–1894; see Obruchev 1956). The first mammal fossils treated as scientific object, but not as "dragon bones", were recorded from this area by J. G. Andersson (1923). They were later identified as of middle Miocene age (Pearson 1928, Hopwood 1935). Since the middle of the 1940s (Meng et al. 1947) it has

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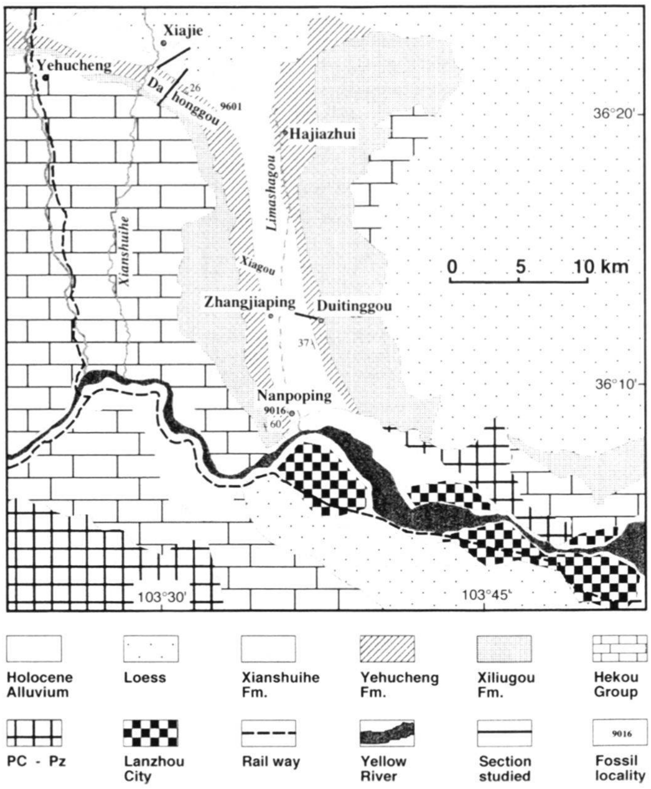


Fig. 1. Simplified geologic map showing distribution and structure of the Tertiary deposits of the Lanzhou Basin. Numbers denote mammal fossil bearing localities.

gradually been known that the majority of the thick series of the "red beds" belonged to the Mesozoic Era, and only a small amount of deposits was of the Cenozoic Era. Being more variable in lithology and easily mappable, the Cenozoic deposits received more attention of the local geologists than the Mesozoic strata. However, until the late 1980s (Qiu et al. 1988) no mammalian fossils older than middle Miocene had been reported, and the time control of these deposits had long been very loose. The work carried out during the last ten years or so has made great progress in our understanding of the Cenozoic stratigraphy of the Lanzhou Basin, especially in regard to the time control of the mid-Tertiary portion of the deposits.

The last three decades have witnessed the ever growing interest in the research of the Tibetan Plateau by geologists and climatologists. The interest was triggered by the wide acceptance of the theory of plate tectonics in the 1970s, and was tremendously increased by the notion that the uplift of the largest plateau in the world may have played a critical role in the formation of the global climate patterns. The study of the Cenozoic deposits south of the Himalayas (Bugti, Murree, Siwaliks) has a long history, and has been enormously intensified since the 1970s. In spite of all these efforts, opinions as to the process, especially the timing, of the uplift of the Tibetan Plateau differ widely. The Lanzhou Basin is situated at the northeast slopes of the Tibetan Plateau, and its basin-fill should somehow reflect the process of the uplift of the plateau like the deposits south of the Himalayas. However, it has not been specifically tied to the uplift of the Tibetan Plateau, partly because of the poor time control of its basin-fill. A comparison of dated basin-fill with those on the south slopes of the Himalayas and the molasse sediments north of the Alps would then be highly interesting for a better understanding of the nature of the uplift of the Tibetan Plateau in a global context.

The present paper presents the major results of some ten years' work in the Lanzhou area carried out not only by the authors of the present paper, but also by a number of colleagues from various institutions who took part in the field and laboratory works at various times. They are: Xie Junyi and Chen Shanqin (Institute of Cultural Relics and Archaeology, Lanzhou, Gansu, China), Yan Defa, Ye Jie, Li Yizheng, Chen Xiaofeng, Dong Junshe (Institute of Vertebrate Paleontology and Paleoanthropology, Beijing, China), Wu Ruijin, Zhang Liren (Institute of Geography and Limnology, Nanjing, Jiangsu, China), Zhang Li (Northwest University, Xi'an, Shaanxi, China), E. H. Lindsay (University of Arizona, Tucson, AZ, USA), L. J. Flynn (Harvard University, Cambridge, MA, USA), W. Downs (Northern Arizona University, Flagstaff, AZ, USA), C. Mödden (Gutenberg Universität, Mainz, Germany), and D. Oppliger (Naturhistorisches Museum, Basel, Switzerland).

## Geological Setting

The studied area, the Lanzhou Basin, lies north and northwest of Lanzhou, covering an area of about 300 km$^2$. Topographically speaking, it is located at the east end of the Qilian Mountains, which constitute the northeastern border of the Tibetan Plateau. Tectonically, the Lanzhou Basin is the easternmost part of the long sedimentary belt stretching all along the northern foredeep of the Qilian Mountains. It is a basin with superimposed structures. After the closing of the "Qilian sea" by the late Paleozoic, the vast area previously occupied by the "sea" emerged into landmasses. The Qilian structural belt became reactivated in the beginning of the Cretaceous. With its uplift into mountains, thick early Cretaceous terrigenous sediments accumulated on its peripheries. The Cretaceous sediments are all faulted and strongly folded. After an apparent hiatus the second phase of sedimentation began: the Tertiary continental deposits composed of the Xiliugou, Yehucheng and Xianshuihe Formations, which are considerably less strongly faulted and folded. They form a simple syncline in the eastern part of the basin with its axis stretching in SSE-NNW direction. The syncline is roughly fan-shaped, with its south end narrowed and its north part much widened (Fig. 1). Along the axis of the syncline runs a small river called Limashagou, which drains south into the Yellow River. The Limasha valley becomes deeper downstream, with its high banks well exposed near the Yellow River. Concomitantly, the wings of the syncline dip more and more steeply towards the south, reaching

70° in some places. In the northernmost part of the studied area, the beds become almost flat-lying. In the northwestern part where the boundary of the Cenozoic basin-fill stretches westward, the structure turns into a monocline, dipping largely northward. The Pleistocene loess cover is vastly developed, especially in the north and east parts of the area (Figs. 1-2).

Three sections were studied: Dahonggou, Xiajie and Duitinggou. The Dahonggou section is the longest and the most complete one, with only the top part of the Tertiary deposits denuded. The Xiajie section comprises only the top of the Tertiary deposits. The two sections add up to a complete stratigraphic sequence of the west part of the Lanzhou Basin. The Duitinggou section runs across the axis of the syncline developed in the east part of the basin. It comprises only the upper part of the Yehucheng Formation to the middle Member of the Xianshuihe Formation.

The total basin-fill is composed of deposits of lower Cretaceous, Paleocene?-Eocene, Oligocene, and early-middle Miocene age as follows:

1) Hekou Group (lower Cretaceous): Variegated, predominantly violet, purple and bluish green sandstone intercalated with siltstone and mudstone, unconformably overlying either Precambrian to Paleozoic (PC-Pz) sedimentary or early Paleozoic igneous rocks. The deposits are 2000-2500 m in total thickness, all being strongly folded and faulted. They crop out particularly well in a vast area west of Lanzhou.

2) Xiliugou Formation (Paleocene?-Eocene): Massive, moderate reddish orange (Munsell colour: 10R 6/6) middle to coarse grained sandstone. It unconformably overlies the Hekou Group, with basal anguclasts well developed. The lower part is often intercalated with thin layers of moderate reddish brown (10R 4/6) clay. Its total thickness, measured in the Dahonggou section, is 201.63 m. The best exposed area with typical lithology of this massive sandstone is near the village Xiliugou, which is located west of Nanpoping. According to Zhai & Cai (1984), its thickness varies from 59 to 593 m.

3) Yehucheng Formation (Eocene-Oligocene): Thin- and medium-layered, gypsiferous, brown sandstone and mudstone. The sandstone is moderate reddish brown (10R 4/6) and the mudstone is dark reddish brown (10Y 3/4) to moderate brown (5YR 4/4-3/4). The gypsum can either be layered or lens-formed, always embedded in grayish yellow green (5GY 7/2) clay. The total thickness measured in the Dahonggou section is 465.22 m. According to Zhai & Cai (1984), its thickness varies from 198 to 831 m.

4) Xianshuihe Formation (Oligocene-middle Miocene): Having separated the underlying Xiliugou and Yehucheng Formations from the once vaguely defined Xianshuihe Formation by Zhai & Cai (1984), the concept of the Xianshuihe Formation became more homogeneous lithologically. It is composed of three major sedimentation cycles, which are separated as three members:

a) Lower Member (Oligocene-?early Miocene): Massive pale reddish brown (10R 5/4) to light-moderate brown (5YR 6/4-4/4) claystone with intercalated siltstone of paler color. The member always starts with a basal layer of dusky yellow (5Y 5/4) conglomeratic sandstone, disconformably overlying the Yehucheng Formation. The sand is poorly sorted, often cross-bedded, containing large amounts of anguclasts. It is informally called „Yellow Sandstone". It can easily be recognized not only for its peculiar color, but also for its richness in fossil plant stems, which are apparently iron-manganesed and black in color. It is the best marker bed of the base of the Xianshuihe Formation. The upper boundary of the Lower Member in the Dahonggou section is rather arbitrarily defined, based on the occurrence of the first thick layer of the „White Sand" (see below) at a level of 1137.21 m measured from the base of the section. This makes the thickness of the Lower Member in the Dahonggou section to be 470.36 m. The thickness of the Lower Member measured in the Duitinggou section is only 99 m.

b) Middle Member (early Miocene): Massive, pale reddish brown (10R 5/4) to light-moderate brown (5YR 6/4-4/4) claystone intercalated by multiple layers or lenses of white sandstone. The member always starts with a thick layer of white to very pale orange (10YR 8/2) conglomeratic sandstone, the „White Sand". The claystone is almost the same as that of the Lower Member, but more sandy. The sand grains of the basal white sandstone are composed mainly of well sorted and rounded quartz, often forming cross-beds of large scale. The sandstone is usually very thick, disconformably overlying the Lower Member of the Xianshuihe Formation. The typical lithology of this member is well exposed in the vicinity of the Duitinggou syncline, where it is ~225 m thick. In the Dahonggou area the separation of the Middle Member from the Lower one is difficult, since no such characteristic white sandstone as in the Duitinggou section is developed there. If the first layer of white sandstone occurred at the level of 1137.21 m measured from the base of the Dahonggou section can be correlated with the basal white sandstone in the Duitinggou section, the thickness of the Middle Member in the Dahonggou section is only 188.17 m.

c) Upper Member (early-middle Miocene): Very pale orange (10YR 8/3) and yellow (5Y 8/6) sandstone and conglomerates, intercalated with pale reddish brown (10YR 5/4) siltstone and mudstone. The percentage of the sandy matrix is much higher compared with the underlying deposits. This member is so far only developed in the Xiajie section. Its top part is covered by Quaternary loess, so that its total thickness is unknown. The measured thickness in the Xiajie section is ~300 m.

## Paleontological dating

The first fossils found from the Cenozoic deposits of the Lanzhou Basin were some pig and proboscidean remains collected by J.G. Andersson from a gully called Quantougou near the village Xianshuihe (now Xiajie) about 40 km northwest of Lanzhou. The pig was identified as *Listriodon* (now

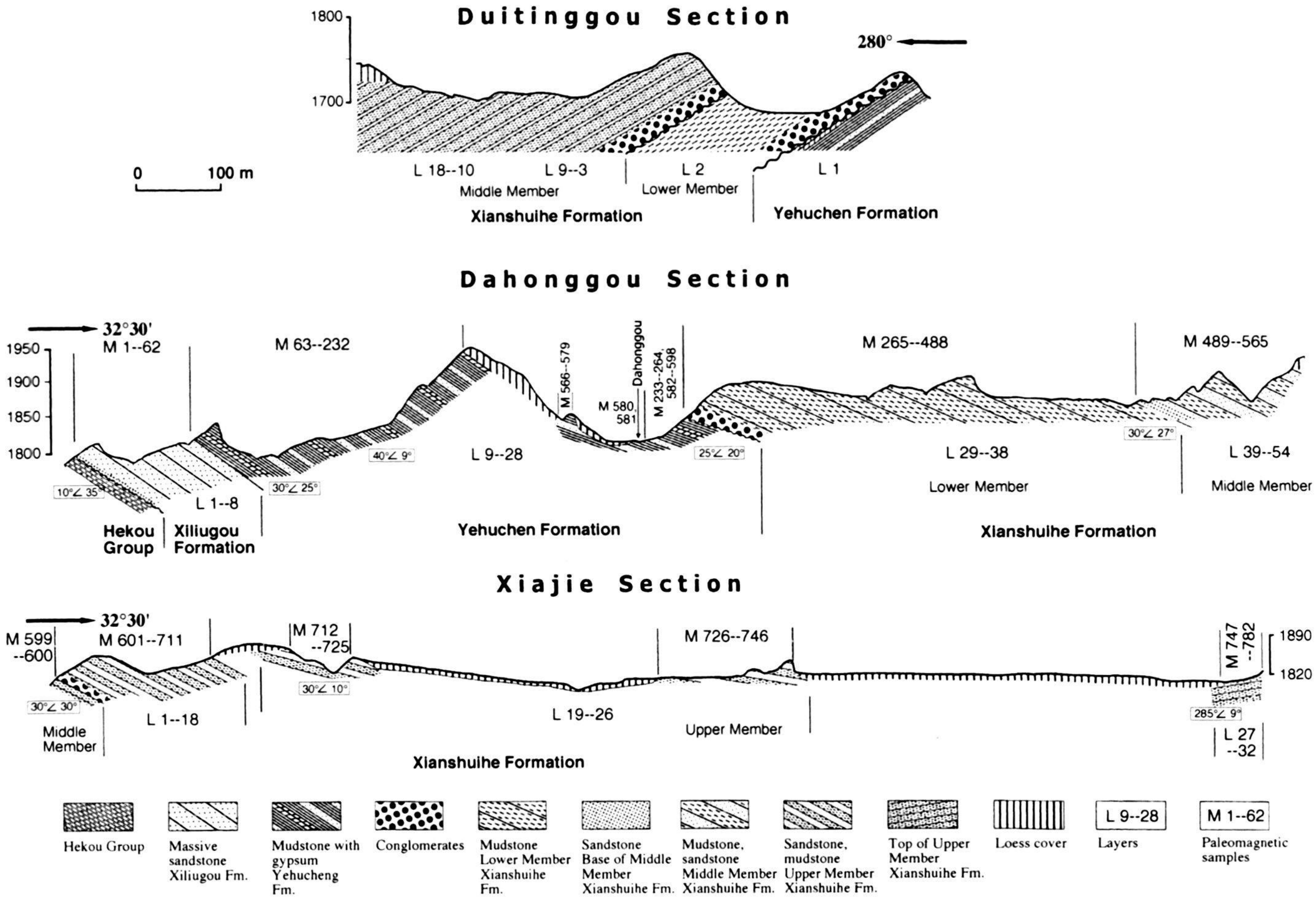


Fig. 2. Schematic profiles of the study sections in the Tertiary deposits of the Lanzhou Basin.

*Kubanochoerus*) *gigas* by Pearson (1928) and the proboscidean *Trilophodon* (now *Gomphotherium*) *wimani* by Hopwood (1935). This locality turned out to be at the very top of the whole sequence of the Tertiary deposits, i.e. in the Upper Member of the Xianshuihe Formation. In the 1950s and 1960s, findings of mammalian fossils in the Lanzhou Basin were sporadically reported by the local geologists. Nevertheless, no systematic search for fossils had ever been made until the late 1980s.

We failed to find any fossils from the Xiliugou Formation, which is practically barren. During the reconnaissance trips in the initial stage of our survey, some mammalian fossils were found from the Yehucheng Formation. In a valley about 1.5 km southeast of Duitinggou some limb bones of large amynodonts were collected from the Yehucheng Formation. In a valley called Fengshan'ao, situated northwest of Yehucheng, some edentulous mandibles and foot bones of a small-sized amynodont (probably *Cadurcodon*) were found from gypsiferous grayish yellow green clay, which is diagnostic of the Yehucheng Formation. These findings clearly show that at least part of the Yehucheng Formation is late Eocene in age.

The majority of the mammalian fossils were found from the Xianshuihe Formation. Altogether about 90 localities yielding large and/or small mammals were catalogued, half of which are important either for their richness in fossils or for their particular stratigraphic position. The most fossiliferous area is the Zhangjiaping-Duitinggou-Qujiajian area (Fig. 3).

Based on their stratigraphic position, the fossil mammals of the Xianshuihe Formation are grouped into five local faunas (hereafter referred to as l. f.):

**1) Nanpoping l. f.** from the basal dusky yellow conglomeratic sandstone of the Lower Member. The name is taken from a village situated on the north bank of the Yellow River (Fig. 1). The locality GL 9016 (the prefix "GL" denotes sites of the Gansu Provincial Museum) is located 300 m west of the village where outcrops of the yellow sandstone are well developed with a rich mammal fossils content.

The fossils (* indicates published species) so far found and identified are:

**Plants:** *Populus davidiana*, *P. simonii*, *P.* spp., *Salix* sp., *Rhus turcomanica* Korov. ex Vassilevsk, *Ulmus carpinoides*, *Zelkova* sp., *Sabaria* sp.

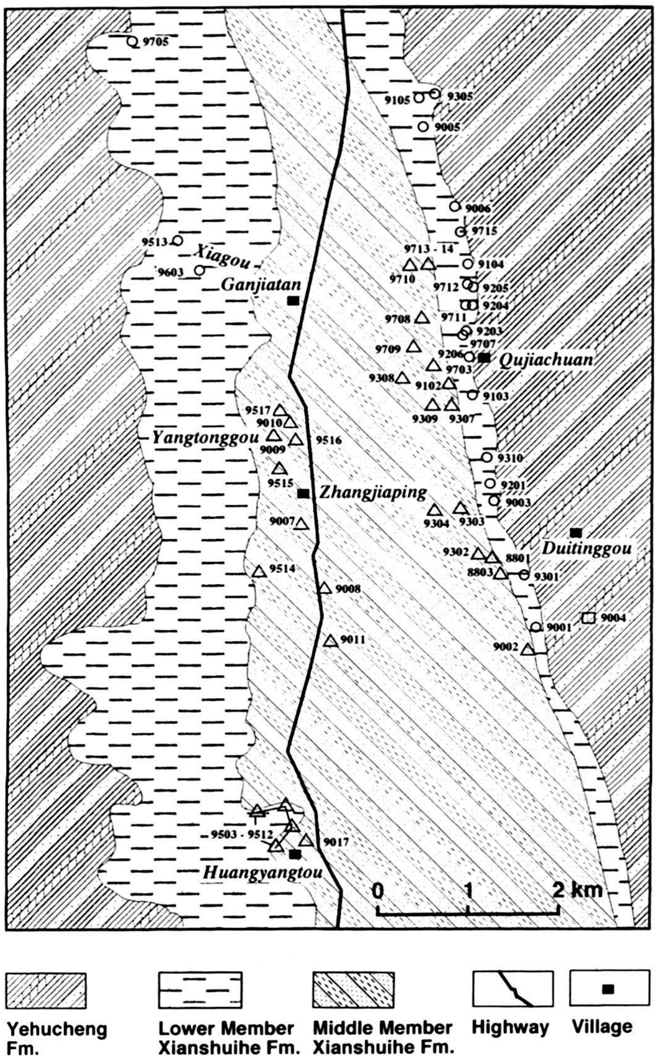


Fig. 3. Distribution of the major fossil localities of the Zhangjiaping-Duitinggou-Qujiachuan area.

**Invertebrates:** **Unio wendli*, **Cuneopsis oblonga*

**Reptiles:** *Tinosaurus* sp. (9602, 9604), *Plaeosaurus* sp. (9604)

**Mammals:** *Desmatolagus pusillus* (Teilhard 1926) (9001, 9005, 9006, 9016, 9303, 9305, 9310), *Ordolagus teilhardi* (Burke 1941) (9001, 9005, 9016),

*Anomoemys lohiculus* (Matthew & Granger 1923) (9001, 9005, 9006), *Tsaganomys altaicus* (Matthew and Granger 1923) (9005, 9006, 9016, 9711, 9715), *Eucricetodon asiaticus* (Matthew and Granger 1923) (9001, 9006), *Parasminthus tangingoli* (Bohlin 1946) (9001, 9005, 9006, 9305), *Parasminthus parvulus* (Bohlin 1946) (9001, 9005, 9006), *Tataromys plicidens* (Matthew & Granger 1923) (9001, 9016, 9301), *Tataromys sigmodon* (Matthew & Granger 1923) (9001, 9005, 9016), *Tataromys minor* (Huang 1985) (9001, 9005, 9006, 9305), *Bounomys bohlini* (Huang 1985) (9001, 9005), *Bounomys ulantatalensis* (Huang 1985) (9001, 9016), *Yindirtemys grangeri* (Bohlin 1946) (9001), *Karakoromys* sp. (9001, 9006),

**Schizotherium ordosium* (Hu 1957) (9016), **Allacerops* cf. *A. turgaica* (Borissiak 1915) (9605), *Paraentelodon* sp. (9310).

The fauna is characterized by the abundant occurrence of *Tataromys* and *Bounomys*. According to Wang (1997), *Bounomys* and *Karakoromys* are restricted to the Wulanbulage Formation (late early Oligocene) in China. On the other hand, *Yindirtemys* appeared only in the late Oligocene, found in Shargaltein, Taben-Buluk, etc. The chalicothere specimens, assigned to *Schizotherium ordosium* (Qiu et al. 1998), are certainly more advanced than *S. turgaicum* from the early Oligocene Chelkarnura and Saryin Suites (Myneskesyek, Kyzyl-Kak, and Chelkar-Teniz) of the Turgai region (Kordikova 1994). *Rhus turcomanica* has so far been found only in Eocene and early Oligocene deposits (Sichuan and Turkmenistan), according to Tao Junrong (pers. comm.). The reptile *Tinosaurus* is known to occur in Paleocene and Eocene, whereas *Plaeosaurus* appears in the Eocene—early Oligocene (Li Jinling pers. comm.). The cooccurrence of these genera seems to indicate that the Nanpoping l. f. is of late early Oligocene age.

**2) Xiagou l. f.** from the massive reddish brown mudstone above the dusky yellow conglomeratic sandstone of the Lower Member. The name is taken from a valley situated northwest of the village Ganjiatan (Fig. 3), where the first most representative locality, GL 9513, was found. In 1996 and 1997 some other localities in the same reddish brown mudstone were also found near the village Qujiajian (GL 9601, 9603, 9707, 9712). It should be noted in particular that the latter three localities (9603, 9707 and 9712) are located at lower levels than the others.

The fossil mammal list (after Wang & Qiu 2000) is:

**Amphechinus* cf. *A. rectus* (Matthew & Granger 1924) (9513), **Amphechinus* cf. *A. minimus* (Bohlin 1942) (9513, 9601, 9712), **Amphechinus* sp. (9513, 9601), *Soricidae indet. (9601)

**Sinolagomys kansuensis* (Bohlin 1937) (9513, 9601, 9603, 9712), **Sinolagomys* cf. *S. major* (Bohlin 1937) (9513, 9601), **Ordolagus* sp. (9712), **Desmatolagus* cf. *D. gobiensis* (Matthew & Granger 1923) (9707)

**Parasminthus asiae-centralis* (Bohlin 1946) (9513, 9601), **P. tangingoli* (Bohlin 1946) (9513, 9601), **P. parvulus* (Bohlin 1946) (9513, 9601), **P.* spp. (9513, 9601), **Litodontomys huangheensis* (Wang & Qiu 2000) (9513, 9601), **Heterosminthus lanzhouensis* (Wang & Qiu 2000) (9513, 9601), **Sinosminthus* sp. (9513), **Tataromys plicidens* (Matthew & Granger 1923) (9707), **Yindirtemys ambiguus* (Wang 1997) (9513), **Y. grangeri* (Bohlin 1946) (9513, 9601), **Y. xiningensis* (Wang 1997) (9513, 9601), **Eucricetodon* sp. (9513, 9601), **Tachyoryctoides*? sp. (9601), **Tsaganomys altaicus* (Matthew & Granger 1923) (9707, 9712)

*Didymoconus berkeyi* (Matthew & Granger 1924) (9513).

Taken as a whole, the Xiagou l. f. is slightly more progressive than the Nanpoping one. This is clearly demonstrated by the appearance of more advanced lagomorph *Sinolagomys*, *Tachyoryctoides* and *Heterosminthus*, and the absence of the primitive tataromyid *Bounomys*. As mentioned above, the fossils from GL 9707 and 9712 seem to be more primitive in character. For example, *Ordolagus* sp. and *Desmatolagus gobiensis*, which are present in these two localities, are known to occur only in early Oligocene. It can not be ruled out that the lower part of the reddish brown mudstone belongs to the early Oligocene.

**3) Zhangjiaping l. f.** from the basal white sandstone of the Middle Member. The name was first used by Qiu (1990) and was taken from a village about 10 km north of Lanzhou, on the highway from Lanzhou to Zhongchuan airport (Fig. 1).

The list of the identified fossils is:

**Molluscs:** **Lepidodesma languilati*, **Lepidodesma ponderosa*, **Cuneopsis oblonga*

**Mammals:** *Sinolagomys kansuensis* (Bohlin 1937) (9303), *Sinolagomys* cf. *S. pachygnathus* (Li & Qiu 1980) (9509, 9708), *Sinolagomys* sp. ( 9017, 9102)

*Tachyoryctoides* sp. (9505, 9506, 9708), *Tataromys plicidens* (Matthew & Granger 1923) (9309), *Tataromys* sp. (9308), *Yindirtemys gobiensis* (Kowalski 1974) (9308), *Yindirtemys* sp. (9009, 9502), ?*Sayimys* sp. (9506)

*Hyaenodon* sp. (?8801, 9010, 9512), *Ictiocyon* cf. *I. socialis* (Schlosser 1904) (9308), *Plesictis* cf. *P. vireti* (Dehm 1950) (9309), Amphicyonidae gen. et sp. indet. (?8801), Proboscidea gen. et sp. indet. (8801, 9508), Indricotheriinae (8801, 9017, 9307, 9512, 9514), **Aprotodon lanzhouensis* (Qiu & Xie 1997) (8801, 9502, 9503, 9504, 9507, 9510, 9511, 9512, 9514, 9517), **Phyllotillon huanghoensis* (Qiu et al. 1998) (9503, 9510, 9512, 9516), Cervidae gen. et sp. indet. (9308, 9506), Bovidae gen. et sp. indet. (9503, 9511).

The Zhangjiaping l. f. is much more advanced than the previous two and bears a distinct Miocene appearance. A distinct indicator of the Miocene age is the appearance of proboscidean, the earliest so far known in China. It is represented by a piece of tusk and some foot bones, including an astragalus and a calcaneus. The fauna is roughly comparable with the early Miocene Xiejia l. f. in Qinghai Province by the commonly shared advanced lagomorph *S. pachygnathus* (Li & Qiu 1980). The fauna seems to be slightly more advanced than the Aral fauna of Kazakhstan, which has often been correlated with the Aquitanian stage in Europe (Akhmetiev & Sychevskaya 1994). *Aprotodon lanzhouensis* is slightly more progressive than *A. aralensis* (Qiu & Xie 1997). The Zhangjiaping l. f. is somewhat close to the Bugti fauna of Pakistan (Raza & Meyer 1984). The Zhangjiaping l. f. is also characterized by the presence of relict Oligocene forms. According to Wang Xiaoming (pers. comm.), the specimens referred by him to *Hyaenodon* represent the largest and most aberrant of the genus so far known. The rhinoceroses, including the giant rhinos and *Aprotodon*, are also the relict forms of Asian Paleogene. The Bugti fauna was recently dated as around 20.5 Ma (Downing et al. 1993). The Zhangjiaping l. f. may be of the same age.

**4) Duitinggou l. f.** from the white sandstone layers intercalated in the reddish brown mudstones of the middle and upper parts of the Middle Member. The name is taken from a village 3 km east of Zhangjiaping (Fig. 1). The Duitinggou section, which starts near Duitinggou village, crosses the axis of the syncline and is composed of the basin-fill up to the Middle Member of the Xianshuihe Formation.

The fauna is represented mainly by the locality GL 9304, which contains: *Sinolagomys* sp., *Megacricetodon* sp., *Democricetodon* sp., *Heterosminthus* sp., *Protalactaga* sp., ?*Parasminthus* sp. *Stephanocemas* sp. The finding of both *Megacricetodon* and *Democricetodon* here is particularly noteworthy, since these two genera made their first appearance in Europe only in MN 4, around 18 Ma. Another locality yielding the earliest *Megacricetodon* in China is Wuertu, Nei Mongol (Wang & Wang 1990). The Wuertu l. f. is characterized by the co-occurrence of both Oligocene relict forms, like *Amphechinus minimus*, *Sinolagomys*, *Distylomys*, *Prodistylomys*, *Tachyoryctoides*, etc., and typical Miocene forms, like gomphothere and *Megacricetodon*. The Sihong l. f. from Jiangsu Province yields more variable cricetodonts. In addition to *Megacricetodon* and *Democricetodon*, there is also *Spanocricetodon* in Sihong. However, the Sihong l. f. is otherwise typically Early Miocene (see Qiu 1990, Qiu & Qiu 1995).

**5) Quantougou l. f.** from the top of the Upper Member of the Xianshuihe Formation. The name is taken from the valley where mammalian fossils were collected by Andersson in 1923 (Fig. 1). A revised faunal list was given as follows (Qiu et al. 1997, Qiu 2000): *Mioechinus* ? *gobiensis* (Qiu 1996), *Heterosminthus orientalis* (Schaub 1930), *Protalactaga grabaui* (Young 1927), *P. major* (Qiu 1996), *Plesiodipus leei* (Young 1927), *Megacricetodon* sp., *Democricetodon* sp., *Kubanochoerus gigas* (Pearson 1928) and *Gomphotherium wimani* (Hopwood 1935). The fauna may be slightly older than that of Tung-gur, Nei Mongol.

## Paleomagnetic dating

A preliminary report on the paleomagnetic work carried out in the Cenozoic deposits of the Lanzhou Basin was published elsewhere (Yue et al. 2000). The following presentation gives the final results with some amendments to the preliminary report.

### *1) Sampling*

The final choice of the Dahonggou and Xiajie sections for paleomagnetic investigation was made for the following three reasons: 1) The combined section is the most complete succession representing the whole Tertiary deposits of the basin, with fewer hiatuses in sedimentation than at Duitinggou. 2) The lithology of the two sections, especially the Dahonggou one, is well suited for paleomagnetic studies. 3) There are at least two mammal fossil bearing layers which provide an age connection to the geomagnetic polarity time scale (GPTS). The paleontologic age data obtained from other sites can also be incorporated through tracing of the marker beds within the basin.

The Dahonggou section is located in the northward dipping monoclinal area (Fig. 1). The Cenozoic part of the deposits is 1325.38 m in total thickness, measured from the base of the Xiliugou Formation, encompassing the Xiliugou (201.63 m), Yehucheng (465.22 m), the Lower Member (470.36 m) and part of the Middle Member (188.17 m) of the Xianshuihe Formation. The Xiajie section is located about 2 km west of the Dahonggou one. It encompasses only the Upper Member of the Xianshuihe Formation and is 289 m in total thickness. The strata of the lowest 66 m are interpreted as overlapping with the upper part of the Dahonggou section, based on layer-to-layer tracing in the field and analysis of paleomagnetic information.

Both sections are well exposed, mostly monoclinally tilted, and can be correlated through visual tracing of sandstone layers. Except the rather friable massive sandstone of the Xiliugou Formation, the rocks of the other formations are well suited for paleomagnetic sampling which was carried out during the autumn field season of 1997 under the direction of one of the authors (Yue L.P.). Altogether 481 oriented samples were collected for the Dahonggou section, with an average of 1 sample per 2.3 m, and 145 for the Xiajie section, with an average of 1 sample per 2 m. Only a few samples were broken during transportation and processing, and 13 samples were excluded from measurement because of the inferred stratigraphical overlap.

As early as 1990, paleomagnetic samples were collected at the Duitinggou section for the purpose of testing the suitability of the rocks for paleomagnetic investigation. Laboratory work was done under the supervision of Dr. N. Opdyke (University of Florida, Gainesville, USA). An interim interpretation of the polarity reversals was reported at a symposium held in Lanzhou (Opdyke et al. 1998).

*2) Laboratory treatment*

The oriented block samples were cut into 2 cm cubes. All specimens were investigated at the Paleomagnetic Laboratory of ETH Zürich, Switzerland. They were demagnetized in a TSD-1 Thermal Demagnetizer and measured using a Cryogenic Magnetometer made by 2G Corporation. Most samples were demagnetized in zero field at temperatures of 100°C, 200°C, 300°C, 400°C, 500°C, 550°C and 600°C, respectively. Some samples were discarded after heating to 200°C, 400°C or 500°C when their NRM became unstable. Others were heated up to 620°C, 640°C, 660°C, 650°C or 680°C when required by very high unblocking temperatures of hematite present. Most samples yielded well defined characteristic natural remanent magnetization (NRM) directions using optically aided line fitting techniques on the demagnetograms, except some of the Xiliugou Formation which were unstable and did not exhibit clear NRM directions, probably because of too coarse ferromagnetic particle size. Two examples from the Yehucheng Formation

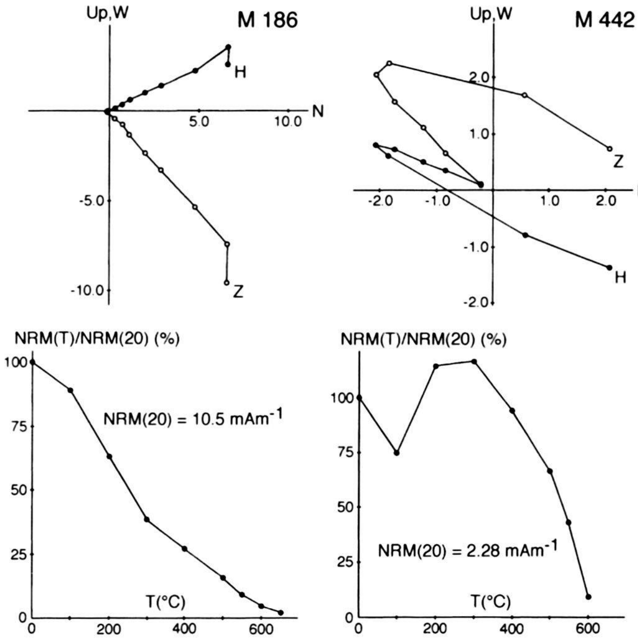


Fig. 4. Thermal demagnetization of two red bed samples from the Dahonggou section. Vector diagrams in stratigraphic coordinates. Z = vertical, H = vertical NRM component. Characteristic normal (sample No. 186) or reversed (No. 442) NRM directions are unblocked at temperatures above 300°C after removal of a present day overprint of probably viscous origin.

(No. 186) and from the Lower Member of the Xianshuihe Formation (No. 442) have been plotted in Figure 4. Opposite polarity of the characteristic NRM components documents the occurrence of well defined normal and reversed directions which predate the folding. Maximum unblocking occurs often at temperatures > 600°C indicating hematite as major NRM carrier. Some 25 of the more than 600 samples were not selected for interpretation because of poor results due to extremely low intensity or instability of NRM. In the end the paleomagnetic data of 601 samples were used for analysis and interpretation.

*3) Results*

The polarity zonation of the combined Dahonggou-Xiajie profile may be compared and correlated with the geomagnetic polarity time scale revised and updated by Berggren et al. (1995). Their scale will be called „BSKA95" hereafter. The best congruent polarity zones at Dahonggou appear to be those which may be correlated with the late Eocene to early Oligocene chrons C13r, C13n and C12r of BSKA95 (Fig. 5). This part of the GPTS is the most diagnostic segment in the mid-Tertiary interval under consideration with two considerably long reversed chrons (2.1 Ma for C12r and 1.1 Ma for C13r) separated by a short normal chron C13n (0.5 Ma). It covers the time span from 34.7 to 30.9 Ma. It is succeeded by higher frequency polarity zonation both in the BSKA95 and in the Lanzhou section if rather constant sedimentation rates are assumed here. The resulting sedimentation rate of this segment in the Dahonggou section is 37.6 mm/ka (143 m / 3.8 Ma).

Taking the above correlation as tie segment, the magnetic reversals of the Lanzhou basin sections can be interpreted as follows.

**1. Dahonggou section (0-1325.38 m):** This section includes the Xiliugou, Yehucheng, and the Lower and (part of the) Middle Members of the Xianshuihe Formations (Fig. 5).

The Xiliugou Formation contains 3 normal polarity zones, which are correlated with C25n-C23n of BKSA95. If correct, their age duration would be approximately from 57 to 50 Ma. Samples taken from the friable sandstone show somewhat scattered reversed NRM directions during thermal demagnetization. Therefore, the reversed polarity zones of the Xiliugou Formation, which are thought to correspond with C25r-C23r, are not so well determined.

The Yehucheng Formation records 8 normal and 8 reversed polarity zones. The normal zones are here suggested to correspond to the interval from C22n to C13n. The two pairs of long reversed intervals with a short normal zone in the section are interpreted as C21r-20r and C13r-C12r in BKSA95, respectively. The match between these four pairs of reversals is pretty good. The segments between the pairs C19-C15 unfortunately cannot be correlated one to one. If the above interpretation is accepted, the Yehucheng Formation will correspond to the interval from C22n to the upper part of C12r, thus covering the time span from 51 to 32 Ma. The average sedimentation rate is calculated as 24.5 mm/ka (465.22 m / 19 Ma). This value seems to be of comparable order of magnitude when compared with the sedimentation rate of 38 mm/ka for the interval C13r-C12r.

The Lower Member of the Xianshuihe Formation in the Dahonggou section records 13 normal and 13 reversed polarity zones. They are interpreted to be equivalent to the chrons from the upper part of C12r to the top of C6n, being 32-19.5 Ma in age. It should be noted that the above interpretation does not match well with the same interval in the BKSA95. At least 19 normal polarity zones are recognized for the same interval in BKSA95. The interval between C6An and C8n witnesses particularly frequent reversals. Chron C6n is the first longer normal polarity zone above the C6An—C8n busy reversals. The uppermost normal zone of the Lower Member is also considerably long compared with those below it. Therefore it has been correlated with C6n in the BKSA98. The average sedimentation rate is 37.6 mm/ka (470.36 m / 12.5 Ma).

The Middle Member of the Xianshuihe Formation in the Dahonggou section is rather short as defined by the first appearance of the thick white sandstone at 1137.21 m of the section. It contains only 3 short normal polarity zones separated by comparatively longer reversed ones (Fig. 5). It is considered to start in the upper part of C6n and to run up to C5Cr, leaving the uppermost normal polarity zone uncorrelated. Thus the Middle Member of the Xianshuihe Formation in the Dahonggou section is dated as 19.5-16.6 Ma, and its sedimentation rate is calculated as 64.9 mm/ka (188.17 m / 2.9 Ma). The higher average sedimentation rate can be accounted for by an increasing percentage of the sand component.

**2. Xiajie section (298.73 m)**: The paleomagnetic results show that the whole section records 5 reversed and 4 normal polarity zones. Compared with the BKSA95, the uppermost normal polarity may correspond to C5Bn, the middle two to C5Cn, and the lowermost to C5Dn. Therefore, the time span of the Upper Member of the Xianshuihe Formation is estimated to be 16.6-15 Ma. A very high average sedimentation rate of 186.7 mm/ka (298.73 m / 1.6 Ma) results. Such a high rate of sedimentation may be due to the large proportion of conglomerates and conglomeratic sandstones in the section.

### Paleomagnetic data versus paleontological data

**1) Xiliugou Formation**: So far no fossils have ever been found in this formation. The polarity zonation obtained from the Xiliugou Formation in the Dahonggou section is the first paleomagnetic information of this formation. It is interpreted as C25n-C23n (57-50 Ma) falling into the late Paleocene to early Eocene. In a letter to one of the authors of the present paper (F. H.) in 1999, N. Opdyke, based primarily on tectonical considerations, expressed serious doubt as to such an interpretation. He was of the opinion that the basin-fill might have started only after the collision of the India and Eurasia plates. With this in mind, Opdyke suggested that the reversed zones recorded in the lower part of the Yehucheng Formation, here interpreted as C20r and C21r, be correlated with C12r and C13r, respectively. Accordingly, he suggested that the base of the whole section be placed at the level around C18, at ~40 Ma. Opdyke's alternative interpretation appears less satisfactory than ours for two reasons. a) It is less compatible with the polarity reversal pattern of the BKSA95, where two pairs of long reversed zones intercalated with short normal zones (C20r-C21r and C12r-C13r) are present during the time span of 51-30 Ma. It is difficult to find a suitable place in BKSA98 to insert the long reversed zone recorded in the top of the Yehucheng Formation if Opdyke's interpretation is accepted. b) It is inconsistent with the paleontological data. The mammal fossils found in the overlying Yehucheng Formation seem to be late Eocene in age. However, if Opdyke's interpretation is accepted, the base of the Yehucheng Formation should have been dated as about 35 Ma, which would be too young for this formation..

**2) Yehucheng Formation**: Although some Eocene mammalian fossils were found in the Yehucheng Formation, no precise control can be achieved. The base of the Yehucheng Formation is here calibrated with the top of the C23n in BKSA98, since it is the best solution to correlate the long reversed zone above it with the long chron C20r in the BKSA95. This places the base of the Yehucheng Formation at 50 Ma, in the early Eocene.

**3) Xianshuihe Formation**: In the Dahonggou section the base of the Xianshuihe Formation falls within the upper part

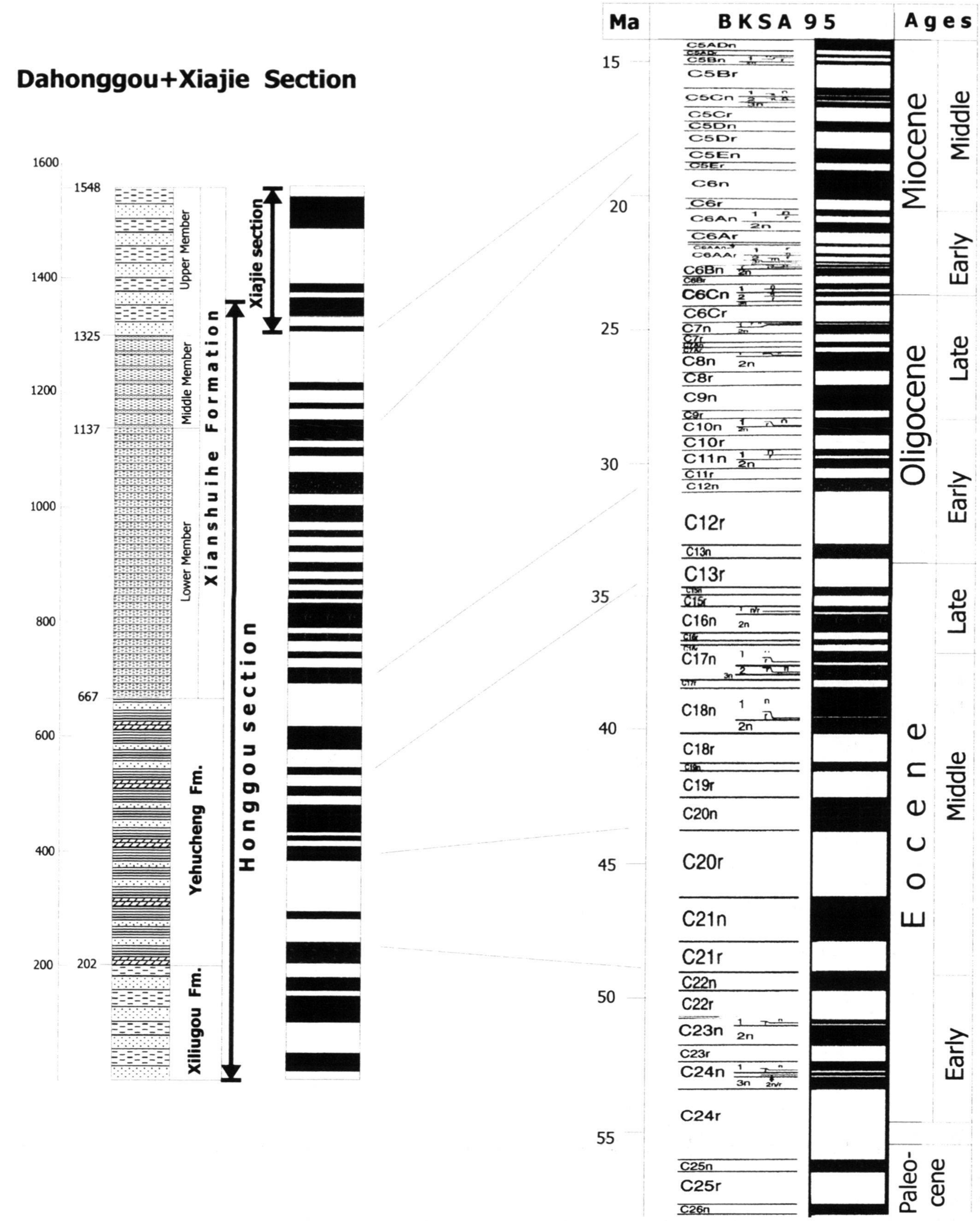


Fig. 5. Paleomagnetic polarity zonation of the Dahonggou-Xiajie section and its correlation with the BKSA95 magnetic polarity timescale.

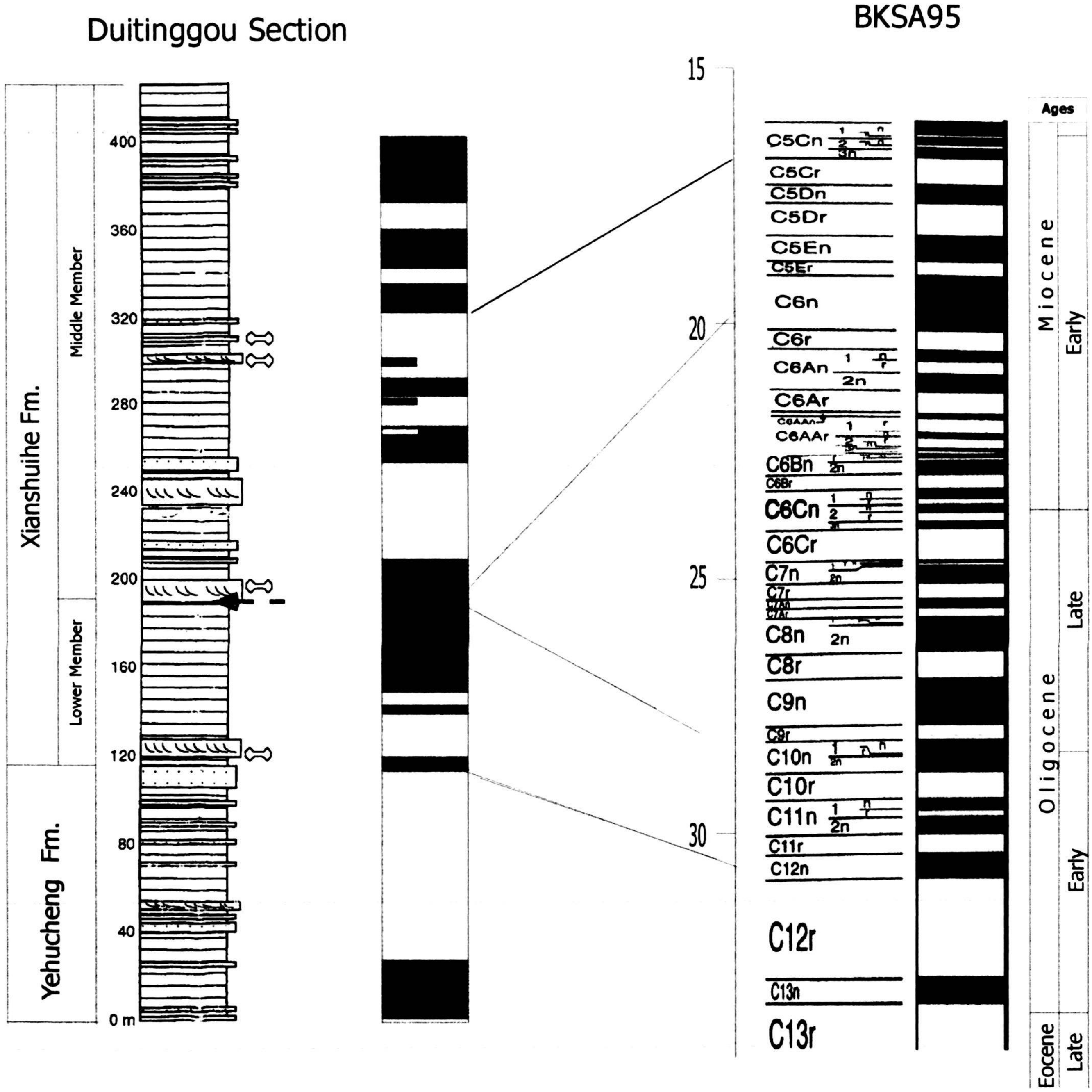


Fig. 6. Paleomagnetic polarity zonation of the Duitinggou section and its re-interpretation using the BKSA95 timescale (adapted from Opdyke et al. 1998).

of C12r. This is in good accordance with the paleontological data, since the Nanpoping l.f. is a typical late early Oligocene fauna. Both paleontology and paleomagnetic data coincide at about 32 Ma. This is taken as the most reliable tie point between paleontology and paleomagnetism and serves the basis for further inter- and extrapolation.

Since the Duitinggou area provides us with the most representative fossils of the Middle Member of the Xianshuihe Formation, Opdyke et al.'s (1998) preliminary interpretation of the polarity reversals of the Duitinggou section is also incorporated into the following discussion (Fig. 6).

According to Opdyke et al. (1998), 24 magnetozones are recorded in the 400 m thick deposits of the Duitinggou section. Of the 12 normal zones two are ill determined, whereas of the 12 reversed zones one is questionable. As in the Dahonggou section, the majority of the Yehucheng Formation of the Duitinggou section is represented by a long reversed polarity zone, which can likewise be correlated with C12r. The base of the Xianshuihe Formation (the dusky yellow conglomeratic sandstone) is reversed in polarity, followed below by a short normal zone. Opdyke et al. (1998) placed the base of the Xianshuihe Formation in C11r, thus at ~30.5 Ma. As discussed above, the base of the Xianshuihe Formation in the Dahonggou section has been correlated to the top of C12r, at ~32 Ma, not to C11r. The time difference between the bases of the Xianshuihe Formation in the two sections thus amounts to 1.5 Ma. A possible explanation of this time difference might be the transgressive character of the Xianshuihe Formation. Deposition started 1.5 Ma earlier in the Dahonggou area than in the Duitinggou area.

The polarity pattern of the upper half of the Duitinggou section is difficult to interpret. In order to accommondate with the paleontological data, Opdyke et al. (1998) assumed an unconformity at 190 m (not 245 m as stated in the text) above the bottom. Probably based on the polarity pattern, they correlated the uppermost three normal zones to C6n, C6An.1n and C6An.2n. This means that the age of the top of the section is ~19 Ma and the bottom of the Middle Member of the Xianshuihe Formation (white sandstone) is estimated ~ 23.8 Ma (just the Oligocene-Miocene boundary). Such an interpretation is incongruous with the paleontological data. In the white sandstone (the base of the Middle Member of the Xianshuihe Formation) the first proboscidean fossils were found, and in the middle part of the Middle Member the earliest *Megacricetodon* and *Democricetodon*. In Europe the above three forms made their first appearance at ~18 Ma. If the questionable zones are omitted, the upper half of the Duitinggou section can be correlated to C5Cn.1n-3n, C5Cr, C5Dn, C5Dr, C5En, C5Er, and the upper part of the C6n. In this case its age would cover only 16-19.3 Ma. An inevitable outcome of such an interpretation is the presence of a long hiatus (~10 Ma long) between the Lower and the Middle Members of the Xianshuihe Formation in the Duitinggou section. The greatly reduced thickness of the Lower Member in the Duitinggou section (~70 m) compared with that of the Dahonggou section (470.36 m) seems to support this interpretation.

The pattern of the polarity reversals of the Upper Member of the Xianshuihe Formation in the Xiajie section is correlated with C5B-C5Cn (15-16.6 Ma) in the BKSA95. Vertebrate paleontology seems to support this interpretation as well, since the Quantougou l.f., which is at the top of the whole section, is dated as of about 15 Ma.

## Timing of uplift of the Tibetan Plateau

Together with the Himalayan Range, the highest mountain range in the world, the Tibetan Plateau with its average elevation exceeding 4500 m occupies an area of about 2 million km$^2$. Although the great influence of this huge elevated body on the formation of the climate patterns of the world is generally accepted, opinions differ widely as to the timing and the altitudes of the uplift. The Lanzhou Basin is one of the basins situated on the northeastern slopes of the Tibetan Plateau. As the other basins around any uplifted areas, sedimentation and geological structures of the Lanzhou Basin should reflect the tectonic activities caused by the convergence of the Indian and Eurasian plates and their resultant, in particular the timing and intensity of the uplift. The tectonic information obtained during the work of the present project can be summed up as follows:

1) The initial collision between the Indian and Eurasian plates may have had little effect on the sedimentation regime in the north boundary areas of the Tibetan Plateau. As it is well established, the collision of the two plates occurred in the middle Eocene, at ~43.6 Ma (Zhang et al. 2000). If our age determination of the Tertiary deposits of the Lanzhou basin is reliable, an inevitable conclusion should be: no evident tectonical reflection of the collision can be observed here in the northeast border area of the plateau.

2) From the point of view of the sedimentation environment, the first obvious change after the Indo-Eurasian collision might have occurred at the boundary between the Yehucheng and Xianshuihe Formations in the Middle Oligocene, i.e. about 32 Ma ago. Being highly gypsiferous, fine-grained, thin-layered and widely spread in area, the Yehucheng Formation consists of typical "playa" sediments of considerably large dimension formed under dry climate. The sedimentation rate of the Yehucheng Formation is very low (24.5 mm/ka). This seems to indicate that the source area, which is presumed to be the present-day Tibetan Plateau, might not have been very high and not strongly differentiated in altitude. On the other hand, the Lower Member of the Xianshuihe Formation is fluvio-lacustrine in character. According to the paleoenvironmental analysis in the interim report prepared by Wu Ruijin and Zhan Liren, the basal yellow conglomeratic sandstone may represent a facies of channel-fill of some braided stream system. The large amount of stems of plants contained in the yellow sandstone indicates that the sedimentation occurred near the water surface, and the anguclasts of the yellow sandstone reflect the intensified stripping of the rocks in the source region. All this indicates that the uplift of the source area should have been moderate. The massive, reddish brown mudstone may represent floodplain deposits. It may not be a mere coincidence that a number of important global events took place around 30 Ma. For example, the largest Tertiary sea regression occurred at the base of the megacycle TB1 (Haq et al. 1987, Woodburne & Swisher 1995); the final sea retreat from the Turgai strait disconnecting the Paratethys from the Arctic Ocean, and the beginning of the molasse deposits in Europe reflecting the strong orogeny of the Alps, all took place in the same period, around 30 Ma.

3) The second change in sedimentation environment occurred at the beginning of the Middle Member of the Xianshuihe Formation, at about 20-19 Ma, i.e., within the lower Miocene. The volume of coarse material as shown by the repetitive occurrence of sandstones and conglomerates is much greater than the underlying strata. The tectonic movement

must have become stronger. A particularly noteworthy fact is the nature of the Zhangjiaping l.f.. It is very similar to the Bugti fauna of Pakistan. The commonly shared large mammals in the two faunas are the first gomphotheres, *Phyllotillon*, giant rhinoceros (primarily Asian form), *Aprotodon* (endemic Asian form), *Paraentelodon* (otherwise only known from Caucasia), etc. Thus no zoogeographic obstacle for exchange of the above mentioned animals existed between the two regions situated north and south of the present-day Tibetan Plateau during the early Miocene around 20-19 Ma. This would mean that, though elevated, the height of the plateau must not have been high enough to prevent the large mammals from more or less free migration. Secondly, the proboscideans seem to have appeared in both Bugti and Lanzhou slightly earlier than in Europe. In Europe the proboscideans appeared no earlier than 18 Ma, while their first appearance in Asia may be slightly earlier. The age determination of the first appearance of the proboscideans in Pakistan is still indefinitive. Downing et al. (1993) dated it as 20.5 Ma based on their work on the Bugti fauna. Welcomme et al. (1997) correlated the beds with the first proboscideans (Levels 1, 3 and 4) with the European MN3b, which should be earlier than 18 Ma, probably around 19 Ma. According to Antoine (pers. comm.), the preliminary identification of the proboscideans of the Levels 1 and 3 was untenable. The proboscideans first appeared from the Level 4 on, and the Levels 1-3 should be assigned to the Oligocene. However, no concrete figure was given by Antoine. If the interpretation of the present paper is correct, the first appearance of the proboscideans in the Lanzhou Basin should be not later than 19.5 Ma. This is in accordance with the recent paleogeographic reconstruction by Steininger et al. (1996), where the land-bridge between South Asia and Africa via Saudi Arabia did exist before the major Burdigalian transgression.

4) A phase of compressive movement in east-west direction can be postulated to have occurred probably during the time span somewhere between 15 Ma and 10 Ma. The deposits in the southeastern part of the Lanzhou Basin are folded into a syncline with both its limbs steeply inclined. The axis of the syncline is basically in north-south direction. No major rotation about a vertical axis is indicated in the more or less N-S streaking NRM directions in the Dahonggou-Xiajie section. Deposition within the Lanzhou Basin ended at about 15 Ma. Deposits with *Hipparion* faunas, which are apparently not the earliest one, but probably around 10 Ma, are generally flatlying and widely distributed in this region. This leads us to suggest that the syncline should have been formed in the time span after the basin-fill of the Lanzhou Basin but before the deposition of blanketing sediments with the *Hipparion* fauna.

Although the timing of the uplift demonstrated by the mid-Tertiary deposits is strongly coincident between the Lanzhou Basin, the southern slopes of the Himalayas (the Chitarwata and Siwaliks Formations) and the northern slopes of the Alps (the molasses), the lithology and sedimentation rates of these areas are widely different. Both the Siwaliks and the molasses are very thick and very coarse in grain size, and taken as a whole, with much higher sedimentation rates. According to Behrensmeyer (1987), the average sedimentation rates for the lower part of the Siwaliks are 140-320 mm/ka, while that for the upper part equals 460-480 mm/ka. According to Schlunegger et al. (1996), the sedimentation rates of the Lower Freshwater Molasse, calculated from three sections, are 280, 430 and 1000 mm/ka, respectively. They are much higher than those of the Lanzhou Basin, which are 24.5, 37.6, 64.9 and 186.7 mm/ka respectively. This can partly be accounted for by the differences in intensity and magnitude of the uplift. On the other hand, much thicker and coarse-grained deposits do exist on the north slopes of the Tibetan Plateau: the Xiyu gravel described by Huang & Chen (1981), and especially by Liu et al. (1996). These gravels are commonly considered as of Plio-Pleistocene in age. Without any reliable dating from paleontology, especially from the fossil mammals, the Plio-Pleistocene age of these gravels remains a problem to be further investigated. A recent magnetostratigraphic study by Zheng et al. (2000), however, assigns an older age limit of 3.8 Ma to the Xiyu Formation which favours models that postulate late Pliocene uplift of the Tibetan Plateau, over an early Oligocene to Miocene upheaval.

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