

Biostratigraphy and palaeoenvironment of the dinosaur-bearing sediments in Lower Cretaceous of Mazongshan area, Gansu Province, China



*F. Tang, †Z.-X. Luo¹, *Z.-H. Zhou, §*H.-L. You, †J. A. Georgi, *Z.-L. Tang and ¶X.-Z. Wang

*Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing 100044, China

†Section of Vertebrate Paleontology, Carnegie Museum of Natural History, Pittsburgh, PA 15213, USA

§Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia PA 19104, USA

¶Department of Geology, Peking University, Beijing 100871, China

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This paper discusses the lithostratigraphy of the Xinminbao Group in the Mazongshan area of Gansu Province, northwestern China, and the correlation of its biota. The Xinminbao Group was deposited in a fluvio-lacustrine setting in Mesozoic graben basins under a semi-arid, subtropical climate. The fossil sites concentrated in the lower part of the group have yielded dinosaurs, mammals and other vertebrates that are comparable to the Aptian–Albian vertebrate assemblages that have been found in Mongolia and Siberia. Based on their invertebrate and vertebrate fossils, sediments of the lower part of the Xinminbao Group are considered to be Late Barremian–Aptian in age, although the middle and upper parts could be as young as Albian. The megafossil plants and conchostracans are comparable to those of the Yixian and Jiufotang Formations in eastern China (Barremian–Aptian). The palynoflora is also comparable to that of the upper Lower Cretaceous elsewhere in northern China, although the presence of two angiosperm taxa, *Asteropollis* and *Tricolpites*, suggests that the main fossil sites are Albian. These biostratigraphic data for the Mazongshan area provide a new temporal calibration for the terrestrial biotas of the Lower Cretaceous of central Asia, where most of the known dinosaur-bearing sediments lack precise palynological, radiometric and magnetostratigraphic dating.

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1. Introduction

The world's terrestrial biotas underwent rapid changes through the transition from the Jurassic to Early Cretaceous (Cifelli *et al.*, 1997; Luo, 1999; Barrett, 2000). This geological time witnessed a rapid turnover among major groups of dinosaurs (Russell, 1993; Sereno, 1997, 1999), early radiation of major clades of birds (Chiappe, 1995; Hou *et al.*, 1996; Ji *et al.*, 1999a; Zhou, 1999), diversification of major groups of mammals (Archer *et al.*, 1985; Kielan-Jaworowska & Dashzeveg, 1989; Hu *et al.*, 1997; Rich *et al.*, 1997; Ji *et al.*, 1999b), rise of flowering plants (Taylor & Hickey, 1996; Sun & Dilcher, 1996; Sun *et al.*, 1998), and emergence of modern orders of pollinating flies (Labandeira *et al.*,

1994; Labandeira, 1997, 1998; Ren, 1998). Many of the lineages that emerged during the Early Cretaceous have since dominated the world's terrestrial biotas and some are still thriving today.

The Gobi Desert of Central Asia has some of the world's richest vertebrate fossil sites within the Upper Jurassic and Lower Cretaceous. However, precise geological ages of many late Mesozoic vertebrate fossil localities in Mongolia and northern China are uncertain (Jerzykiewicz & Russell, 1991; Currie & Eberth, 1993; Eberth *et al.*, 1993). Although some vertebrate sites within this geological interval in Gansu have been known since the 1920s (Bohlin, 1953), their biostratigraphy has been poorly understood owing to the lack of reliable biostratigraphic data for the vertebrate fossils collected in the early twentieth century. A better understanding of evolution of the terrestrial

¹Correspondence to Z.-X. Luo (luoz@carnegiemuseums.org)

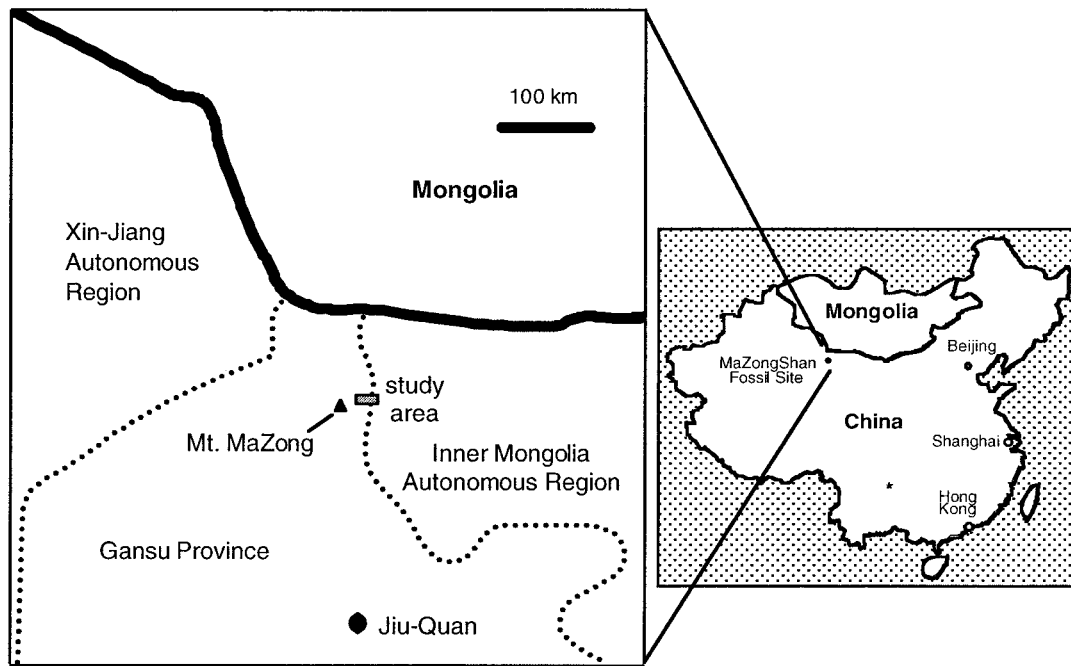


Figure 1. The geographic location of the Mazongshan (Horse Mane Mountains) area, Gansu Province, China. It is approximately 240 km north of the city of Jiuquan. Mount Mazong itself is located within Gansu Province. The Suanjingzi Basin is a part of Mazongshan township, E-Ji-Na County, Inner Mongolia. The adjacent Gongpoquan Basin is in the northern part of Su-Bei County, Gansu Province.

biotas through the Jurassic/Cretaceous transition requires better biostratigraphic correlation (Swisher *et al.*, 1999; Luo, 1999; Barrett, 2000) of the main fossil sites of central Asia, such as those in the Mazongshan area of Gansu Province, China.

Mazongshan (the 'Horse Mane Mountains') is a mountainous terrain in northern Gansu (Kansu) Province near the China-Mongolia border (Figure 1). The area is a part of the Trans-Altai ('western') Gobi Desert with a xeric climate, located in the large tectonic depression between the Mongol-Gobi Altai to the north and the Tibet-Qinghai Plateau to the south. The mountain ranges in the Mazongshan area are known as the northern highlands (or 'Beishan') in northwestern Gansu Province, approximately 240 km north of the city of Jiuquan (Figure 1).

Lower Cretaceous sediments are extensively exposed in the badlands of the two Mesozoic basins in the Mazongshan area: the Gongpoquan Basin and the Suanjingzi Basin (Figure 2). The sediments are developed in the neighbouring Jiuquan Basin (Jiayuguan area) where some fragmentary vertebrate fossils were recovered by the Sino-Swedish expedition in the 1920s (Bohlin, 1953). Comparable Lower Cretaceous dinosaur-bearing sediments are also known in adjacent regions of Inner Mongolia (Eberth *et al.*, 1993), Xinjiang (Zhao, 1980; Zhao *et al.*, 1987), the

Pre-Altai ('northern') Gobi Desert (Trofimov, 1978, 1980; Jerzykiewicz & Russell, 1991), and Siberia (Maschenko & Lopatin, 1998), although only two of these dinosaur sites have been dated by palynology, or palaeomagnetic stratigraphy and radiometrics (Eberth *et al.*, 1993; Hicks *et al.*, 1999).

Sediments in the Mazongshan area have yielded one of the richest vertebrate fossil assemblages yet discovered in the Lower Cretaceous of the Gobi Desert, thanks to several palaeontological expeditions. The occurrence of fragmentary dinosaur bones was first reported by the local ranchers to the Chinese Academy of Sciences in 1986, and brought to the attention of the Institute of Vertebrate Palaeontology and Palaeoanthropology (IVPP) (Dong, 1992, 1993, 1997a). A field crew from IVPP searched briefly for vertebrate fossils in the Mazongshan area in 1988. More field exploration and excavation was carried out during the Sino-Japanese Silk Road Dinosaur Expedition in 1992–1993 (Dong, 1997a). All of these periods of field work were aimed at finding dinosaurs and other vertebrate fossils (Dong, 1993, 1997a, b); no stratigraphic studies were attempted.

The age of the dinosaur-bearing deposits of the Mazongshan area has been equivocal. In the earliest geological survey of 1969 by the Bureau of Geology and Mineral Resources of Inner Mongolian

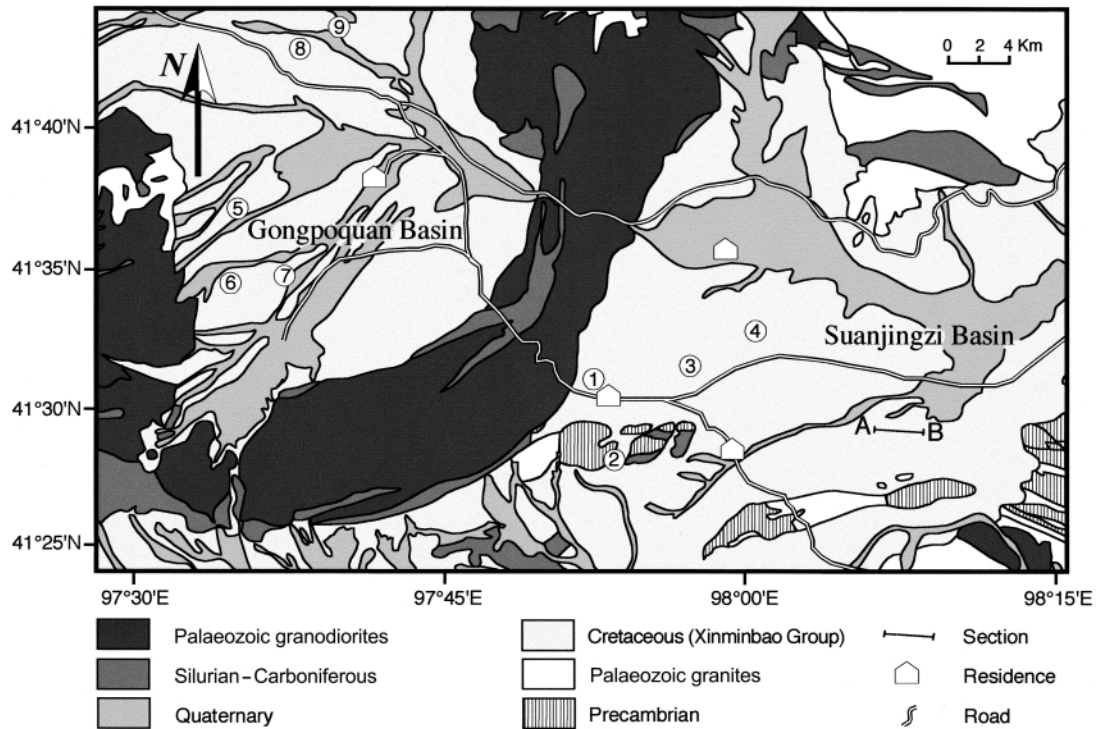


Figure 2. Geological map of the Gongpoquan and Suanjingzi basins, the Mazongshan area (modified from the geological map published by the Bureau of Geology and Mineral Resources, 1991). 1, Suanjingzi locality (*Psittacosaurus*); 2, *Psittacosaurus mazongshanensis*; 3, the ankylosaurid site; 4, the theropod site; 5, Laobugou sites (sauropods, iguanodontids, theropods, turtles, crocodiles, fragments of unidentifiable mammals); 6, the ceratopsian graveyard (*Psittacosaurus*, *Archaeoceratops*, iguanodontids, ornithomimids, gobiconodontids); 7, the hypsilophodontid site; 8, *Archaeoceratops oshimai* type locality; 9, the segnosaur site. A–B, stratigraphic section in the eastern Suanjingzi Basin.

Autonomous Region, all of the Mesozoic sediments were recognized as a single lithostratigraphic unit and tentatively considered to be Late Jurassic (Bureau of Geology and Mineral Resources of Nei Mongol Region, 1991). In a stratigraphic study of Mesozoic sediments in the Jiuquan Basin (240 km south of the Mazongshan area), Ma (1982) established the Xinminbao Group, which consists of three formations (in successively younger sequence): the Chijinbao (=Chijinchiao), the Digou (=Diwoupu), and the Zhonggou (Xinminbao) formations. The Chijinbao Formation was considered to be Late Jurassic, whereas the Digou and Zhonggou Formations were considered to be Early Cretaceous. By comparison with the stratigraphic sequence in the Jiuquan Basin (Ma, 1982), the lower part of the Mesozoic sediments in the Mazongshan area was regarded as Late Jurassic while the upper part was considered to be Early Cretaceous in age. However, Qi (1984) suggested that the Xinminbao Group throughout northern Gansu, including the Jiuquan Basin, should be regarded as the Early Cretaceous, a conclusion endorsed by Niu (1987). Because of the lack of palynological

data and other index fossils, Dong (1997c) inferred that the Mesozoic dinosaur-bearing sediments in the Gongpoquan and Suanjingzi basins of the Mazongshan area are Early Cretaceous on the basis of the evolutionary grade of the ceratopsian dinosaurs.

Joint expeditions by the Institute of Vertebrate Palaeontology and Palaeoanthropology (Beijing), Carnegie Museum of Natural History (Pittsburgh) and University of Pennsylvania (Philadelphia) during 1997–1999 led to extensive palaeontological exploration and stratigraphic studies in the Mazongshan area. This Sino-American expedition discovered major new fossil sites and completed a stratigraphic survey of both the Suanjingzi and Gongpoquan basins. A stratigraphic section was established for the Xinminbao Group in the Suanjingzi Basin; the sedimentary facies were documented; and the stratigraphic position of major vertebrate fossil localities was determined (Tang *et al.*, 1998).

This paper provides new information on the biostratigraphy of the Xinminbao Group in the Mazongshan area, and its correlation with Lower Cretaceous terrestrial sediments elsewhere in northern

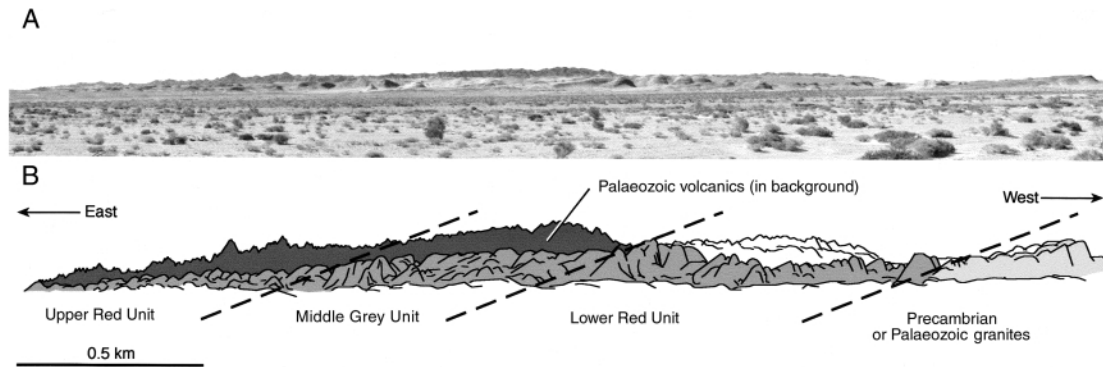


Figure 3. The main stratigraphic section of the Xinminbao Group in the eastern part of Suanjingzi Basin. A, the stratigraphic section viewed from north. B, schematic drawing (the vertical height is magnified by $\times 2$) to illustrate the approximate divisions of the Lower Red, Middle Grey and Upper Red units. Dashed lines indicate the approximate boundaries between these units. The exposure extends for about 4 km; the total thickness of sediments is >150 m. Deposition of the units was continuous. The base (A, Figure 2) is near $41^{\circ}29'27''\text{N}$ and $98^{\circ}05'31''\text{E}$; the top (B, Figure 2) is near $41^{\circ}29'15''\text{N}$ and $98^{\circ}07'29''\text{E}$ (see Appendix for lithostratigraphy).

China and Mongolia. Based on the latest data from the palaeontological exploration and field stratigraphic studies in the Mazongshan area, we confirm that the sediments of the Xinminbao Group are of Early Cretaceous age (Dong, 1992). The newly collected invertebrates and vertebrates suggest that the group in the Mazongshan area was deposited during the Late Barremian–Albian. We also provide palynological evidence that helps further to refine the age of Xinminbao Group to Albian, and suggest that the fossiliferous sediments of this group were deposited in a fluviolacustrine setting under a semi-arid, subtropical climate.

2. Geological setting and lithostratigraphy

2.1. Tectonic setting

The Suanjingzi and Gongpoquan basins (Figure 2) belong to a series of graben basins that developed during the late Mesozoic in an extensional tectonic setting. Both are part of a larger depression between the Altai mountain ranges of Mongolia and the Qilian mountain range of the Qinghai Plateau (Chen *et al.*, 1996), and are strike-slip basins on the Tarim basement block (Vincent & Allen, 1999). The terrains around these basins consist mostly of late Palaeozoic granites and granodiorites, some early Palaeozoic neutrobasic igneous rocks, some Precambrian metamorphic rocks (slates), and small amounts of Palaeozoic marine sediments (Figure 2). These mountain ranges resulted from tectonic activities between the Tarim and Kazakhstani blocks and the North China block (Chen *et al.*, 1996). Their orogeny coincided with the Yanshan tectonic movement of the early Mesozoic (Bureau of Geology and Mineral Resources

of Inner Mongolia, 1991; Chen *et al.*, 1996), which has been correlated with widespread volcanic and tectonic activities in all of northern China.

Both the Suanjingzi and the Gongpoquan basins are rift-related inland basins that received fluvial, lacustrine, and intermontane fluvial-fan sediments during the Early Cretaceous, as in other basins of the Hexi ('west of the Yellow River') corridor of Gansu Province and the Alashan area of Inner Mongolia (Vincent & Allen, 1999). In this paper we follow Ma (1982) and Qi (1984) in recognizing the Xinminbao Group as the main lithostratigraphic unit for the Mesozoic sediments of the Mazongshan area. This unit is best represented by a fully exposed stratigraphic section (>150 m thick) in the eastern part of the Suanjingzi Basin (Figure 3A, B; Appendix). This continuous stratigraphic sequence is divisible into three informal lithostratigraphic units: Lower Red Unit, Middle Grey Unit and Upper Red Unit (Figures 3, 4; Appendix; see also Tang *et al.*, 1998).

2.2. Lower Red Unit

The Lower Red Unit is about 63 m thick in the most complete stratigraphic section in the eastern Suanjingzi Basin (Figures 3, 4; Appendix). It rests unconformably on Precambrian slates or Palaeozoic granites/granodiorites in the eastern part of the basin. Elsewhere in the Mazongshan area it may lie unconformably over Palaeozoic igneous rocks. The bottom part of the unit consists of coarse conglomerates. These grade upward into fine sandstones that develop cross stratification locally. This graded sequence represents a set of alluvial fan to river channel deposits.

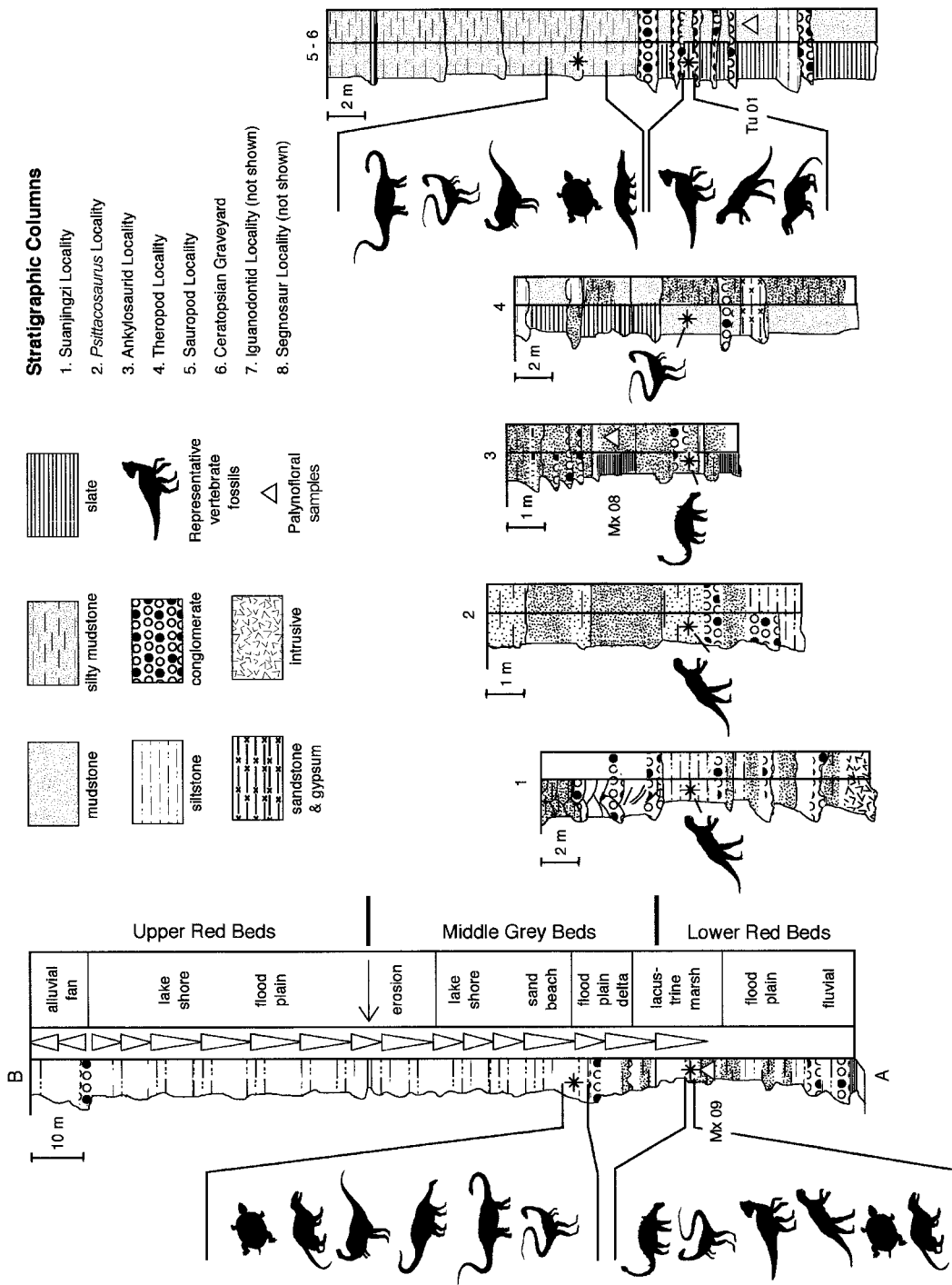


Figure 4. Stratigraphy of the Lower Cretaceous Xinminbao Group in the Gongpoquan and Suanjingzi Basins. Column A-B (left) represents the most complete lithostratigraphic section in the eastern part of the Suanjingzi Basin; see Figure 3 for field photograph of the section A-B. 1, stratigraphy of the Suanjingzi Village locality (site of a *Psittacosaurus* skeleton 1.2 km north of the village, Suanjingzi Basin; Lower Red Unit); 2, stratigraphy of the *Psittacosaurus mazongshanensis* type locality (south of Suanjingzi Basin; Lower Red Unit); 3, stratigraphy of the ankylosaurid locality (central Suanjingzi Basin, Lower Red Unit); 4, stratigraphy of the theropod localities (Suanjingzi Basin, Lower Red Unit); 5, 6, stratigraphy of the Laobugou locality (Gongpoquan Basin, Middle Grey Unit) and the ceratopsian graveyard locality (Gongpoquan Basin, Lower Red Unit). This last section (5-6) is applicable to the *Archaeoceratops* type locality. Vertebrate fossil localities are indicated on Figure 2; * indicates horizons with vertebrate fossils; Mx 08 and Tu 01 (triangles) are the stratigraphic levels of palynological samples.

The upper part of the Lower Red Unit consists of a set of red clastic sediments with alternating sand-, silt- and mudstones that reflect either overbank deposition in a meandering fluvial environment, or accumulation in shallow lacustrine or marsh environments. It has yielded many vertebrate fossils, including ceratopsians, iguanodontids, hypsilophodontids, ankylosaurids, theropods, turtles, scutes of crocodiles, and occasionally mammals (Figure 4A, B). The weathered surface of the red sediments near the fossil sites frequently contain recrystallized gypsum.

2.3. Middle Grey Unit

The Middle Grey Unit is dominated by massive grey siltstones and calcareous mudstones (*c.* 58 m thick in the more complete section in the eastern Suanjingzi Basin). Locally there are thinly laminated mudstones and yellowish grey shales. The unit comprises two distinctive graded sequences indicating fluvial lacustrine sedimentary environments, with some floodplain deposits and some lakeshore deposits. It also contains some red calcareous concretions and tubules; these are frequently associated with the vertebrate fossil sites. Locally, shales rich in plant debris and invertebrates (gastropods and insects) are intercalated within the massive grey siltstones and mudstones. At the Laobugou locality (Figure 2), the lower part of the Middle Grey Unit consists of massive fossiliferous exposures of dinosaur bones in an area nearly 2 km². Some complete turtle carapaces have been found within large calcareous mudstone concretions. The upper part of the Middle Grey Unit in the Gongpoquan Basin has yielded petrified tree trunks.

2.4. Upper Red Unit

The Upper Red Unit (*c.* 38 m in maximum thickness) consists of massive red siltstones and mudstones that form a series of upwardly coarsening cycles of lacustrine sediments. The contact of the Upper Red Unit with the Middle Grey Unit is marked by an erosional plane. The clastic rocks of this unit are typically horizontally stratified and contain local concentrations of gypsum. Weathered surfaces reveal alternating bands of red and grey colours. The top of the section consists of some coarse, intermontane, fluvial-fan deposits. The Upper Red Unit is extensively exposed in the central (and topographically lower) parts of the basins. No fossils were found in it during our field exploration in 1997–1999.

2.5. Lithostratigraphic comparisons

The Xinminbao Group in the Mazongshan area is lithologically similar to the dinosaur-bearing deposits

in Tebch (Uradi Hou-Qi, Inner Mongolia) about 700 km to the east, in the northern Alaxan terrain of the Lang Shan mountain range (Bohlin, 1953; Bureau of Geology and Mineral Resources of Inner Mongolia, 1991; Eberth *et al.*, 1993). Eberth *et al.* (1993) considered the dinosaur-bearing deposits in Tebch to be of Barremian or possibly early Aptian age on the basis of palynology and radiometric dating. The overall coarsening-upward sequence at this locality (Eberth *et al.*, 1993) is similar to the sedimentary sequence of the Xinminbao Group in Mazongshan. The dinosaur-bearing terrestrial deposits of the Tugulu Group (Dong, 1992) in the Junggar and Turpan basins of northern Xinjiang also consist of similar fluvial lacustrine deposits. Although the Tugulu Group as a whole is considered to be Early Cretaceous in age on the basis of palynological evidence (Yu, 1990a), there is no precise dating of the vertebrate sites.

3. Palaeontology

3.1. Palynology

Early Cretaceous palynological assemblages have been documented for several areas of northern China; e.g., the Jehol Group of northeastern China (Yu, 1990a, b), the Minhe Basin of Qinghai and Gansu provinces (Yu *et al.*, 1982), and the Junggar and Turpan basins of Xinjiang (Yu, 1990a). Palynological data are also available for the Lower Cretaceous of the Jiuquan Basin (Hsu & Chow, 1956) and for the type stratigraphic section of the Xinminbao Group (Hsu *et al.*, 1974). However, before this study, no deposits had been sampled for palynomorphs from the northern highland (Beishan) area of Gansu Province, of which the Mazongshan area is a part.

Eleven samples from grey marls, siltstones and shales at dinosaur localities 1–5 (see Figure 4) were processed for palynomorphs. Only three samples from the lower portion of the section yielded well-preserved palynofloras (Figures 4, 5); Mx 08 from locality 3, Suanjingzi Basin; Mx 09 from the Suanjingzi East section A–B; and Tu 01 from locality 5, Gongpoquan Basin. Mx 08 and Tu 01 proved to be comparatively rich in palynomorphs. The total palynoflora is made up of abundant gymnospermous pollen (80%). Pteridophytic palynomorphs are common (16%), with nearly equal amounts of schizaeaceous and lygodiaceous spores (Figures 5, 6). Angiospermous taxa are rare (4%) and include some tricolpate pollen grains (Figure 7).

Diverse genera attributed to the Pinaceae dominate the gymnospermous component (Figure 7): *Piceapollenites*, *Pinuspollenites*, *Abietinaepollenites*, *Abiespollenites*,

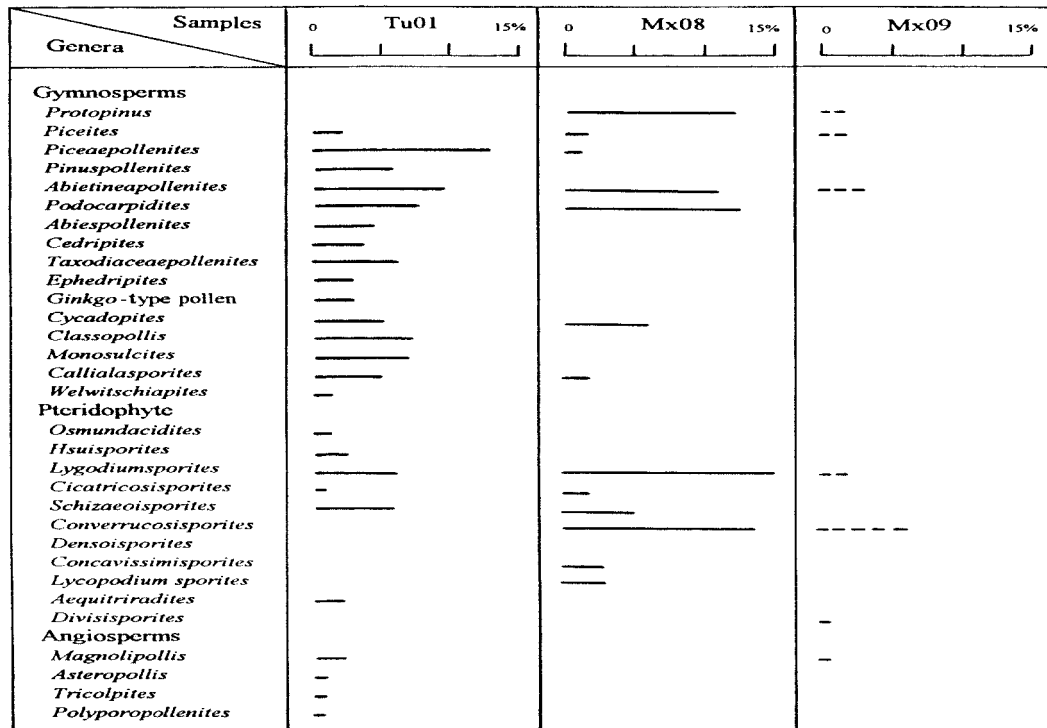


Figure 5. Taxonomic distribution and relative abundance of components of the palynoflora from the green shale or marl of the lower parts of the Xinminbao Group in the Mazongshan area. Sample Mx 08 is from near the ankylosaurid site, Suanjingzi Basin; Mx 09 is from the eastern Suanjingzi Basin section; Tu 01 is from Laobugou sites in the Gongpoquan Basin. The pteridophyte spore *Crybelosporites* sp., and angiospermous *Retitricolpites* sp. are rare, and not included in this distribution chart.

Cedripites, and *Monosulcites* along with a few other primitive representatives of the Coniferales, such as *Classopollis* and *Piceites*. Pollen of the Cycadales, Ginkgoales, Podocarpaceae and Taxodiaceae are also common (*Cycadopites*, *Podocarpites*, *Taxodiaceapollenites* and *Ginkgo-type*). The pteridophytic spores are dominated by *Cicatricosisporites*, *Schizaeoisporites* and *Lygodiumsporites*.

The angiosperm pollen species (Figures 5, 7) suggest a late Early Cretaceous age, possibly Albian (see Agasie, 1969; Hsu *et al.*, 1974; Chiang & Young, 1978; Song *et al.*, 1981; Miao, 1982; Wang, 1982; Yu *et al.*, 1982; Song, 1986; Wang & Yu, 1987; Yu, 1989, 1990a, b; El Beialy, 1993; Brenner, 1996; Taylor & Hickey, 1996; Hicks *et al.*, 1999). The composition of the gymnosperm and pteridophyte assemblages is consistent with this determination.

The taxonomic composition of the Mazongshan samples is similar to those of palynological assemblages from other regions in northern China. For example the Lianmuxin Formation in the Tugulu Group in northern Xinjiang has yielded *Cicatricosisporites*, *Schizaeoisporites certus*, *S. kulandyensis*, *Densoisporites*, *Hsuisporites*, *Piceapollenites*, *Cedripites*,

Abietinaepollenites, *Pinuspollenites*, *Classopollis*, *Ephedripites*, *Asteropollis*, and *Tricolpites* (Yu, 1990a). The Fuxin and Jiufutang formations in the Jehol Group of western Liaoning (Yu, 1989) also share the following palynological genera with the Mazongshan assemblages: *Lygodiumsporites*, *Aequitriradites*, *Schizaeoisporites*, *Osmundacidites*, *Asteropollis*, and *Tricolpites*; a few specimens of *Retitricolpites* sp. have also been recorded.

The palynofloras of the lower Xinminbao Group in the neighboring Huahai Basin (Chiang & Young, 1978) and Jiuquan Basin (Hsu *et al.*, 1974) in western Gansu are comparable to the palynological assemblage of the Lower Red Unit and Middle Grey Unit of the Xinminbao Group in that they all include *Lygodiumsporites*, *Cicatricosisporites*, *Schizaeoisporites*, *Lygodiumsporites*, *Monosulcites*, *Classopollis*, *Callialasporites*, *Abietinaepollenites*, *Piceapollenites*, *Cedripites* and the angiosperm *Magnoliapollis*; however, they lack the three other angiosperm taxa (Song, 1986; Yu, 1990b). The presence of more angiosperm palynomorphs in the Lower Cretaceous succession of Mazongshan suggests that this may be younger than the deposits in the Huahai and Jiuquan basins. Similar

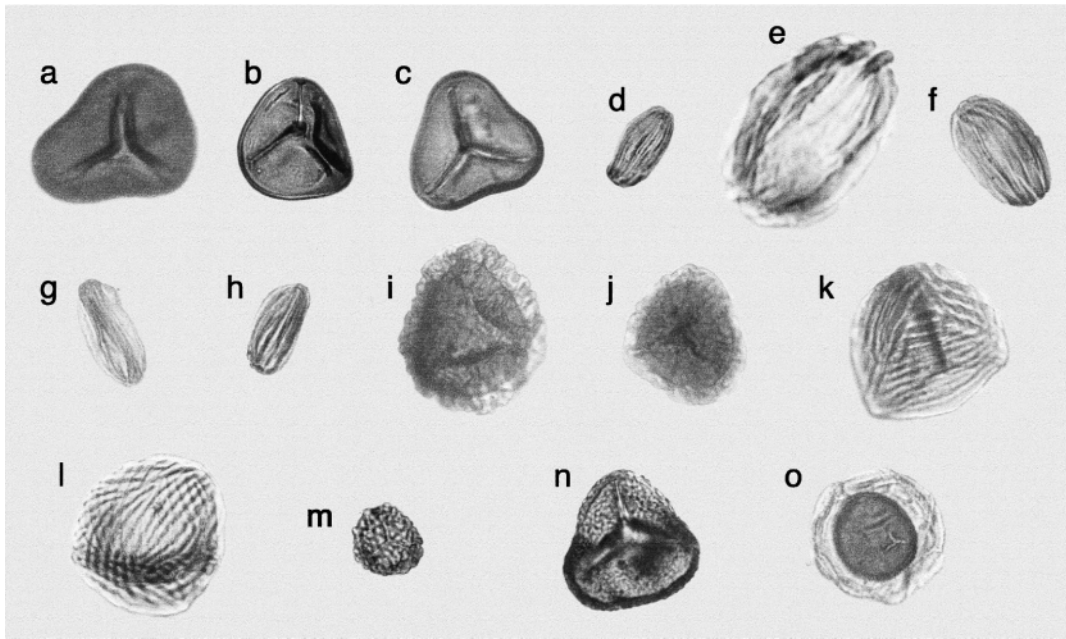


Figure 6. Pteridophyte palynomorphs (sample Tu 01) from the Lower Red Unit: see Figure 4 for stratigraphic horizon and Figure 5 for taxonomic list; all $\times 444$. a–c *Lygodiumsporites subsimplex*; d, *Schizeaoisporites kulandyensis*; e, *Schizeaoisporites disertus*; f–h, *Schizeaoisporites* sp. i, j, *Hsuisporites multiradiatus*; k, l, *Cicatricosisporites myrtellii*; m, *Converrucosisporites* sp., n, *Concavissimisporites minor*, o, *Crybelosporites* sp.

palynological assemblages are also known from the Hekou Formation in the Minhe Basin, Qinghai Province on the Tibetan Plateau (Yu *et al.*, 1982), and the Gecun Formation in the Jurong Basin, Jiangsu Province, southeast China (Song *et al.*, 1981).

Hicks *et al.* (1999) have recently argued that *Asteropollis* and *Tricolpites* are stratigraphically important palynomorphs, and that their presence in middle latitude sites in central Asia indicates an age of Middle–Late Albian. They suggested that the Cretaceous sediments of the Khuren Dukh site in east central Mongolia should be Albian, based on these two taxa. Because they are also present in the ceratopsian graveyard and Laobugou localities in the Xinminbao Group (Figure 7), it is reasonable to also date these two most fossiliferous sites as Albian.

The grey shales in the Middle Grey Unit have yielded fragmentary megaplant fossils, including *Coniopteris* sp., which is widely distributed in the flora of northern China from the Upper Jurassic–Lower Cretaceous, such as in the Jehol flora in Liaoning Province.

3.2. Invertebrate palaeontology

The conchostracans *Yanjiestheria hanhsiaensis*, *Y. cf. yumenensis* and *Eosestheria* sp. have been recorded

from vertebrate fossil locality 5 (Figures 4, 5). These taxa range from latest Jurassic to mid-Gallic (Albian) age (Wang, 1985; pers. comm., 1998). The insect *Ephemeropsis trisetalis* is also present in shales of the Middle Grey Unit. *Eosestheria* and *Ephemeropsis* are key representatives of the Jehol faunas in eastern China (Chen, 1983; Chen & Chang, 1994). Abundant fossil gastropods have also been collected, but these have not yet been identified and so provide no further information about the age of the deposits.

The conchostracans and insects clearly indicate strong affinities between the faunas of Mazongshan and the Jehol biotas in northeastern China (Chen, 1983; Chen & Chang, 1994). During the Late Jurassic–Early Cretaceous, the invertebrate fauna of Mazongshan was a part of the Junggar–North China biogeographical province (Yin, 1988).

3.3. Vertebrate palaeontology

The first vertebrate fossil reported from the Mazongshan area was that of an iguanodontid, which was recovered by the Chinese Academy of Sciences in 1986 (Dong, 1997a). The Sino-Japanese Silk Road Dinosaur Expedition of 1992 collected numerous vertebrate remains including dinosaurs and crocodiles in the Gongpoquan and Suanjingzi basins (Dong,

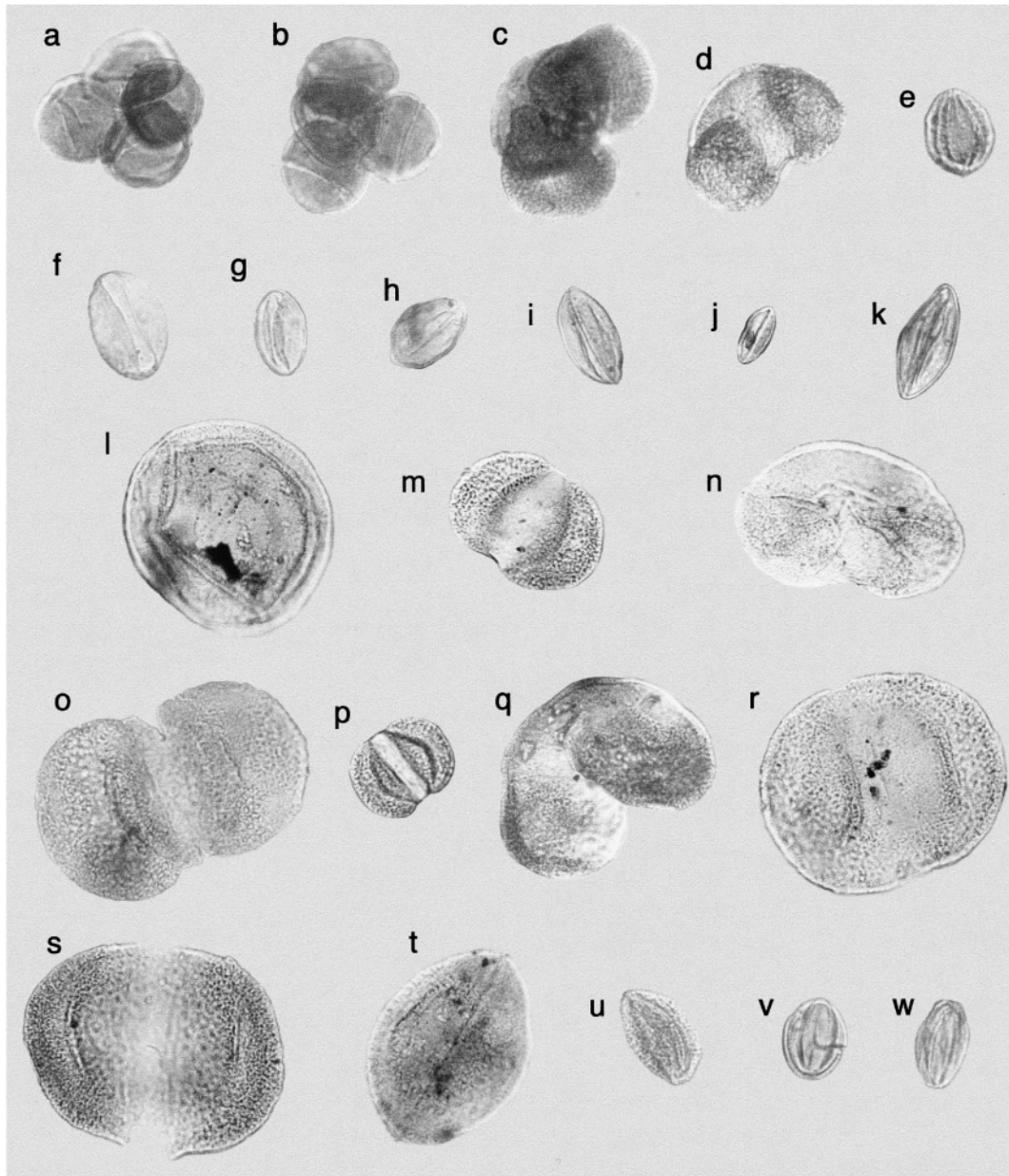


Figure 7. Gymnosperm and angiosperm palynomorphs (sample Tu 01; see explanation of Figure 6 for comments) from the Lower Red Unit; all $\times 444$. Gymnosperms: a, b, *Classopollis* sp., c, d, *Pinuspollenites* sp., e, *Ephedripites rotundus*, f–k, *Cycadopites* sp., l, *Perinopollenites* sp., m, *Albietinaepollenites* sp., n, *Piceapollenites* sp., o, p, *Podocarpidites* sp., q, *Cedripites* sp., r, *Piceites* sp., s, *Pseudopicea* sp. Angiosperms: t, u, *Retitricolpites* sp., v, w, *Tricolpites* sp.

1997b). The dinosaurian taxa found in the Mazongshan area (Dong, 1997b) include *Siluosaurus zhangqiani* (Hypsilophodontidae) (Dong, 1997d), *Probactrosaurus mazongshanensis* (Iguanodontidae) (Lu, 1997), *Psittacosaurus mazongshanensis* (Psittacosauridae) (Xu, 1997), *Archaeoceratops oshimai* (Neoceratopsia) (Dong & Azuma, 1997), *Nanshiungosaurus bohlini* (Segnosauria), and a few theropod and sauropod fragments. Ankylosaurids, mamenchisaurids

and well-preserved ornithomids were found during 1998–1999, as were gobiconodontid mammals.

These vertebrate fossils provide important information for correlation with vertebrate assemblages elsewhere in Asia. Psittacosaurids are known only from the Lower Cretaceous of Asia. Phylogenetic analyses of the psittacosaur species show that *Psittacosaurus mazongshanensis* and *P. xinjiangensis* are sister species. This clade is more closely related to

P. mongoliensis (Mongolia and Siberia) than the chronologically older *P. sinensis*, *P. meilyingensis* and *Chaoyangsaurus* from eastern China (Xu, 1997; Zhao *et al.*, 1999). *P. mongoliensis* is also known from a series of other sites in Mongolia, including Khoobur (Jerzykiewicz & Russell, 1991), and from the Shestakovo site in Siberia (Maschenko & Lopatin, 1998). It is generally regarded as Aptian–Albian in age (Barsbold & Perle, 1984; Weishampel, 1990; Dodson, 1996).

The type specimen of *Archaeoceratops oshimai* is represented by a nearly complete skull associated with an incomplete skeleton (Dong & Azuma, 1997). Additional incomplete skulls and several associated partial skeletons were discovered during the 1998 and 1999 field seasons. Recent phylogenetic analysis confirms that *Archaeoceratops* is more derived than *Psittacosaurus* and furthermore shows that *Archaeoceratops* is the most primitive taxon of the neoceratopsian clade (You *et al.*, 1999). *Archaeoceratops* is represented by the best material among all basal neoceratopsians, some of which have broad distributions in the Lower Cretaceous of Mongolia and northern China (Dodson, 1996; Sereno, 1997, 1999).

Two complete teeth (a premaxillary tooth and a maxillary tooth) are referred to *Siluosaurus*, a new taxon of the Hypsilophodontidae (Dong, 1997d). Hypsilophodontids have several representatives in Lower Cretaceous. These include *Hypsilophodon* in the Lower Cretaceous (Barremian–Aptian) of England and Spain, and probably also in the Lower Cretaceous of Texas, USA. The hypsilophodontid *Zephyrosaurus* is from the Lower Cretaceous (Aptian–Albian) Cloverly Formation of Montana, USA, and *Leaellynasaura* is from the Lower Cretaceous (Aptian–Albian) of Australia (Rich & Rich, 1989). Among iguanodontids, *Proactrosaurus mazongshanensis* (Lu, 1997) was recovered from the siltstone and silty sandstone in the Middle Grey Unit of the Mazongshan area in 1992. It is noteworthy that most of the known iguanodontids have been recorded from Lower Cretaceous deposits in Europe, Asia and Australia.

Three teeth and a caudal vertebra of sauropods from the uppermost part of the Xinminbao Group are similar to those of nemegtosaurids from the Upper Cretaceous of Mongolia and the Albian of Normandy, France, and are tentatively referred to the Nemegtosauridae (Dong, 1997e). However, nemegtosaurids are diagnosed by apomorphies of the mandible and the temporal region of the skull (Upchurch, 1998, 1999), which are not preserved in the fossils from the Mazongshan area. Thus the

isolated teeth of ‘nemegtosaurid sauropods’ provide no information for correlation.

Additional sauropod material, referable to the Mamenchisauridae, was collected in 1999 (study in progress). Mamenchisaurids are common elements of the dinosaurian faunas in the Upper Jurassic of China (Dong, 1992; Russell, 1993). They are endemic to Asia (Russell, 1993). Upchurch (1995, 1998) proposed that they are nested within the euhelopodid clade. Most euhelopodids are from the Upper Jurassic, and were probably endemic to Asia. However, the euhelopodid clade is questioned by Wilson & Sereno (1998). In any case, mamenchisaurids in the Xinminbao Group resemble older sauropod assemblages elsewhere in China. The relationship between the mamenchisaurid fossils in the Xinminbao Group and other mamenchisaurids requires further study.

The most notable fossil mammal is a new taxon of the Gobiconodontidae (study in progress) from two stratigraphic levels. Teeth and skull fragments of gobiconodontids were discovered in the Lower Red Unit. One isolated upper molar of gobiconodontid is known from the Middle Grey Unit. *Gobiconodon* has three known species (Trofimov, 1978; Jenkins & Schaff, 1988; Kielan-Jaworowska & Dashzeveg, 1998). *Gobiconodon borissiaki* and *G. huborensis* have been recorded from the Khoobur locality in Guchin-Uus Pre-Altai (North) Gobi, Mongolia (Trofimov, 1978; Kielan-Jaworowska & Dashzeveg, 1998). *G. huborensis* is present at the Shestakovo site in Kemerovo Province of western Siberia, Russia (Maschenko & Lopatin, 1998). *Gobiconodon ostromi* (Jenkins & Schaff, 1988) is known from the Cloverly Formation in Montana. All sites yielding *Gobiconodon* have been regarded as Aptian–Albian in age. However, so far no therian or multituberculate mammals have been found in the Lower Cretaceous of Mazongshan, in marked contrast to more diverse therian and multituberculate mammalian faunas in the northern (Pre-Altai) Gobi sites in Mongolia (Dashzeveg, 1979, 1994; Trofimov, 1980; Dashzeveg & Kielan-Jaworowska, 1984; Kielan-Jaworowska *et al.*, 1987; Kielan-Jaworowska & Dashzeveg, 1989; Wible *et al.*, 1995), and in the Jehol Group of Liaoning, northeast China (Wang *et al.*, 1995; Hu *et al.*, 1997; Ji *et al.*, 1999b). Mammals in the Xinminbao Group are less diverse than in the Aptian–Albian Cloverly Formation (Cifelli *et al.*, 1998; Cifelli, 1999).

4. Geological age

Until now the precise age of the terrestrial red beds of Mazongshan area has been uncertain. The

published Chinese geologic maps (1:200,000) for the Mazongshan area were surveyed in 1969 (Bureau of Geology and Mineral Resources of Inner Mongolia, 1991). These incorrectly referred the clastic sequence of the Xinminbao (=Chijinbao) Group of the Mazongshan area to the Upper Jurassic. This situation did not change until very recently when vertebrate palaeontological work suggested that the deposits are of Early Cretaceous age and comparable to the 'Xinminbao Group' in the Jiuquan (Chiuchuan) Basin (Dong, 1997c).

Our new data from the invertebrates, vertebrates and megafossil plants suggest that the Xinminbao Group in Mazongshan ranges from Barremian to Albian in age. The *Eosetheria-Ephemeropsis* invertebrate assemblage, now known from the Middle Grey Unit, is best documented in the Jehol fauna in Liaoning Province. The Yixian Formation has a rich fossil record of the Jehol fauna (Chen, 1983; Chen and Chang, 1994). The middle part of the Yixian formation is now dated to 126 Ma (Swisher *et al.*, 1999) and can, therefore, be correlated with the Barremian in the standard marine sections of Europe (Gradstein *et al.*, 1995). By correlation of *Eosetheria* and *Ephemeropsis* occurrences, the lower part of the Xinminbao Group could well be Barremian.

The best available evidence for the age is from palynomorphs. The composition of spores referable to the Schizaeaceae and Lygodiaceae are typical of other Barremian–Aptian deposits elsewhere in China (Hsu *et al.*, 1974). The presence of the Schizaeaceae clearly rules out a Jurassic age for the lower part of the Xinminbao Group in the Mazongshan area. Moreover, Late Cretaceous pteridophyte assemblages are characterized by the dominance of Schizaeaceae and very few or no spores of the Lygodiaceae. Hence, the almost equal proportions of spores of the Lygodiaceae and Schizaeaceae also rule out a Late Cretaceous age.

The composition of the gymnosperm taxa from the Lower Red Unit and Middle Grey Unit is consistent with a Late Barremian–Albian determination. The presence of small amounts (4%) of pollen of four angiosperm species rule out a pre-Barremian age (Song, 1986; Yu, 1990b; Taylor & Hickey, 1996; Brenner, 1996; Hicks *et al.*, 1999; but see Sun *et al.*, 1998 who argued for an earlier origin of angiosperms). On the other hand, the abundance of angiosperm pollen is far below the level of 10% of the total palynoflora that is typical of the Late Cretaceous angiosperm assemblages (Song, 1986; Yu, 1990b), thus precluding a Late Cretaceous age for the Xinminbao Group. As discussed earlier, the presence of *Asteropollis* sp. and *Tricolpites* sp. (Hicks *et al.*, 1999), suggests that the main fossil sites might well be Albian.

The independent data from the invertebrates are consistent with an interpretation that the lower part of the group is Barremian–Albian. The upper part of the group has not yielded invertebrate fossils.

The best available evidence from vertebrate fossils is from the ceratopsian dinosaurs *Psittacosaurus mazongshanensis* and *Archaeoceratops oshimai*. *P. mazongshanensis*, *P. xinjiangensis*, and *P. mongoliensis* are closely related (Xu, 1997). The distribution of *P. mongoliensis* has been found to be widespread in several Aptian–Albian sites. *Archaeoceratops* is the most primitive among neoceratopsians, and forms the sister taxon to a clade of all other neoceratopsians. Neoceratopsians first appeared during the latest part of the Early Cretaceous. The evolutionary grade of ceratopsians is suggestive of late Early Cretaceous.

5. Palaeoenvironment

In both the Gongpoquan and Suanjingzi basins, the outcrops of the sediments are smaller in surface exposure and the dip of their strata is greater (*c.* 10° NE–N) to the north than in the south where the exposure is extensive and the dip is shallower (3°–5° NE–N) on the southern side of the basins. We interpret the palaeogeographic scene to be generally multigeomorphic, comprising mountains and lowlands. The main dinosaur and mammal sites are near the foothills of the mountain ranges formed of the Palaeozoic volcanic rocks on the basin margins. In the Cretaceous, the Mazongshan area was situated at about the same palaeolatitude as today (Chen *et al.*, 1996).

Our preliminary analysis suggests that the main sedimentary sequences at Mazongshan were deposited in a fluvio-lacustrine environment (Tang *et al.*, 1998). The Lower Red Unit represents river channel beds and alluvial fan deposits near foothills formed by the Palaeozoic volcanics around the basin margin in a generally warm, arid climate. During the latest Jurassic and Cretaceous periods, the climate in northern China and Mongolia was warmer than today (Francis & Frakes, 1993; Barron *et al.*, 1994), resulting in widespread deposition of red clastics. The Tarim Basin of Xinjiang, Kazakhstan and north China was mostly in a subtropical zone (Yin, 1988). The current consensus is that the climate was both subtropical and semi-arid (Yin, 1988; Chen *et al.*, 1996). However, the new palynological data on pinaceous pollen suggest that there were episodes of more humid, and possibly cooler, climates during the deposition of the Xinminbao Group. The large amounts of Pinaceae pollen in samples Tu 01 and Mx 08 (Lower Red Unit) may have come from coniferous

trees in hilly or intermontane areas where conditions were cooler and more humid (Wang, 1987). Winds and water probably carried them into the wet lowlands that were dominated by plants referable to the Taxodiaceae. The mixed assemblage of spores referable to the Schizaeaceae and Lygodiaceae is not inconsistent with a semi-arid environment. The first appearance of the flowering plants may have been related to the diversification of ornithischians (Lessem, 1996), although this has been questioned (e.g., Sereno, 1999).

The Middle Grey Unit comprises a set of fluvio-lacustrine sediments that probably accumulated in a wetter climate. Fluvial erosion and deposition probably played an important role in the deposition of the dinosaur-bearing sediments, because many sauropod bones appear to be disassociated at the Laobugou site in the lower part of the unit. Conchostracans preserved in the intercalated shales along with fragments of cycadophytes and other plants, gastropods, crocodiles, and turtles, all indicate shallow lacustrine conditions of deposition.

In summary, the climate of the Mazongshan area changed during the deposition of the Xinminbao Group. Most of the Lower Red Unit reflects a warm, arid climate, but its upper part indicates a transition towards a more temperate, wetter climate, as implied by the Middle Grey Unit. The massive silt- and mudstones of the Upper Red Unit that are devoid of fossils probably reflect a further change to warm, semi-arid conditions.

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Appendix

Lithostratigraphic section of the Xinminbao Group (upper Lower Cretaceous) in the eastern part of the Suanjingzi Basin; for geographical location, see Figures 2 and 3.

| | | |
|-----|--|--------|
| | Top of section incomplete, covered by Quaternary deposits or cut by a fault | metres |
| | <i>Upper Red Unit</i> | 62.9 |
| 16. | Purplish red mudstone beds intercalated with four layers of light grey to yellowish grey silty mudstone; upper part consists of silty mudstone with horizontal bedding; bottom part comprises grey sandy siltstone and conglomerate. | 11.8 |
| 15. | Purplish red mudstone alternating with laminated greyish yellow mud- or siltstone. | 7.1 |
| 14. | Red mudstone with three thin layers of light grey muddy siltstone; the top consists of a thin layer of silty mudstone with greenish grey bands. | 15.2 |
| 13. | Red mudstone with five thin layers of light grey muddy siltstone; the base (1.8 m thick) consists of thin layers of light grey sandstone. | 28.8 |
| | <i>Middle Grey Unit</i> | 58.2 |
| 12. | Thin silty mudstone with red colour band, intercalated with three layers of laminated light grey muddy siltstone. | 13.6 |
| 11. | Laminated light grey siltstone alternating with greenish grey muddy siltstone, forming three graded sequences. | 14.7 |
| 10. | Yellowish grey sandstone and siltstone intercalated with two thin layers of light grey silty mudstone. | 13.4 |
| 9. | Light grey siltstone, with a thin sandstone bed and gravel 3–12 cm in diameter at the bottom. | 5.7 |
| 8. | Light grey muddy siltstone intercalated with laminated beds of yellowish grey siltstone; imbricated structures of thin layers of fine sandstone near base. | 10.8 |
| | <i>Lower Red Unit</i> | 38.2 |
| 7. | Red mudstone with thin layers of light grey muddy siltstone; the top consists of a thin layer of red silty mudstone. | 6.2 |
| 6. | Laminated red mudstone alternating with yellowish grey silty siltstone mudstone. | 7.2 |
| 5. | Light purple mudstone (0.4 m thick) in the lower part, red siltstone beds (3.4 m thick) in the middle part, yellowish grey silty mudstone (0.8 m thick) in the upper part. | 4.6 |
| 4. | Red mudstone and muddy siltstone with a thin, light grey sandstone in the lower part, red siltstone with horizontal stratification in the upper part. | 5.9 |
| 3. | Yellow to yellowish grey muddy siltstone, slightly cross-bedded. | 4.6 |
| 2. | Yellowish grey and light grey conglomerate in the lower part, with horizontal stratification, containing bean-shaped and rounded pebbles; fine sandstone in the upper part; red siltstone and mudstone at the top. | 3.0 |
| 1. | Light grey fine sandstone, thin layer of light grey sandstone with gravel at the base. | 6.7 |
| | --Unconformity-- | |
| | Underlying strata: Precambrian slate or Palaeozoic granite. | |