$^{40}Ar/^{39}Ar$ dating of Lujiatun Bed (Jehol Group) in Liaoning, northeastern China

H. Y. He,[1] X. L. Wang,[2] Z. H. Zhou,[2] F. Jin,[2] F. Wang,[1] L. K. Yang,[1] X. Ding,[3] A. Boven,[4] and R. X. Zhu[1]

Received 22 November 2005; revised 7 January 2006; accepted 18 January 2006; published 24 February 2006.

[1] The Lujiatun bed of the Yixian Formation is famous for its extraordinary preservation of three-dimensional fossils and its implication for the most dramatic catastrophic mass mortality event in the Jehol Biota. The precise age of the fossil bearing deposits, however, remains to be established. $^{40}Ar/^{39}Ar$ step heating analyses on bulk K-feldspars from the fossil bearing tuff gave a weighted mean age of 123.2 ± 1.0 Ma (2σ). This date suggests the Lujiatun bed was most likely deposited at about the same time as the Jianshangou bed of the lower Yixian Formation, representing a stage when the dinosaurs displayed the most significant radiation in the Early Cretaceous. **Citation:** He, H. Y., X. L. Wang, Z. H. Zhou, F. Jin, F. Wang, L. K. Yang, X. Ding, A. Boven, and R. X. Zhu (2006), $^{40}Ar/^{39}Ar$ dating of Lujiatun Bed (Jehol Group) in Liaoning, northeastern China, *Geophys. Res. Lett.*, *33*, L04303, doi:10.1029/2005GL025274.

1. Introduction

[2] The Lujiatun bed of the Yixian Formation has usually been considered as the lowermost fossil-bearing horizon of the Jehol Group in western Liaoning Province, China [*Wang et al.*, 2001; *Zhou et al.*, 2003]. This bed has recently become important for paleontologists and geologists mainly for its extraordinary preservation of three-dimensional fossils, that is, dinosaurs and mammals, which contain anatomical and behavior information (such as parental care and sleeping posture of dinosaurs, and mammals eating dinosaurs) that is rarely preserved in other beds of the Jehol Group [*Meng et al.*, 2004; *Xu and Norell*, 2004; *Hu et al.*, 2005], and for its implication for the most dramatic catastrophic mass mortality event in the Jehol Biota.

[3] Despite the significant and high profile biological discoveries, the stratigraphic position and age of the fossil-bearing sediments in the Jehol Group is not yet fully resolved. Although much progress has been made in dating the Jianshangou bed of the Yixian Formation (124.6 ± 0.3 Ma; 125.0 ± 0.2 Ma) [*Swisher et al.*, 1999, 2002] and the Jiufotang Formation (120.3 ± 0.7 Ma) [*He et al.*, 2004] in recent years, little is known about the exact age of the Lujiatun bed, one of the richest fossil-bearing horizons in the Jehol Group. Many workers consider it as the lowest horizon or the first volcanic cycle of the Yixian Formation [*Wang and Zhou*, 2003; *Zhou et al.*, 2003] whereas other researchers have suggested that the Lujiatun bed is younger than the Yixian Formation [*Ji*, 2003]. Still other researchers have suggested that the Lujiatun bed represents a different sedimentary facie of the Jianshangou bed of the lower Yixian Formation [*Chen et al.*, 2005].

[4] The age of the Lujiatun bed was tentatively proposed to be older than 128Ma (Hauterivian) [*Wang et al.*, 2001] based on a $^{40}Ar/^{39}Ar$ date of the basalt presumably capping the Lujiatun bed at the Huangbanjigou section, which is about 6 km from the Lujiatun locality. However, the relationship between the Huanbanjigou basalt and the fossil-bearing tuffs of the Lujiatun bed is ambiguous, thus the age of the Lujiatun bed remains questionable. To clarify this contentious issue and obtain the direct age of Lujiatun bed, we undertook $^{40}Ar/^{39}Ar$ step heating experiments on K-feldspar from the fossil-bearing tuff at the Lujiatun locality in Beipiao, Liaoning. In this paper we report the result of this study and discuss its implications for correlation of the Lujiatun bed with other Jehol deposits and evolution of the Jehol Biota.

2. Sampling

[5] The Lujiatun fossils are preserved in thick tuff exposed close to the Lujiatun village, (120°54′41″E, 41°36′26″N), Shangyuan, Beipiao City, Liaoning Province, northeastern China (Figure 1a). From the bottom to top, the stratigraphic sequence (Figure 1b) of this locality consists of conglomerates of the Tuchengzi Formation, a bottom conglomerate, which unconformably overlies the Tuchengzi Formation, and fossil-bearing tuffs with a thickness of 5 to 20 meters, without bedding planes, suggesting that this sediment resulted from a rapid deposition of volcanic debris. The reddish lava overlies the tuffs, and the ~20cm baking contact zone is very clear. Samples L3003 and L3004 were collected from the middle and upper part of the tuffs (Figure 1b). Field excavations by the Institute of Vertebrate Paleontology and Paleoanthropology of the Chinese Academy of Sciences in 2000 resulted in the discoveries of hundreds of vertebrate fossils including dinosaurs, lizards and mammals in these tuffs [*Wang and Zhou*, 2003].

[6] Thin section studies show that sample L3003 and L3004 are composed of sanidine and orthoclase, plagioclase, quartz, altered biotite as well as accessory minerals such as zircon and opaque minerals. K-feldspars (sanidine and orthoclase) are fresh and therefore chosen for analysis.

3. Method

[7] Tuff samples were crushed and sieved between 40–80 mesh (380–200 μm) fractions, and washed with distilled

[1]Laboratory of Paleomagnetism and Geochronology (SKL-LE), Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China.
[2]Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, China.
[3]Marine School, Chinese University of Geosciences, Beijing, China.
[4]Brussels, Belgium.

0094-8276/06/2005GL025274$05.00

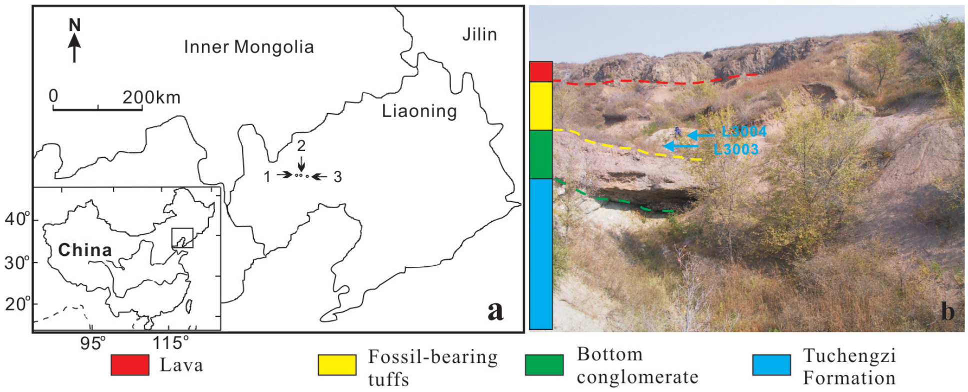

Figure 1. (a) Sketch map showing the location of Lujiatun section in western Liaoning. 1 is Huangbanjigou locality, 2 is Jianshangou locality and 3 is Lujiatun locality. (b) Field photo showing the stratigraphic sequence of Lujiatun locality. From bottom to top, this section consists of the Tuchengzi Formation, bottom conglomerate and fossil-bearing tuffs of Lujiatun Formation, and the reddish lava. Hundreds of vertebrate fossils including dinosaurs, lizards and mammals have been discovered in fossil-bearing tuffs with a thickness of 5 to 20 meters.

water. After heavy liquid separation the K-feldspars (sanidine and orthoclase) were obtained and washed with acetone in an ultra-sonic bath for 20 minutes and rinsed several times with acetone.

[8] Cleaned K-feldspars were wrapped in Al foil and irradiated together with Ga1550-biotite standards, optical CaF_2 and K-glass monitors in position H8 of the 49-2 reactor, Beijing, China, for 47.5 hours with 0.5mm cadmium foil shield. The fast neutron dose is about 1.1×10^{18}n/cm^2.

[9] ^{40}Ar/^{39}Ar step-heating analysis by furnace was performed at the Laboratory of Paleomagnetism and Geochronology (SKL-LE) at the Chinese Academy of Sciences, Beijing, on a MM5400 mass spectrometer operating in a static mode. The total system blanks (1000°C, 20 minutes) were in the range of $4.9–5.8 \times 10^{-16}$ moles for mass 40, $0.9–1.4 \times 10^{-18}$ moles for mass 39, $8.7–9.2 \times 10^{-19}$ moles for mass 37, and $1.8–2.1 \times 10^{-18}$ moles for mass 36. Mass discrimination (0.009934–0.009958 per atomic mass unit) was monitored by everyday analysis of ^{40}Ar/^{36}Ar air pipette aliquots. Ca, K correction factors were calculated from the CaF_2 and K-glass monitors: $(^{40}Ar/^{39}Ar)_K = 1.13 \times 10^{-2}$, $(^{39}Ar/^{37}Ar)_{Ca} = 7.24 \times 10^{-4}$, $(^{36}Ar/^{37}Ar)_{Ca} = 2.39 \times 10^{-4}$. The data were corrected for system blanks, mass discriminations, interfering Ca, K derived argon isotopes, and the decay of ^{37}Ar since the time of the irradiation. The decay constant used throughout the calculations is $\lambda = (5.543 \pm 0.010) \times 10^{-10}$ a^{-1}, as recommended by *Steiger and Jäger* [1977]. The uncertainty of J-value (0.5% in this work) is one standard deviation of mean and was propagated into the final plateau and isochron ages, and contributes about 40% to the total uncertainty in these age determinations. The uncertainties of the ages were reported as internal error and external error, where internal error combines the analytical error and the error on the J-value, external error adds the systematic error on the total decay constant λ. Internal error could be used for the comparison of ^{40}Ar/^{39}Ar ages based on the same standard intercalibration and external error could be used for the comparison to ages derived from other methods. We use the reference age 98.79 ± 0.96 Ma [*Renne et al.*, 1998] for GA-1550 biotite standard. Details of the step-heating analysis were outlined by *He et al.* [2004]. The plateau and isochron ages were calculated using ArArCALC [*Koppers*, 2002]. The results of the ^{40}Ar/^{39}Ar experiments (see auxiliary material[1]) are plotted as age spectrum and isotope correlation diagrams in Figure 2 and Figure 3.

4. Results

[10] The K-feldspar separated from sample L3003 yields a slightly disturbed age spectrum with small percentages of low temperature gas giving younger ages and high temperature gas giving slightly older ages than the weighted mean plateau ages (Figure 2a). The discordant, lower temperature steps may indicate minor argon loss because of alteration, while slightly older steps may reflect poorly characterized high temperature blanks. Despite these discordances, seven consecutive steps, which account for 75.1% of the total ^{39}Ar released, define a plateau age of 123.0 ± 1.4 Ma (internal error, 2σ; external error = 1.5 Ma, 2σ). An inverse isochronal age of 123.5 ± 1.5 Ma (internal error, 2σ; external error = 1.6 Ma, 2σ), calculated from all steps that formed the plateau, is in agreement with the plateau age. The ^{40}Ar/^{36}Ar intercept of 291.8 ± 5.2 (2σ) is not distinguishable from the air ratio, and MSWD = 1.36 (Figure 2b).

[11] The K-feldspar separated from sample L3004 gives a nearly concordant age spectrum (Figure 3a). Nine consecutive steps, which account for 77.9% of the total ^{39}Ar released, define a plateau age of 123.3 ± 1.3 Ma (internal error, 2σ; external error = 1.4 Ma, 2σ). An inverse isochron age of 123.1 ± 1.5 Ma (internal error, 2σ; external error = 1.5 Ma, 2σ), calculated from all steps that formed the plateau, is in agreement with the plateau age. The ^{40}Ar/^{36}Ar intercept of 298.0 ± 7.3 (2σ) is not distinguishable from the air ratio, and MSWD = 1.33 (Figure 3b). Since the isochron ages are from the same minerals in the same tuff, they are combined into a single inverse-variance weighted mean age of 123.2 ± 1.0 Ma (2σ, MSWD = 0.24).

[12] These experiments on bulk K-feldspar (sanidine and orthoclase) may not be sufficient to reveal small amounts of potential xenocrystic or detrital contamination of the age by

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL025274.

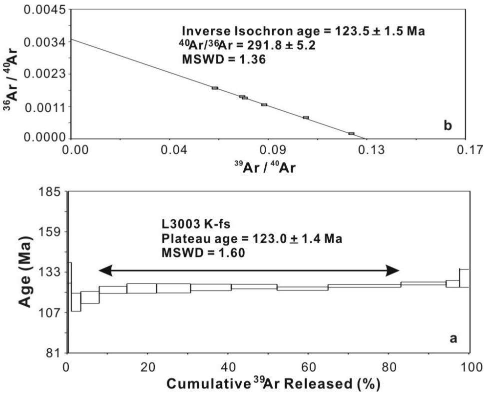

Figure 2. (a) Age spectrum of K-feldspar separate from sample L3003. (b) Inverse isochron plot of K-feldspar separate from sample L3003.

older crystals, but the good agreement between the ages of sample L3003 and L3004 indicates that the probability of contamination is low, although the possibility of subtle xenocrystic contamination cannot be ruled out. The concordant age spectra, uniform K/Ca ratio (see auxiliary material), and the atmospheric $^{40}Ar/^{36}Ar$ intercept value indicate that there is no apparent alteration and excess argon contamination, therefore, 123.2 ± 1.0 Ma(2σ) reflect the time since eruption of fossil-bearing tuff in the Lujiatun bed.

5. Discussion and Conclusions

[13] $^{40}Ar/^{39}Ar$ step heating of the K-feldspar from the tuffs of the Lujiatun locality provides the first direct age for the fossil-bearing sediments of the Lujiatun bed. Our result (123.2 ± 1.0 Ma, Aptian) does not support previous assumptions that the bed is much older than the Jianshagou bed [*Wang et al.*, 2001], It also questions the estimate of 18 Ma duration for the Jehol Biota [*Zhou et al.*, 2003]. We use the reference age 98.79 ± 0.96 Ma [*Renne et al.*, 1998] for GA-1550 biotite standard to calculate our results, so the age can be compared directly with the $^{40}Ar/^{39}Ar$ age for the Jianshangou tuff which is 124.6 ± 0.3 Ma (1σ) and 125.0 ± 0.2 Ma (1σ) with a relative age of 28.02 Ma for Fish Canyon Sanidine monitor mineral [*Swisher et al.*, 1999, 2002]. Thus our dates are in agreement with the age of the Jianshangou bed at the 95% confidence level and we believe the Lujiatun bed was most likely deposited at the same time as the Jianshangou bed of the lower Yixian Formation.

[14] Unlike most of the other fossil-bearing deposits of the Jehol Group that comprises shales or mudstones with interbedded tuffaceous layers, the Lujiatun bed comprises fossil-bearing tuffs without obvious bedding planes, which recorded a single catastrophic mass mortality event in the Early Cretaceous, usually nicknamed as the "Cretaceous Pompeii" [*Zhou et al.*, 2003]. As a result, many vertebrates are preserved three-dimensionally, and more importantly as many of them were killed in life and buried without much postmortem transportation, we are able to reconstruct the habit and behavior of these ancient lives. For instance, Psittacosaurus, the most common herbivorous ornithischian dinosaur in the Jehol Biota, is also abundant in the Lujiatun bed. And in one extreme case it was preserved as an aggregation of one adult and 34 juveniles, indicating the presence of post-hatching parental care in dinosaurs, a homologous character among crocodilians and birds [*Meng et al.*, 2004].

[15] A troodontid dinosaur, Mei, was even preserved with a sleeping posture similar to birds, adding further evidence for the dinosaurian origin of birds [*Xu and Norell*, 2004]. Other dinosaurs from the bed also include Hongshanosaurus, an psittacosaurid [*You et al.*, 2003], Jeholosaurus an ornithopod [*Xu et al.*, 2000], Incisivosaurus, a specialized herbivorous oviraptorosaur [*Xu et al.*, 2002a], Liaoceratops, the most basal neoceratopsian (horned dinosaur) [*Xu et al.*, 2002b], Sinovenator, a basal troodontid [*Xu et al.*, 2002c], Graciliraptor, a dromaeosaurid [*Xu and Wang*, 2004a], Sinucerasaurus, another troodontid [*Xu and Wang*, 2004b], and Dilong, a basal tyrannosaurid [*Xu et al.*, 2004]. Since many dinosaurs have also been described from the Jianshangou bed (i.e., Caudipteryx, Sinosauropteryx, Sinornithosaurs, Beipiaosaurus etc.), our conclusion that the Lujiatun and the Jianshangou beds are contemporaneous suggests that the lower Yixian Formation (late Barremian - Aptian) records the most diverse dinosaur assemblage known from the Jehol Biota, and the most significant and rapid dinosaur radiation in the Early Cretaceous.

[16] More mammals have been preserved in the Lujiatun bed than in any other horizons of the Jehol Group. Repenomamus is recognized as the largest mammal of the Mesozoic, and shows an ossified Meckel's cartilage with bearing on the origin of the mammalian middle ear [*Li et al.*, 2001; *Wang et al.*, 2001]. Further, one specimens of Repenomamus preserved a baby dinosaur, Psittacosaurus, in its stomach, providing the first direct evidence for a mammal eating a dinosaur, adding to our knowledge of the diet diversification of early mammals [*Hu et al.*, 2005]. Gobiconodon is another mammal preserved in the Lujiatun bed [*Li et al.*, 2003]. In addition to dinosaurs and mammals, the Lujiatun bed also preserved a number of lizards and frogs, many of which await to be described.

[17] Finally, recent biostratigraphic and isotope dating has shown that the Jehol Biota had experienced early, middle and late stages of the evolution, as represented by the fossil assemblages from the Dabeigou Formation, about 131 Ma [*Liu et al.*, 2003; H. He et al., $^{40}Ar/^{39}Ar$ dating of

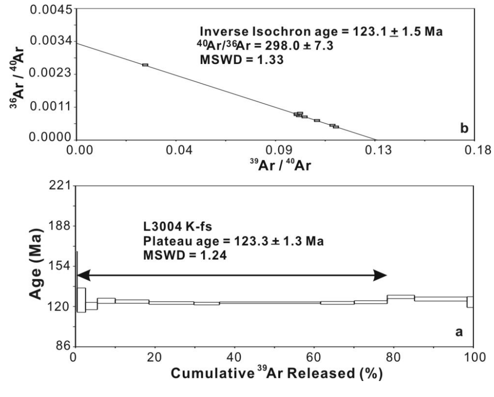

Figure 3. (a) Age spectrum of K-feldspar separate from sample L3004. (b) Inverse isochron plot of K-feldspar separate from sample L3004.

the early Jehol Biota from Fengning, Hebei Province, northern China, submitted to *Geochemistry, Geophysics, Geosystems,* 2005], Yixian Formation, about 125 Ma [*Swisher et al.*, 1999, 2002] and Jiufotang Formation, about 120 Ma [*He et al.*, 2004], respectively [*Chen*, 1999; *Tian et al.*, 2004; *Zhou*, 2006], therefore, the Lujiatun bed no longer represents the lowermost horizon of the Jehol Group. As part of the lower Yixian Formation, the Lujiatun bed and the Jianshangou bed, which are nearly contemporaneous, represent the beginning of the major radiations of the Jehol Biota, a process that has lasted for at least 5 Ma from 125 to 120 Ma [*Swisher et al.*, 1999, 2002; *He et al.*, 2004].

[18] **Acknowledgments.** We thank F. Zhang, J. Zhang, Y. Wang and Q. Leng for discussion in the field. The authors gratefully acknowledge comments by Brad Singer and an anonymous reviewer, which significantly improved the paper's presentation and accuracy. This work was supported by the NSFC (40221402, 40121202, 40573040) and Chinese Academy of Sciences (KZCX3-SW-142).

References

Chen, P. J. (1999), Distribution and spread of the Jehol Biota (in Chinese), *Palaeoworld*, *11*, 1–5.

Chen, P. J., Q. F. Wang, H. C. Zhang, M. Z. Cao, W. B. Li, S. Q. Wu, and Y. B. Shen (2005), Jianshangou bed of the Yixian Formation in west Liaoning, China, *Sci. Chin. Ser. D*, *48*, 298–312.

He, H. Y., X. L. Wang, Z. H. Zhou, F. Wang, A. Boven, G. H. Shi, and R. X. Zhu (2004), Timing of the Jiufotang Formation (Jehol Group) in Liaoning, northeastern China and its implications, *Geophys. Res. Lett.*, *31*, L12605, doi:10.1029/2004GL019790.

Hu, Y. M., J. Meng, Y. Q. Wang, and C. K. Li (2005), Large Mesozoic mammals fed on young dinosaurs, *Nature*, *433*, 149–152.

Ji, Q. (2003), Progress and discusion, in *Mesozoic Jehol Biota of Western Liaoning, China* (in Chinese), edited by Q. Ji, pp. 346–351, Geological, Beijing.

Koppers, A. A. P. (2002), ArArCALC—Software for ^{40}Ar/^{39}Ar age calculations, *Comput. Geosci.*, *28*, 605–619.

Li, C. K., Y. Q. Wang, Y. M. Hu, and J. Meng (2003), A new species of Gobiconodon (Triconodonta, Mammalia) and its implication for the age of Jehol Biota, *Chin. Sci. Bull.*, *48*, 1129–1134.

Li, J. L., Y. Wang, Y. Q. Wang, and C. K. Li (2001), A new family of primitive mammal from the Mesozoic of western Liaoning, *China, Chin. Sci. Bull.*, *46*, 782–786.

Liu, Y. Q., P. X. Li, and S. G. Tian (2003), SHRIMP U-Pb zircon age of late Mesozoic tuff (lava) in Luanping basin, northern Hebei, and its implications (in Chinese), *Acta Petrol. Mineral.*, *22*, 237–244.

Meng, Q. J., J. Y. Liu, A. J. Varricchio, T. Huang, and C. L. Gao (2004), Parental care in an ornithischian dinosaur, *Nature*, *431*, 145–146.

Renne, P. R., C. C. Swisher, A. L. Deino, A. B. Karner, T. L. Owens, and A. J. DePaolo (1998), Intercalibration of standards, absolute ages and uncertainties in ^{40}Ar/^{39}Ar dating, *Chem. Geol.*, *145*, 117–152.

Steiger, R. H., and E. Jäger (1977), Subcommission on geochronology: Convention on the use of decay constans in geo- and cosmochronogy, *Earth Planet Sci. Lett.*, *36*, 359–362.

Swisher, C. C., Y. Q. Wang, X. L. Wang, X. Xu, and Y. Wang (1999), Cretaceous age for the feathered dinosaurs of Liaoning, China, *Nature*, *400*, 58–61.

Swisher, C. C., X. L. Wang, Z. Z. Zhou, Y. Q. Wang, F. Jin, J. Zhang, X. Xu, F. Zhang, and Y. Wang (2002), Further support for a Cretaceous age for the feathered-dinosaur beds of Liaoning, China: New ^{40}Ar/^{39}Ar dating of the Yixian and Tuchengzi formations, *Chin. Sci. Bull.*, *47*, 135–138.

Tian, S. G., Q. Q. Pang, S. W. Niu, P. X. Li, and Y. Q. Liu (2004), Terrestrial Jurassic–Cretaceous boundary stratotype candidate in Luanping basin, northern Hebei (in Chinese), *Geol. Bull. China*, *23*, 1170–1179.

Wang, S. S., H. G. Hu, P. X. Li, and Y. Q. Wang (2001), Further discussion on geologic age of Sihetun vertebrate assemblage in western Liaoning, China: Evidence from ^{40}Ar/^{39}Ar dating, *Acta Petrol. Sin.*, *17*, 663–668.

Wang, X. L., and Z. H. Zhou (2003), Mesozoic Pompeii, in *The Jehol Biota*, edited by M. Chang et al., pp. 19–35, Shanghai Sci. and Technol. Press, Shanghai, China.

Wang, Y., Y. Hu, J. Meng, and C. Li (2001), An ossified Meckel's cartilage in two Cretaceous mammals and origin of the mammalian middle ear, *Science*, *294*, 257–361.

Xu, X., and M. A. Norell (2004), A new troodontid dinosaur from China with avian-like sleeping posture, *Nature*, *431*, 838–841.

Xu, X., and X. L. Wang (2004a), A new dromaeosaur (Dinosauria: Theropoda) from the Early Cretaceous Yixian Formation of western Liaoning, *Vertebr. PalAsiat.*, *42*, 111–119.

Xu, X., and X. L. Wang (2004b), A new troodontid (Theropoda: Troodontidae) from the Lower Cretaceous Yixian Formation of western Liaoning, China, *Acta Geol. Sin. Engl. Transl.*, *78*, 22–26.

Xu, X., X. L. Wang, and L. H. Hou (2000), A primitive ornithopod from the Early Cretaceous Yixian Formation of Liaoning, *Vertebr. PalAsiat.*, *38*, 318–325.

Xu, X., Y. N. Cheng, X. L. Wang, and C. H. Chang (2002a), An unusual oviraptorosaurian dinosaur from China, *Nature*, *419*, 291–293.

Xu, X., P. J. Makovicky, X. L. Wang, M. A. Norell, and H. L. You (2002b), A ceratopsian dinosaur from China and the early evolution of Ceratopsia, *Nature*, *416*, 314–317.

Xu, X., M. A. Norell, X. L. Wang, P. J. Makovicky, and X. Wu (2002c), A basal troodontid from the Early Cretaceous of China, *Nature*, *415*, 780–784.

Xu, X., M. A. Norell, X. W. Kuang, X. L. Wang, Q. Zhao, and C. K. Jia (2004), Basal tyrannosauroids from China and evidence for protofeathers in tyrannosauroids, *Nature*, *431*, 680–684.

You, H. L., X. Xu, and X. L. Wang (2003), A new genus of Psittacosauridae (Dinosauria: Ornithopoda) and the origin and early evolution of Marginocephalian dinosaurs, *Acta Geol. Sin., Engl. Transl.*, *77*, 15–20.

Zhou, Z. (2006), Adaptive radiation of the Jehol Biota and its evolutionary ecological background, in *Originations and Radiations-Evidences From the Chinese Fossil Record* (in Chinese, with English abstract), edited by J. Rong et al., Sci. Press, Beijing, in press.

Zhou, Z., P. M. Barrett, and J. Hilton (2003), An exceptionally preserved Lower Cretaceous ecosystem, *Nature*, *421*, 807–814.

A. Boven, Graystreet 133, B-1050 Brussels, Belgium.

X. Ding, Marine School, Chinese University of Geosciences, Beijing 100083, China.

H. Y. He, F. Wang, L. K. Yang, and R. X. Zhu, Laboratory of Paleomagnetism and Geochronology (SKL-LE), Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China. (huaiyuhe@mail.igcas.ac.cn)

X. L. Wang, Z. H. Zhou, and F. Jin, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing 100044, China.