

New evidence for Cretaceous age of the feathered dinosaurs of Liaoning: zircon U-Pb SHRIMP dating of the Yixian Formation in Sihetun, northeast China

Wei Yang^a, Shuguang Li^{a,*}, Baoyu Jiang^b

^a Department of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China

^b Department of Earth Sciences, Nanjing University, Nanjing 210093, China

Accepted 30 May 2006
Available online 25 January 2007

Abstract

We present the first report of U-Pb SHRIMP dating of zircons from three tuffs interbedded within the “feathered dinosaur”-bearing deposits in western Liaoning, China. One is a sample from the Bed 6 tuff (LX-SHT-12) of the Yixian Formation in Sihetun, for which our zircon U-Pb SHRIMP analyses gave a Cretaceous age (124.7 ± 2.7 Ma), in agreement with a previously published sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ age (124.60 ± 0.25 Ma). The other two are from the Bed 1 tuff (LX-HBJ-1) and Bed 8 tuff (LX-HBJ-6) of the Yixian Formation in Huangbanjigou; the former gave an age of 124.9 ± 1.7 Ma, the latter an age of 122.8 ± 1.6 Ma. The three consistent ages indicate that the Yixian Formation was deposited in the Early Cretaceous within a very short time period (ca. 2 Ma).

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Keywords: Zircon U-Pb SHRIMP dating; Yixian Formation; Feathered dinosaurs; Liaoning; Jehol Biota

1. Introduction

Recently, a wide variety of spectacular fossils, including the “feathered dinosaurs” *Sinosauropteryx* (Chen et al., 1998), *Protarchaeopteryx* and *Caudipteryx* (Ji et al., 1998), and the primitive birds *Confuciusornis* (Hou et al., 1995) and *Liaoningornis* (Hou, 1996), have been recovered from the lacustrine beds of the Yixian Formation in western Liaoning, China. These well-preserved fossils provide new evidence of, and clues to, the origin and early evolution of birds. Although the “primitive” appearance of some of these fossils has suggested temporal links with the Tithonian (Late Jurassic) faunas of Europe, such as the *Archaeopteryx*-bearing Solnhofen limestone of southern Germany, other fossil data indicate a much younger, mid Early Cretaceous age. The determination of the chronology of the Yixian Formation is, therefore, important, especially because it is

still the subject of disagreement. Previously K-Ar and Rb-Sr dating results for the volcanic rocks of the formation have yielded Jurassic ages of 137 ± 7 Ma and 142.5 ± 4 Ma (Wang and Diao, 1984). More recently, additional support for a Jurassic age has come from the biotite $^{40}\text{Ar}/^{39}\text{Ar}$ age (145.3 ± 4.4 Ma) obtained by Lo et al. (1999a, b).

However, other age determinations suggest that the formation is Cretaceous. Swisher et al. (1999, 2001) and Wang et al. (2001b) reported laser Ar-Ar dating ages of 124.6 ± 0.25 Ma and 125.0 ± 0.19 Ma for the sanidine in the Bed 6 tuff of the Yixian Formation at Sihetun and a zircon U-Pb (TIMS) dating age of 125.2 ± 0.9 Ma for the same tuff. Wang et al. (2001a) also reported Ar-Ar ages of 128.4 ± 1.4 Ma and 122.3 ± 0.5 Ma for Bed 2 basalt and diabase in the upper beds of the formation in Huangbanjigou, respectively, which gives a relatively longer time period (ca. 6 Ma) for the deposition of the formation.

It is well known that the Ar system is easily disturbed by alteration or by a trapped Ar component. For example, Jiang et al. (2000), utilizing the dates of Lo et al. (1999a, b), considered

* Corresponding author.

E-mail address: lsg@ustc.edu.cn (S. Li).

that Swisher's sample from Sihetun was altered by a nearby basaltic sill. In contrast, Swisher et al. (2001) pointed out that there is excess Ar in the biotite of the sample collected by Lo from Hengdaozi. Zircon is chemically resistant and refractory, and can survive both weathering and alteration processes as well as high temperature metamorphism and anatexis. It has, therefore, been largely used in dating igneous rocks to obtain their crystallization age. However, only one zircon U-Pb age using the conventional dilution method has been reported for the Yixian Formation. More U-Pb dates from the formation are required to confirm its Cretaceous age. Here, in order to avoid the influence of xenocryst zircons, we have used the U-Pb SHRIMP method for dating magmatic zircon in the volcanic rocks.

2. Geological setting and samples

Among the most well-known localities of the Yixian Formation in western Liaoning are Sihetun, Jianshangou, Zhangjiagou, and Huangbanjigou. The fossiliferous lacustrine deposits of Sihetun extend over an area 12–14 km long and 4–5 km wide. A composite stratigraphic section of the formation at Sihetun and vicinity is shown in Fig. 1. It is composed of three members and nine beds. Member I (bed 1) is a coarse conglomerate, representing alluvial deposition. Member II (beds 2–4) consists of lava flows. Member III (beds 5–9) comprises both shallow and deep lacustrine shales and

sandstones. The total thickness of the composite stratigraphic section is 100–120 m (Wang et al., 2000). Bed 6 is the lower Sihetun fossil bed with birds and theropod dinosaurs with feathers or fibre-like integuments. Bed 8 is the upper Huangbanjigou fossil bed with fishes, angiosperms, conchostracans and insects (Wang et al., 1998).

Tuff sample LX-SHT-12 was collected from the excavated section at Sihetun (N 41°35'17.2", E 120°47'26.4"), belonging to Yixian Bed 6. The crystal clasts in the tuff mainly comprise quartz, plagioclase and biotite. Sample LX-HBJ-1 is a grey tuff interbedded with coarse conglomerate within Yixian Bed 1 at Huangbanjigou (N 41°37'0.1", E 120°49'47.8"). Sample LX-HBJ-6 is a pink tuff collected from Yixian Bed 8 in Huangbanjigou (N 41°36'54.9", E 120°50'8.7").

3. Analytical method and results

Zircons were concentrated from the three tuff samples by gravity and electromagnetic sorting from crushed rock fragments less than 1 mm in diameter, and were picked out under a binocular microscope for U-Pb analysis. There are two types in each sample: one (type A) is obviously colourless, transparent and euhedral prismatic in shape, with crystal faces commonly well preserved. Ranging in size from 200–400 μm , they are more or less granular, without any fracture. The other (type B) is light yellow, semi-transparent, with distinct marks of resorption or abrasion on the crystal faces. Transmitted and reflected light micrographs and cathodoluminescence images were obtained for both types to reveal their internal structures and textures. Oscillatory zoning was found only in type A crystals, indicating a magmatic crystallization origin (Fig. 2). Zircons of type B may be xenocrysts entrapped from the basement rocks in the process of magma ascent. Accordingly, zircons of type A were analyzed in this study.

Measurements of U, Th, and Pb were carried out using the SHRIMP II ion microprobe at the Beijing Center of Ion Microprobe Analysis, following the procedure outlined by Williams and Claesson (1987) and Song et al. (2002). The $^{206}\text{Pb}/^{238}\text{U}$ ratios were corrected using the zircon standards of CL13 (572 Ma) from Cililanca and TEM (417 Ma) from Australia. We analyzed only one spot on each zircon grain. The analytical spot size was 40 μm in average diameter during each analytical run. Each spot was rastered over 80 μm for 3 min prior to analysis (5 mass scans) to remove common Pb on the surface or contamination from the gold coating. One spot on the standard zircon (TEM) was analyzed after every three analyses of sample-spots. Squid and Isoplot programs of Ludwig (2001) were used for data processing and age calculation. Table 1 shows the analytical results of the spots. We analyzed 8–10 spots for each sample but only four zircons from each are shown on Fig. 2 for brevity. The final results are the weighted mean of the $^{206}\text{Pb}/^{238}\text{U}$ ages because these are more precise than $^{207}\text{Pb}/^{235}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ages for young zircons. The common lead is corrected by assuming $^{206}\text{Pb}/^{238}\text{U} - ^{208}\text{Pb}/^{232}\text{Th}$ age-concordance. Errors on individual spots are based on counting statistics and are at the

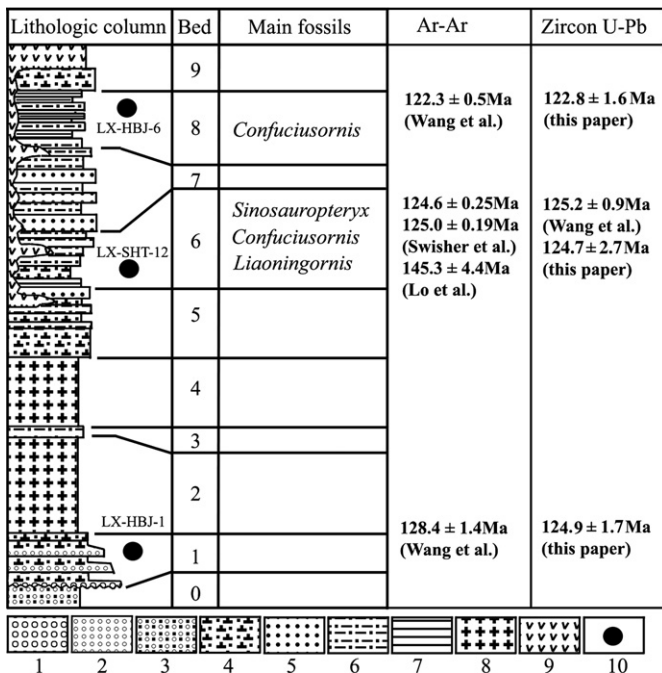


Fig. 1. Composite stratigraphic column of the Yixian Formation in Sihetun and neighbouring areas (after Wang et al., 1998). Bed 0: Tuchengzi Formation; Beds 1–9: Yixian Formation. Legend: 1, Coarse conglomerate; 2, medium-fine grained conglomerate; 3, sandy conglomerate; 4, tuffaceous sandstone and tuff; 5, medium grained sandstone; 6, silt and silty mudstone; 7, greyish-black shale; 8, basic lava; 9, basic subvolcanic rock; 10, sample horizon.

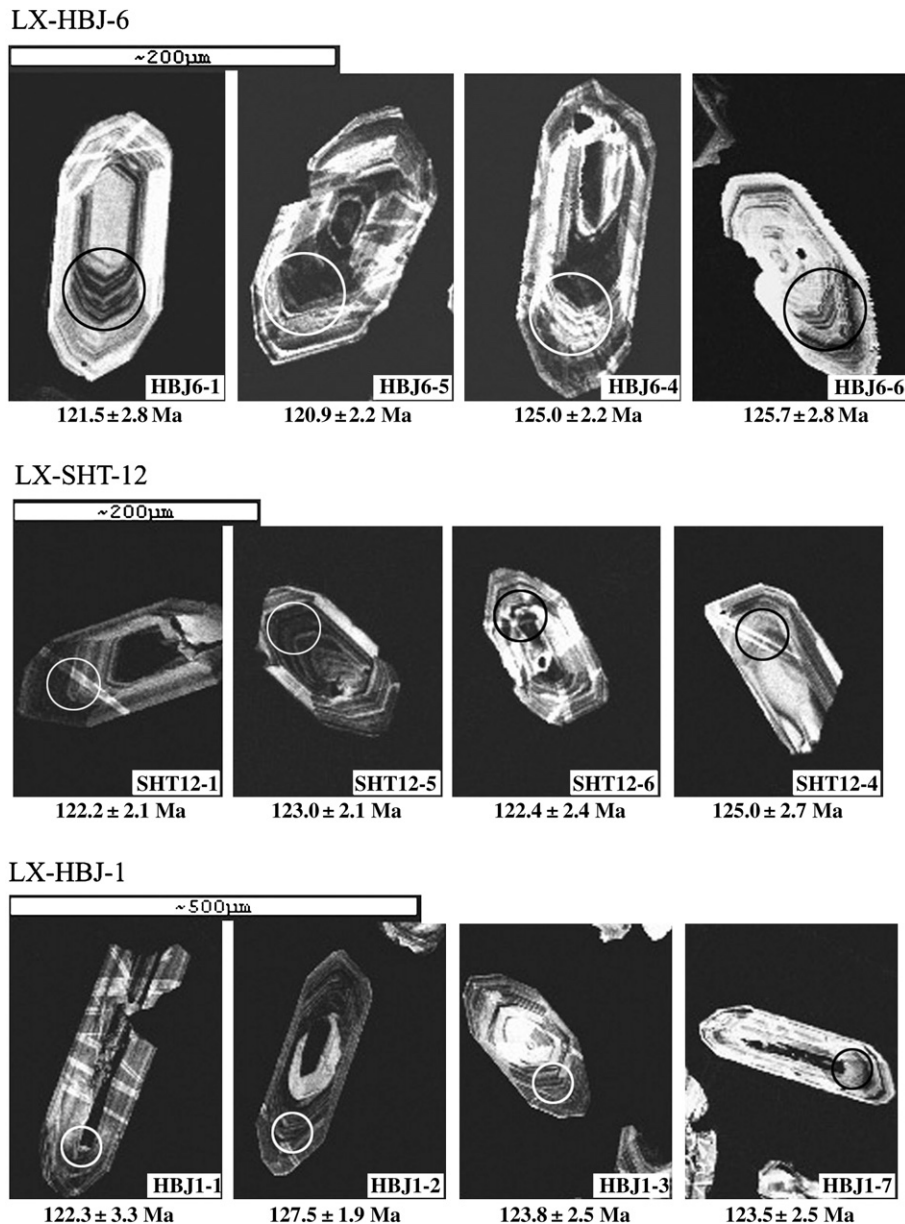


Fig. 2. Cathodoluminescence images of the zircons in the tuffs (the circles in the figure indicate the positions of the analyzed spots).

1 σ level, but the average weighted ages are quoted at 2 σ or 95% confidence. The analytical results are given in Table 1, and shown on U-Pb Concordia plots in Fig. 3.

Table 1 and Fig. 3A show that the analytical results on ten spots of zircons from tuff sample LX-HBJ-6 of Yixian Bed 8 are thoroughly consistent with each other, and yielded a weighted mean $^{206}\text{Pb}/^{238}\text{Pb}$ age of 122.8 ± 1.6 Ma.

Table 1 and Fig. 3B show the SHRIMP U-Th-Pb results on nine spots of zircons from tuff sample LX-SHT-12 of Yixian Bed 6. Apart from spot SHT12-9, whose $^{206}\text{Pb}/^{238}\text{Pb}$ is notably higher, and deviates from the population of the other $^{206}\text{Pb}/^{238}\text{U}$ values, all gave a weighted mean $^{206}\text{Pb}/^{238}\text{Pb}$ age of 124.7 ± 2.7 Ma, which is interpreted as the deposition age of Yixian Bed 6.

The analytical results on ten spots of zircons from tuff sample LX-HBJ-1 of Yixian Bed 1 are shown on Table 1 and Fig. 3C. The zircon at spot HBJ1-9 gave an apparently higher $^{206}\text{Pb}/^{238}\text{Pb}$ age than the other zircons, and because of the high ^{207}Pb analytical error, the zircon at spot HBJ1-8 failed to give $^{207}\text{Pb}/^{235}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ages; these were not included in the calculation of the weighted mean. The remaining eight spots gave a weighted mean $^{206}\text{Pb}/^{238}\text{Pb}$ age of 124.9 ± 1.7 Ma.

4. Discussion

The weighted mean $^{206}\text{Pb}/^{238}\text{Pb}$ age of zircons in tuff sample LX-SHT-12, 124.7 ± 2.7 Ma, is in agreement with

Table 1
Zircon SHRIMP U-Pb dating on tuffs of the Yixian Formation from Sihetun and Huangbanjigou

Spot No.	²⁰⁶ Pbc (ppm)	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	²⁰⁶ Pb/ ²³⁸ U	Age(Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb	±%	²⁰⁷ Pb/ ²³⁵ U	±%	²⁰⁶ Pb/ ²³⁸ U	±%
LX-HBJ-6 (Yixian bed 8) Weighted mean = 122.8 ± 1.6 Ma													
HBJ6-1	3.06	152	107	0.73	2.50	121.5	2.8	0.0491	5.5	0.1287	5.9	0.01903	2.0
HBJ6-2	0.93	301	261	0.90	5.04	122.6	2.5	0.0415	4.1	0.1099	4.4	0.01920	1.7
HBJ6-3	0.65	293	464	1.64	4.96	124.3	3.0	0.0407	4.4	0.1093	4.7	0.01946	1.7
HBJ6-4	1.79	391	228	0.60	6.62	125.0	2.2	0.0451	3.3	0.1217	3.6	0.01958	1.6
HBJ6-5	0.38	944	763	0.83	15.5	120.9	2.2	0.0454	2.3	0.1185	2.7	0.01893	1.6
HBJ6-6	2.66	206	164	0.82	3.53	125.7	2.8	0.0440	4.8	0.1193	5.2	0.01968	1.9
HBJ6-7	2.15	301	233	0.80	4.93	120.6	2.5	0.0474	4.2	0.1235	4.6	0.01889	1.7
HBJ6-8	0.69	451	357	0.82	7.54	123.5	2.3	0.0481	3.1	0.1282	3.4	0.01935	1.6
HBJ6-9	0.94	445	260	0.60	7.32	121.9	3.2	0.0516	2.9	0.1357	3.7	0.01909	2.4
HBJ6-10	4.48	207	138	0.69	3.47	122.5	2.7	0.0431	11	0.114	11	0.01918	1.9
LX-SHT-12 (Yixian bed 6) Weighted mean = 124.7 ± 2.7 Ma													
SHT12-1	1.37	319	177	0.57	5.27	122.2	2.1	0.0472	3.4	0.1246	3.7	0.01914	1.6
SHT12-2	1.65	327	183	0.58	5.72	129.6	2.8	0.0512	9.3	0.143	9.5	0.02030	1.9
SHT12-3	3.06	167	108	0.67	2.86	126.0	2.8	0.0475	5.4	0.1292	5.7	0.01974	2.0
SHT12-4	2.08	181	118	0.67	3.09	125.0	2.7	0.0477	4.9	0.1287	5.2	0.01958	1.9
SHT12-5	0.57	678	555	0.85	11.3	123.0	2.1	0.0466	2.4	0.1238	2.8	0.01927	1.5
SHT12-6	0.94	402	416	1.07	6.71	122.4	2.4	0.0460	3.4	0.1216	3.7	0.01917	1.6
SHT12-7	0.35	327	313	0.99	5.73	128.6	2.6	0.0486	3.5	0.1350	3.8	0.02015	1.6
SHT12-8	3.97	119	75	0.65	2.10	−95	±160	1.923	1.3	−3.881	2.4	−0.01464	2.1
SHT12-9	0.58	292	187	0.66	6.34	160.7	3.0	0.0513	2.9	0.1786	3.4	0.02525	1.7
LX-HBJ-1 (Yixian bed 1) Weighted mean = 124.9 ± 1.7 Ma													
HBJ1-1	1.60	871	173	0.20	14.5	122.3	3.3	0.0452	3.1	0.1193	3.6	0.01916	1.8
HBJ1-2	1.40	454	120	0.27	7.82	127.5	1.9	0.0474	2.6	0.1305	3.0	0.01998	1.5
HBJ1-3	3.86	225	208	0.96	3.82	123.8	2.5	0.0398	4.9	0.1064	5.2	0.01939	1.6
HBJ1-4	1.07	383	588	1.58	6.42	124.0	2.5	0.0493	2.8	0.1320	3.2	0.01941	1.5
HBJ1-5	3.16	168	150	0.92	2.91	127.4	2.9	0.0447	4.7	0.1230	5.0	0.01997	1.8
HBJ1-6	4.88	126	102	0.84	2.20	127.3	3.3	0.0435	7.1	0.1197	7.4	0.01994	2.2
HBJ1-7	0.89	195	117	0.62	3.27	123.5	2.5	0.0453	4.8	0.1210	5.1	0.01935	1.8
HBJ1-8	5.95	147	77	0.54	2.55	126.3	2.9	#NUM!		#NUM!		0.01978	2.0
HBJ1-9	2.74	189	71	0.39	3.65	132.5	6.9	−0.0125	22	−0.0359	21	0.02076	1.8
HBJ1-10	2.32	153	111	0.75	2.50	120.4	2.8	0.0542	4.7	0.1409	5.1	0.01885	2.0

Errors on individual spots are based on counting statistics and are at the 1σ level, but the average weighted ages are quoted at 2σ or 95% confidence.

Pbc and Pb* indicate the common and radiogenic portions, respectively.

#NUM! indicates no calculated results because of high common Pb.

The common lead is corrected by assuming ²⁰⁶Pb/²³⁸U = ²⁰⁸Pb/²³²Th age-concordance.

the sanidine ⁴⁰Ar/³⁹Ar age of 124.60 ± 0.25 Ma reported by Swisher et al. (2001), and with the zircon U-Pb TIMS age of 125.0 ± 0.19 Ma reported by Wang et al. (2001b). As a result, we suggest that this is the deposition age of Yixian Bed 6 and therefore the age of the feathered dinosaurs. The age of 124.9 ± 1.7 Ma for zircons from tuff sample LX-HBJ-1 is significantly younger than the ⁴⁰Ar/³⁹Ar age of 128.4 ± 1.4 Ma for Yixian Bed 2 basalt reported by Wang et al. (2001a), while the age of 122.8 ± 1.6 Ma for zircons from sample LX-HBJ-6 is in agreement with the ⁴⁰Ar/³⁹Ar age of 122.3 ± 0.5 Ma for diabase in an upper bed of the Yixian Formation reported by these authors. The three consistent ages obtained from U-Pb SHRIMP dating of zircons suggest that Beds 1–8 of the Yixian Formation were deposited during a relatively short interval (from 124.9 to 122.8 Ma) in the Early Cretaceous.

These ages indicate that the formation is mid Barremian or early Aptian according to the International Commission on Stratigraphy (2002 and 2004, respectively). There is

palaeontological support for both of these ages. Li et al. (2003) described the early Cretaceous mammal *Gobiconodon zofiae* (Triconodonta) from the Yixian Formation and concluded that it was Hauterivian based on the Ar-Ar age of 128 Ma. However, our U-Pb zircon ages suggest that it is Late Barremian–Aptian in age, which ties in with occurrences of *Gobiconodon* elsewhere, such as in Gansu (China), Mongolia and Montana (USA); these have been considered to be Aptian–Albian or late Barremian–Aptian (Trofimov, 1978; Jenkins and Schaff, 1988; Tang et al., 2001). An angiosperm genus, *Sinocarpus*, described by Leng and Friis (2003) from the formation, belongs to a basal lineage of eudicots. They concluded that its occurrence is in line with current understanding of the timing of early angiosperm radiation, which places the first appearance of this lineage in the Barremian. Based on the correlation with the alternating marine and non-marine Jixi Group in eastern Heilongjiang, Jiang (2003) concluded that the age-range of the Yixian Formation is late Hauterivian–Barremian. All of these determinations

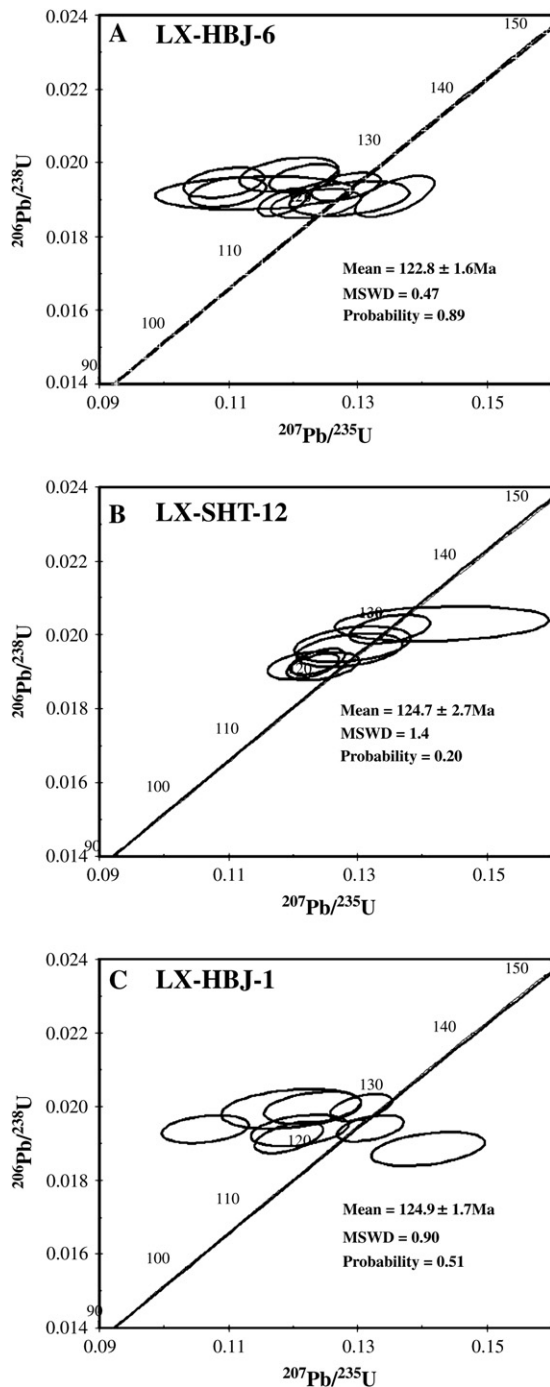


Fig. 3. U-Pb Concordia diagrams for zircons from tuff samples of the Yixian Formation. Error bars are 2σ .

point to a late Hauterivian or Barremian–Aptian age-range for the formation.

Acknowledgements

We thank Sha Jingeng for his critical comments and an early review of the manuscript. This work was financially supported by the Pilot Project of the Knowledge Innovation

Program, Academia Sinica (KZCX2-114), and the Natural Science Foundation of China (Grant 40573010).

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