The existing time of Sihetun vertebrate in western Liaoning, China

——Evidence from U-Pb dating of zircon

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Abstract **In different opinions, the stratigraphic time of the feathered dinosaurs and early birds in Sihetun and its neighboring areas in Beipiao, western Liaoning is appointed to different epoches of eras, such as Late Jurassic, Early Cretaceous and Late Jurassic-Early Cretaceous. Even the recently dating data are still very different. This note first reported the U-Pb age of (125.2±0.9) Ma of zircon separated from tuff of Sihetun vertebrates horizon. The age reveals that Sihetun vertebrate belongs to Early Cretaceous. The method is more objective, because of the strong ability of disturbance resistance and high U-Pb blocking temperature of zircons.**

Keywords: Sihetun, vertebrates, tuff, zircon, U-Pb dating.

Recently, thousands of early birds and theropod dinosaurs with feathers or fiber-like integuments have been unearthed from the interlayered lacustrine deposits of the Yixian Formation that is mainly distributed in Sihetun and its neighboring areas in Beipiao, western Liaoning[1—6]. The discoveries of these rare fossils provide important evidence and clew for the study of the origin and early evolution of birds. Consequently, the stratigraphic time and geological age of the Yixian Formation with these fossils become important and remarkable. Because of the difficulties of the contrast to the terrestrial formation, there are different opinions about the stratigraphic time of the Yixian Formation, such as Late Jurassic[7,8] and Early Cretaceous[9,11]. Later, some scholars suggest that this stratum is a transition between Jurassic and Cretaceous. Along with the constant discoveries of the vertebrate faunas and other kinds of fossils in Sihetun and its neighboring areas, new disputations and debate have arisen. Similarly three opinions exist: Late Jurassic[1,12,13] Early Cretaceous[14,15] and Late Jurassic-Early Cretaceous[2,3,16]. There are also divergences in the study of the chronology of the Yixian Formation, in western Liaoning, for example, (137±7) Ma (K-Ar isochron) and (142.5±4) Ma (Rb-Sr isochron)[17]; 115.0—144.0 Ma (K-Ar isochron), 125.4—129.2 Ma (Ar-Ar plateau age), 119.0—130.0 Ma (Rb-Sr isochron) and 112.0—136.0 Ma (U-Pb isochron)[18]; (120.2±0.3)—(123.0±0.3) Ma (laser Ar-Ar)[19]. What should be pointed out is that these samples were not collected from the Sihetun and its neighboring areas. The horizons of these samples and the Sihetun vertebrates should be studied further. Swisher et al.[20] and Lo et al.[21,22] reported the laser Ar-Ar determined results of the sanidine and biotite in the tuff in Sihetun-Jianshangou area, respectively. The ages of the sanidine given by the former are (124.60±0.25) and (124.61±0.20) Ma. The ages of the biotite given by the latter are (145.3±4.4) Ma (average) and (147.1±1.8) Ma (converse isochron). No matter which geological time scale is adopted, these results indicate that there are divergences about the samples' horizon, whether they belong to Early Cretaceous or Late Jurassic. The high U-Pb blocking temperature and geochemical properties of zircon determines that the ability of geological disturbance resistance is prior to K-Ar and Rb-Sr systems. Here we take U-Pb dating of authigenetic zircon in the tuff, then have a discussion about the ascription of the horizons with vertebrates of the Yixian Formation in Sihetun.

1 Geological setting

The distribution of lacustrine deposition with vertebrates in Sihetun is about 12—14 km long and 4—5 km wide. The most famous localities in this area are Sihetun, Jianshangou, Zhangjiagou, Huangbanjigou, Tuanshangou and so on. The composite stratigraphic section of the Yixian Formation in Sihetun and its neighboring areas is shown in fig. 1. The deposit is composed of three members and 9 beds. Member Ⅰ (bed 1) is coarse conglomerate, representing the alluvial deposition.Member Ⅱ (beds 2—4) represents the lava. Member Ⅲ (beds 5—9) represents the shore or shallow lacustrine, half-deep or deep lacustrine shale and sandstone. The total thickness of the composite stratigraphic section is 100—120 m[5]. Bed 6 represents the lower Sihetun fossil bed with birds and theropod dinosaurs with feathers or fiber-like integuments. Bed 8 represents the upper Huangbanjigou fossil bed with fishes, angiosperms, conchostracans and insects. YL31 tuff was collected from the excavated section in Sihetun, it belongs to sub-bed 6 in bed 18 as mentioned in ref. [4], its horizon corresponds to bed 6 in the composite stratigraphic section. The tuff is yellow to light brown, appears stratiform and unconspicuous liquid bedding with a thickness of 15—25 cm. The tuff has pyroclastic structure, the crystal-clast in tuff mainly comprises K-feldspar (sanidine), quartz, plagioclase and biotite. Most of the grain diameters of the crystals are 0.15—0.25 mm and only few can reach 0.5 mm, and these crystals are distributed evenly. The volcanic ash has deglassed and turned into clay mineral crystallite. The accessory minerals are

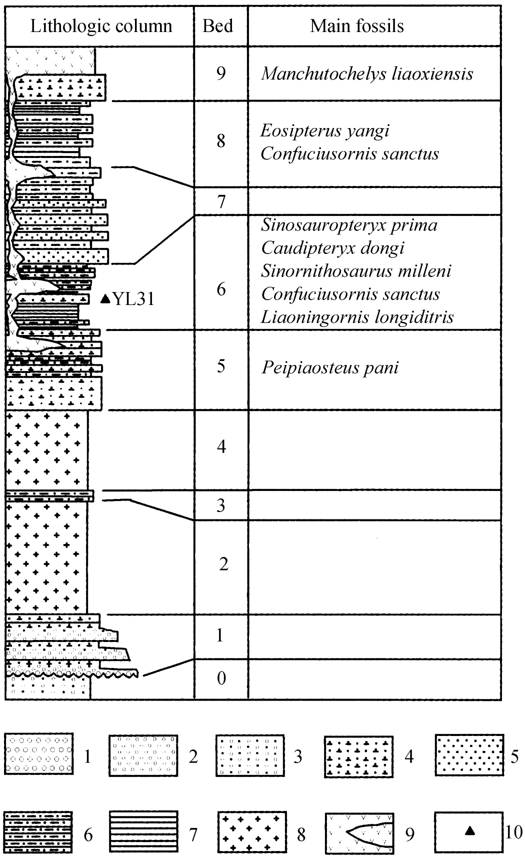

Fig. 1. The composite stratigraphic column of Yixian Formation in Sihetun and its neighboring areas (after Wang et al.[4,14]). Bed 0: Tuchengzi Formation of Late Jurassic; Beds 1—9: Yixian Formation. 1, Coarse conglomerate; 2, medium-fine grained conglomerate; 3, sandy conglomerate; 4, tuffaceous sandstone and tuff; 5, medium grained sandstone; 6, silt and silty mudstone; 7, greyish-black shale; 8, intermediate-basic lava; 9, intermediate-basic subvolcanic rock; 10, sample horizon.

composed of zircon, apatite, allanite and so on.

2 Characteristics of zircons and experimental results

We selected 20 mg zircons from the 8 kg YL31tuff. In the microscope, zircons can be divided into two types (fig. 2). Type-A zircons are colorless or light yellow, transparent, euhedral, slender prismatic or isometric. The crystal faces of these zircons are well preserved without any traces of resorption or ablation. They should be crystal zircons produced at the stage of the formation of the tuff according to their characteristics; that is to say, they are authigenic. Type-B zircons are purple, semitransparent, semi-euhedral and prismatic with traces of resorption on the crystal faces. They are defined as captured zircons according to their characteristics; that is to say, they are captured from the lower old stratum in the process of the magma ascent. The majority of the total zircon grains are

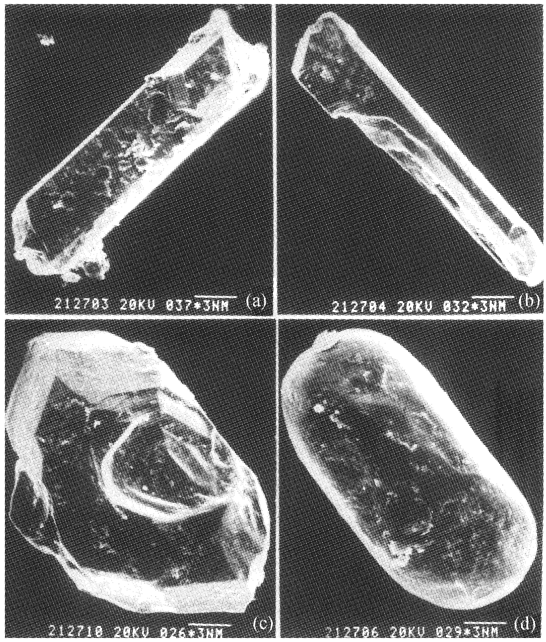

Fig. 2. The microphotograph of zircons separated from YL31 tuff. (a, b) Slender prismatic authigenic zircons; (c) isometric authigenic zircon; (d) xenocryst of zircon.

the type-A autogenetic ones.

The U-Pb dating of zircons of the two types are carried out respectively. We put more emphasis on type A, and only analyzed one group of type B in order to make sure whether it is xenocryst or not. For the chemical analysis process of zircons see ref. [23]. ^{205}Pb-^{235}U mixed spike is adopted and the isotope determination is carried out on the MAT-261 mass spectrometer. The experimental results are shown in table 1 and fig. 3, in which the decay constant of the ^{235}U is $9.8485\times10^{-10}a^{-1}$ and that of the ^{238}U is $1.55125\times10^{-10}a^{-1}$. The uranium isotope ratio is 137.88.

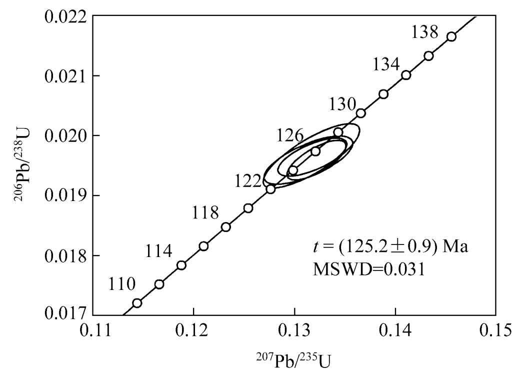

Fig. 3. U-Pb concordia diagram of zircon in YL31 tuff.

Table 1 U-Pb analytic results of zircons in YL31 tuff

Anal. No.	C. Z.[a)]	Weight /μg	U /μg • g^{-1}	Pb /μg • g^{-1}	Isotopic ratios[b)]					Apparent age/Ma		
					$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
1	A-1	25	563	14	1522 {424}	0.3813	0.01966 (44)	0.1317 (39)	0.04860 (88)	125.5	125.7	128.6
2	A-2	25	705	17	1263 {464}	0.3450	0.1964 (26)	0.1318 (28)	0.04870 (78)	125.4	125.8	133.5
3	A-2	25	766	19	1464 {513}	0.3485	0.01959 (23)	0.1322 (24)	0.04892 (62)	125.1	126.0	144.1
4	A-1	25	518	13	1045 {358}	0.3671	0.01959 (33)	0.1314 (36)	0.04864 (96)	125.1	125.3	130.5
5	B	10	349	157	14357 {2520}	0.05275	0.4317 (21)	9.352 (48)	0.1571 (2)	2314	2373	2425

a) Characteristic of zircons. A-1, Colorless, transparent, slender prismatic, euhedral crystal; A-2, light yellow, transparent, isometric, euhedral crystal; B, purple, semitransparent, semieuhedral xinocryst. b) The corrections of spike and experiment blank for $^{206}Pb/^{204}Pb$ have been done; {}: original measured value, no correction; Pb isotopes in other ratios are all radiogenic; numerical value in ( ) is 2σ error; for example, 0.01966 (44) represents 0.01966 ± 0.00044 (2σ).

3 Discussion

The apparent ages of four groups of type-A zircons (analytic Nos. 1—4) and one group of type-zircon (analytic No. 5) are entirely different which indicates the origins of type-A and type-B zircons are different. Four data points of the type-A authigenetic zircons are all on the concordia curve within the range of experimental error. For the young zircons, apparent age of $^{206}Pb/^{238}U$ is usually more precise than the ages of other two groups. The weighted mean $^{206}Pb/^{238}U$ apparent ages of the four-group zircons is (125.2 ± 0.9) Ma. We suggest this age to be the forming time of these authigenetic zircon crystals and the forming time of YL31 tuff as well. It reveals that the fossils found in bed 6 of the composite section should be 125 MaBP, which include feathered dinosaurs (*sinosauropteryx prima*, *caudipteryx zoui*, *c. dongi*, *beipiaosaurus inexpectus* and *sinornithosaurus milleni*), early birds (*confuciusornis sanctus*, *c. dui*, *Liaoningornis longiditris* and *eoenantiornis buhleri*) and great number of vertebrates (*zhangheotherium quinquecuspidens*, *jeholodens jenkinsi*).

The $^{207}Pb/^{206}Pb$ apparent age of the old zircons is usually believed to be more close to the true age. The 2425 Ma (analytic No. 5 in table 1) suggests that the type-B purple captured zircons derive from the deep metamorphic rock of Paleoproterozoic.

The two tuff samples determined by Swisher et al. are collected from the Sihetun and Jianshangou sections. They are referred to bed 6 (fig. 1) and their horizons are the same as that of the YL31 tuff. The sanidine $^{40}Ar/^{39}Ar$ ages shown by Swisher et al. are fit with the zircon U-Pb age reported by this note within the error range. Tuff samples determined by Lo et al. were collected from Hengdaozi east of the Sihetun. Their horizons are referred to bed 9 in fig. 1. Some biotite was separated from the YL31 tuff and then carried through conventional Ar-Ar step-heating dating. We find that the 15 steps apparent ages vary in a wide range (112—184 Ma) and the integrated gas age is 152.7 Ma, which is very different from zircon age. The EPMA of five pieces of biotite selected stochastically demonstrates that the contents of the K_2O in biotite are 0.01%—0.24%, which are far smaller than the normal value. The XRD shows that the biotite almost entirely weathered to vermiculite. The K element largely ran off during the weathering stage, which led to the open of the K-Ar system, so this Ar-Ar age has little geological meaning. It is not known whether the biotite determined by Lo et al.[21,22] has also undergone some extent of weathering.

About the Jurassic-Cretaceous boundary age, there are continuous disputations internationally. The Chinese geochronologists refer to (135 ± 5) Ma[27] among the two dates, named 135 Ma[24] and 144 Ma[25,26]. The date of 135 Ma suggested by Odin is also referred to the age data of the Jiande Formation in Zhejiang, China, reported by Chinese authors. No matter which opinion is adopted finally, the existing time of Sihetun vertebrates should belong to Early Cretaceous, and it cannot be much earlier.

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