PALAEOWORLD Editorial Office
State Key Laboratory of Palaeobiology and Stratigraphy
Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences
Beijingdonglu 39, 210008 Nanjing, PR China
e-mail: palaeoworld@nigpas.ac.cn

PALAEOWORLD online submission:
http://ees.elsevier.com/palwor/

PALAEOWORLD full-text (Volume 15 –) available at:
http://www.sciencedirect.com/science/journal/1871174X

辽西义县组火山凝灰岩激光单晶氩氩与钾氩同位素年龄分析研究

罗清华[1)] 陈丕基[2)] 邹东羽[1)] 孙贤钵[3)] 李寄嵎[1)]

1) 台湾大学地质学系 台北 106—17

2) 中国科学院南京地质古生物研究所 南京 210008

3) 澳大利亚 16 Giffen Close, Holt, Canberra ACT2615

提要 近年来,辽西地区义县组早期鸟类(孔子鸟、辽宁鸟、辽西鸟)与长毛恐龙(中华鸟龙、原始祖鸟、尾翼鸟)的发现,不但改变了科学家们对早期鸟类演化的看法,更提供了地球上鸟类是否源于恐龙的重要线索。过去的几年间,虽然已有相当数目的相关研究工作,作了深入的探讨。然而,由于义县组含化石部分属湖相地层,以致于学者们对这些鸟类与长毛恐龙的演化序列、年代归属,仍缺乏一致的看法。例如辽西北票四合屯、尖山沟地区出现上述化石的义县组的地层年代,即引起相当大的争议。依据化石记录或同位素测年资料,有些学者认为应属早白垩世;然而,也有学者认为应属晚侏罗世。究其主因,仍在于巨厚的义县组乃一多次喷发的火山沉积岩层,夹有几层含化石湖相沉积,对比工作相当困难所致;另则,义县组内白垩纪侵入岩体的重置作用,也可能是部分原因。为了确实了解辽西孔子鸟类与长毛恐龙化石层的绝对年代,本研究工作采集了四合屯、尖山沟地区义县组底部化石层上覆的火山喷发岩,利用 Nd-YAG 激光氩氩测年法,进行单矿物测年。分析结果显示,黑云母单矿物氩氩年代分布在 136.2Ma—155.4 Ma 之间,平均值为 145.3±4.4Ma,同位素对比作图则呈现 147.1±1.8Ma 之反等时线年代,同时具有相当合理的($^{40}Ar/^{36}Ar$)i 截距值(280±11)与线性关系(MSWD=1.95),显示标本内的黑云母同位素系统,并未受后期风化作用所影响;因此,黑云母年代应有其地质意义。相对地,基质部分的玻璃质物质,由于受到后期风化作用影响,则呈现相当不一致的分析结果。此外,本研究工作亦采取了孔子鸟标本(*Confuciusornis sanctus* Hou *et al*.)上覆之火山灰,进行钾氩测年分析,所得结果为 147.3±0.3Ma。此一年代与上述黑云母单矿物氩氩年代完全一致,指示辽西地区义县组底部出现孔子鸟类与长毛恐龙的化石层,应属晚侏罗世的提塘期(Tithonian),此一结论与化石层所出现的许多动物化石所得结论,亦属吻合。果真如此,则中国的中生代鸟类与长毛恐龙应与德国的始祖鸟约略出现于同一时间或稍晚一些;亦即提塘期时期,中国地区的"侏罗纪公园"不但存活着会飞的早期鸟类,亦存在有许多长着华丽羽毛的恐龙行走于地面。

关键词 氩氩和钾氩测年 火山凝灰岩 义县组 辽西

$^{40}Ar/^{39}Ar$ LASER SINGLE-GRAIN AND K-Ar DATING OF THE YIXIAN FORMATION, NE CHINA

Ching-Hua LO[1), Pei-Ji CHEN[2), Tung-Yu TSOU[1), Shen-Su SUN[3), Chi-Yu LEE[1)

1) *Department of Geology, National Taiwan University, Taipei* 106—17

2) *Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences, Nanjing* 210008

3) 16 *Giffen Close, Holt, Canberra, ACT* 2615, *Australia*

ABSTRACT: Recent findings of spectacular 'feathered' dinosaurs and birds (*Liaoningornis*, *Confuciusornis*, *Caudipteryx*, *Protarchaeopteryx* and *Sinosauropteryx*) from NE China have provided an excellent opportunity to examine the long-running debate on the hypothesis that birds evolved from dinosaurs, and to reveal the early evolution of feathers. K-Ar radiometric dating of volcanic ash recovered from a rock specimen containing *Confuciusornis sanctus* Hou *et al*. suggests 147.3 ± 0.3 Ma for the age of the fossil. $^{40}Ar/^{39}Ar$ laser single-grain dating on individual biotite grains collected from a volcanic bed, about 13 – 19 m above the stratigraphic position of the fossil bed, in the lower member of the Yixian Formation yields ages in the range of 136.2 Ma – 155.4 Ma (mean age of 145.3 ± 4.4 Ma) with an intercept age of 147.1 ± 1.8 Ma. These two ages are in excellent agreement and thus, resolve a controversy regarding age of these fossils. It is now firmly established that the feathered theropods in NE China lived in the late Jurassic, the same time period as *Archaeopteryx* found in Bavaria.

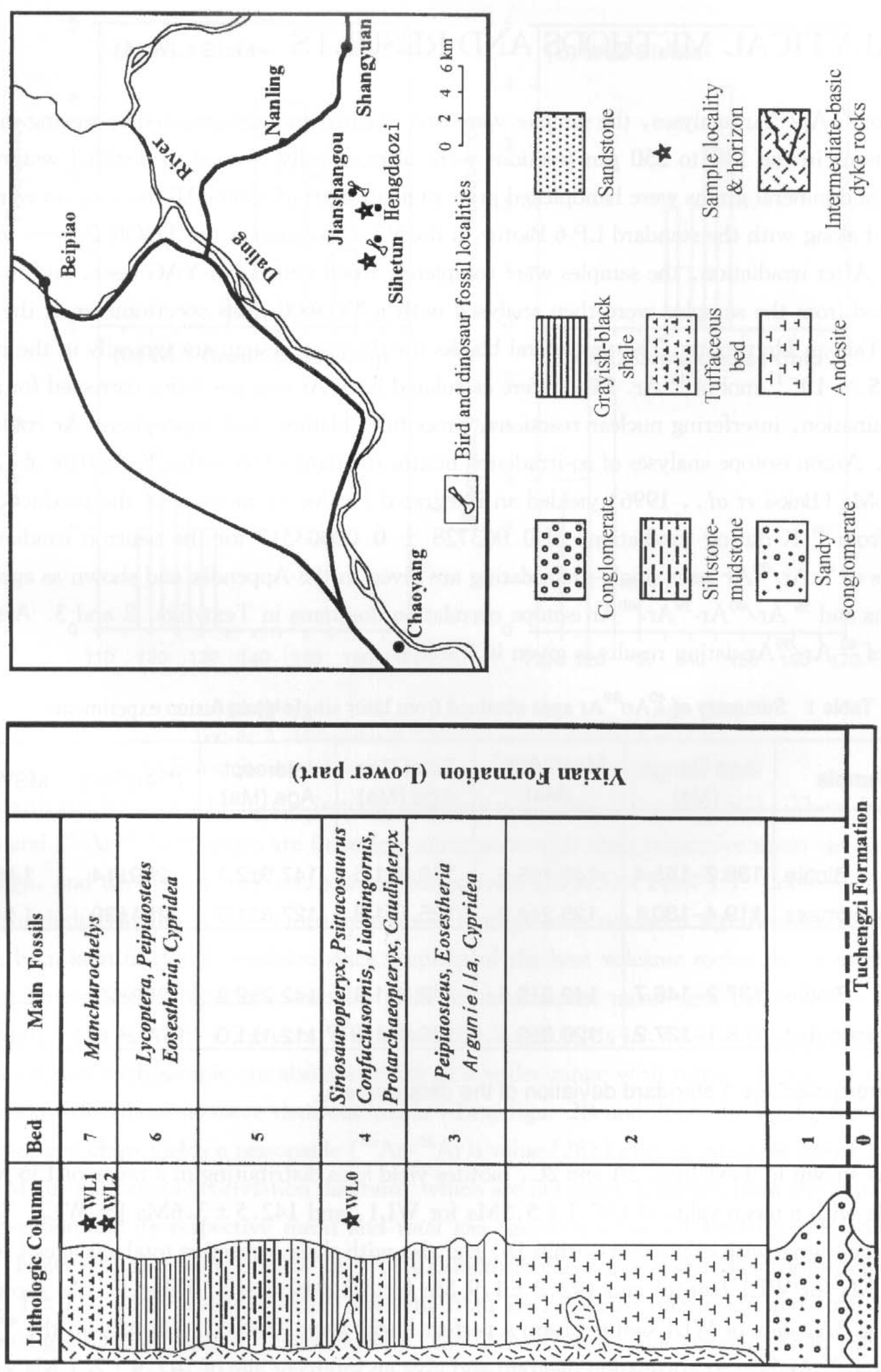
INTRODUCTION

Since *Archaeopteryx* was found in Bavaria in 1861, whether birds evolved from dinosaurs has been a subject of debate for decades and scientists, due to the dearth of feathered fossils. Recently, the blooming findings of spectacular 'feathered' dinosaurs and early birds (Hou *et al*., 1995; Chen *et al*., 1998; Ji *et al*., 1998; Hou and Cher, 1999; Xu *et al*., 1999) —— *Liaoningornis*, *Confuciusornis*, *Liaoxiornis*, *Caudipteryx*, *Protarchaeopteryx*, *Beipiaosaurus*, and *Sinosauropteryx*, from the lower part of the Yixian Formation in Liaoning, NE China have fired up hot debate over the origin and evolution of avian flight, as well as the definition of 'birds' (Padian, 1998). These findings have also narrowed the gap between dinosaurs and birds in avian family tree (Chiappe, 1995; Hou *et al*., 1996; Unwin, 1998; Padian, 1998). All these fossils are well preserved in volcanic and sedimentary beds of the lower part of the Yixian Formation, in Sihetun – Jianshangou areas of Beipiao Liaoning, NE China. Several months ago the present authors made a brief report on the age of *Sinosauropleryx* and *Confuciusornis* by using $^{40}Ar/^{39}Ar$ laser single-grain and K-Ar dating (Lo *et al*., 1999). The methods, results, and discussion will described herein in detail.

SAMPLES

In order to obtain precise age information for these fossils, a detailed geological and chronostratigraphical survey for the Yixian Formation in Sihetun and Jianshangou areas has recently been carried out by the Institute of Vertebrate Paleontology and Paleoanthropology, Beijing and the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences respectively. The latter measures three profiles in the Sihetun, Huangbanjigou and Jianshangou areas show that the lower part of the Yixian Formation is mainly composed of alluvial and lacustrine deposits with a number of interlayering volcanic beds. Lithostratigraphically, it can be divided into seven beds: (1) basal conglomerates and sandstones, 3 – 24 m in thickness, unconformably overlying on the late-Middle Jurassic Tuchengzi Formation; (2) andesite, 0.1 – 40 m; (3) siltstones and mudstones, 2 – 13 m; (4) lower lacustrine shales with members of volcanic beds, 5 – 10 m; (5) massive siltstones and sandy mudstones, 13 – 19 m; (6) upper lacustrine shales, 2 – 7 m; and (7) sandstones and tuffaceous beds on the surface (Text-fig. 1A). The fossil-bearing beds for the feathered theropods and birds, including *Liaoningornis*, *Protarchaeopteryx*, *Caudipteryx*, *Confuciusornis*, and *Sinosauropteryx*, were confirmed to belong to the Bed 4. It is also shown that after deposition, these sedimentary and volcanic beds were intruded by a number of intermediate-basic dykes (Text-fig. 1A). Building on this stratigraphic framework we have embarked a study of K-Ar and $^{40}Ar/^{39}Ar$ laser probe dating of volcanic samples from the fossil beds to further delineate the absolute age of these feathered theropods and birds.

More than 80 biotite grains and groundmass chips extracted from two volcanic rock samples (WL1 and WL2) were analyzed by the $^{40}Ar/^{39}Ar$ laser single grain fusion method. The rock samples were collected from a volcanic bed —13 m above the main fossil bed of the lower part of the Yixian Formation berween Hengdaozi and Jianshangou (Text-fig. 1B). The rock samples are yellowish-gray in color, and display typical pyroclastic texture and consist mainly of fine-grained groundmass (>80% in volume) with euhedral biotite and feldspar phenocrysts. Under microscope, feldpsar and groundmass are clearly altered to varying degrees, but there is no sign of alteration in biotite. Geochemical analyses of these volcanic samples have trachytic-rhyolitic. Nevertheless, the high content of loss-on-ignition (L. O. I.) (up to 9%) demonstrates that alteration reactions may have introduced a substantial amount of volatile materials. It is believed that the volcanic beds in the Yixian Formation represent the altered remnants of vitric fallout ash or clastics from large-scale explosive volcanism resulted from the late Mesozoic extension tectonism in NE China (Xu, 1990). In addition, a volcanic ash sample (WL0) collected from the coverture of fossil *Confuciusornis sanctus* Hou *et al*. was dated by K-Ar method.



Text-fig. 1 Composite stratigraphic column of Sihetun and Jianshangou areas with positions of the dated samples labeled

ANALYTICAL METHODS AND RESULTS

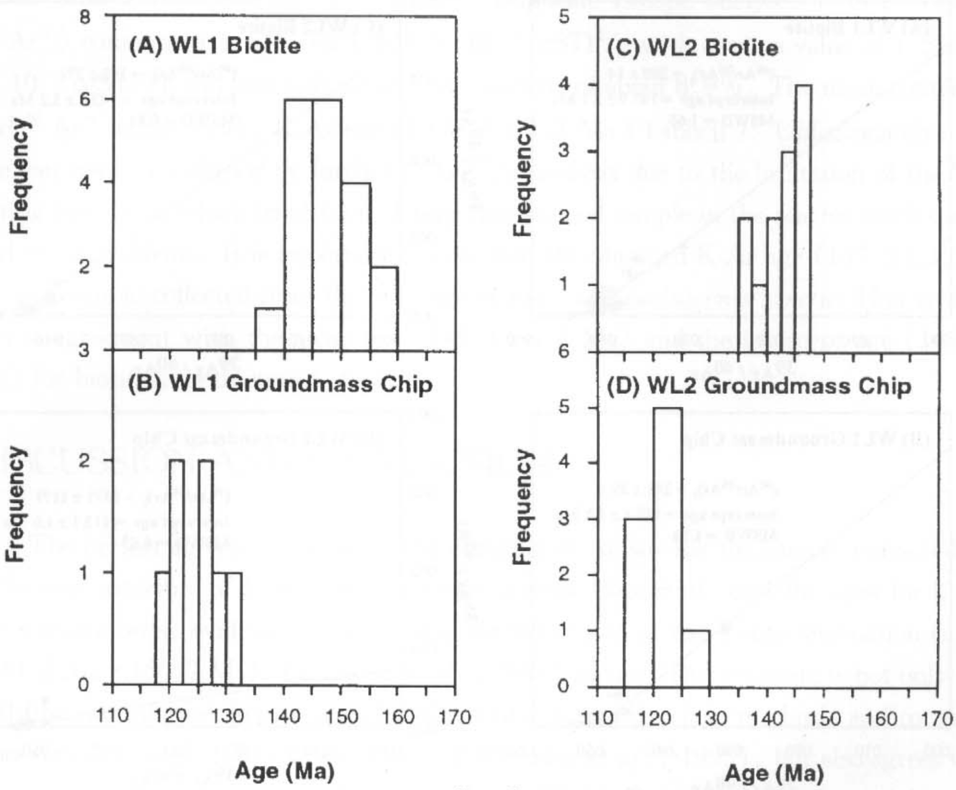
For $^{40}Ar/^{39}Ar$ analyses, the samples were first crushed and desegregated by sieving in water. Grains in the 140 to 250 μm fractions were ultrasonically cleaned in distilled water and dried, and mineral grains were handpicked prior to neutron irradiation. All the samples were irradiated along with the standard LP-6 Biotite in the VT-C position at the THOR Reactor for 30 hours. After irradiation, the samples were completely fused with a Nd-YAG laser, and the gas extracted from the samples were then analysed with a VG3600 mass spectrometer at the National Taiwan University. The procedural blanks for the laser system are typically in the range of $3-5\times10^{-17}$ mol of ^{40}Ar. Dates were calculated from Ar isotopic ratios corrected for mass discrimination, interfering nuclear reactions, procedural blanks, and atmospheric Ar contamination. Argon isotope analyses of co-irradiated biotite standard LP-6 with a K-Ar date of 127.8 ±0.7 Ma (Baksi *et al.*, 1996) yielded an integrated J value (a measure of the production of ^{39}Ar from ^{39}K during irradiation) of 0.003728 ± 0.00003517 for the neutron irradiation. Results of $^{40}Ar/^{39}Ar$ laser single-grain dating are given in the Appendix and shown as age histograms and $^{36}Ar/^{40}Ar$-$^{39}Ar/^{40}Ar$ isotope correlation diagrams in Text-figs. 2 and 3. A summary of $^{40}Ar/^{39}Ar$ dating results is given in Table I.

Table I Summary of $^{40}Ar/^{39}Ar$ ages obtained from laser single-grain fusion experiments

Sample	Age Range (Ma)	Mean Age^{+} (Ma)	Total Gas Age (Ma)	Intercept Age (Ma)	$(^{40}Ar/^{36}Ar)_i$	MSWD
WL1						
Biotite	136.2~155.4	147.1±5.5	146.8±1.5	147.9±2.1	289±14	1.65
Groundmass	119.4~130.1	125.2±4.2	125.1±1.8	127.8±1.9	281±39	1.54
WL2						
Biotite	137.2~146.7	142.5±3.6	142.2±1.9	142.2±2.2	292±27	0.81
Groundmass	116.1~127.2	120.8±3.1	120.0±1.1	112.1±1.0	1371±1171	0.63

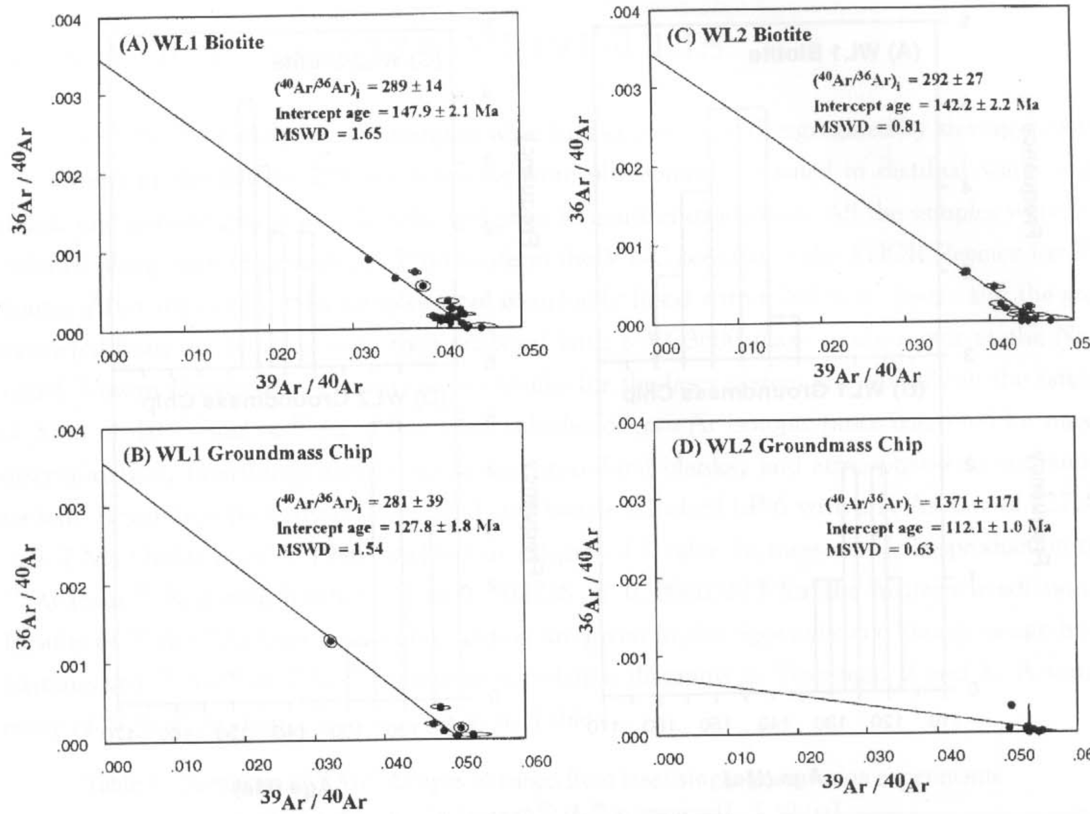
+: Errors cited are 1 standard deviation of the data spread.

As shown in Text-figs. 2A and 2C, biotites yield ages distributing in a range of 136 Ma – 155 Ma with a mean value of 147.1 ± 5.5Ma for WL1, and 142.5 ± 3.6Ma for WL2. These mean ages agree with each other within 1σ, and also with their respective total gas ages (146.8 ± 1.5 Ma for WL1 biotites and 142.2 ± 1.9 Ma for WL2 biotites) (Table I). As shown in Text-fig. 3A, data of WL1 biotites form a perfect linear array (MSWD = 1.65) on the $^{40}Ar/^{39}Ar$ and $^{36}Ar/^{40}Ar$ correlation diagram and give an intercept age of 147.9 ± 2.1 Ma with a $^{40}Ar/^{36}Ar$ intercept [cited as $(^{40}Ar/^{36}Ar)i$] value of 289 ± 14. Whereas, regression of the data for WL2 biotites yields an intercept age of 142.2 ± 2.2 Ma and a $(^{40}Ar/^{36}Ar)i$ value of 292 ±



Text-fig. 2 Histograms of $^{40}Ar/^{39}Ar$ ages for biotites (A and C), and groundmass chips (B and D) in the volcanic rock samples (WL1 and WL2).

27 (with MSWD = 0.81) in the isotopic correlation diagram (Text-fig. 3C). These intercept ages and $(^{40}Ar/^{36}Ar)i$ values are in perfect agreement with their respective mean age and total gas age, and the atmospheric composition respectively (295.5) (Table Ⅰ). Consequently, we can conclude that the K-Ar isotope systems in biotites have not been significantly altered and have been kept in closed condition since eruption of the host volcanic rocks. In contrast to biotites, groundmass chips from samples yield much different mean ages between the samples (Table Ⅰ), as 125.2 ± 4.2 Ma in WL1, and 120.8 ± 3.1 Ma in WL2. The data for groundmass chips in each sample are also scattering in a wider range with respect to that of biotites, with some distribute in more then one mode (Text-figs. 2B and 2D). In WL1, the data for groundmass chips yields a reasonable $(^{40}Ar/^{36}Ar)i$ value (281) and an intercept age of 127.8 ± 1.9 Ma in the isotopic correlation diagram, which are not much different from the atmospheric composition and its respective mean and total gas ages respectively (Text-fig. 3B and Table Ⅰ). However, regression of data for WL2 groundmass chips appear to indicate an intercept age (112.1 ± 1.0 Ma) which is much different from its respective mean age and total gas age (Text-fig. 3D and Table Ⅰ). Additionally, the $(^{40}Ar/^{36}Ar)i$ value obtained from the isotope correlation plots for the groundmass chips from WL2 is also much different from that expected from atmospheric composition, although it is not apparent for the groundmass chips in WL1 (Table Ⅰ). Many possible factors (for instance, more than one population of samples, alter-



Text-fig. 3 $^{36}Ar/^{40}Ar-^{39}Ar/^{40}Ar$ isotope correlation plots for biotites and groundmass chips in WL1 (A and B) and WL2 (C and D). Individual data are represented by solid circles with error ellipse in 2σ. The cubic least-squares fitting scheme oulined in York (1969) was employed in regressing the data. Intercept age and $(^{40}Ar/^{36}Ar)_i$ were calculated from the intercepts. MSWD denotes the goodness of fitting.

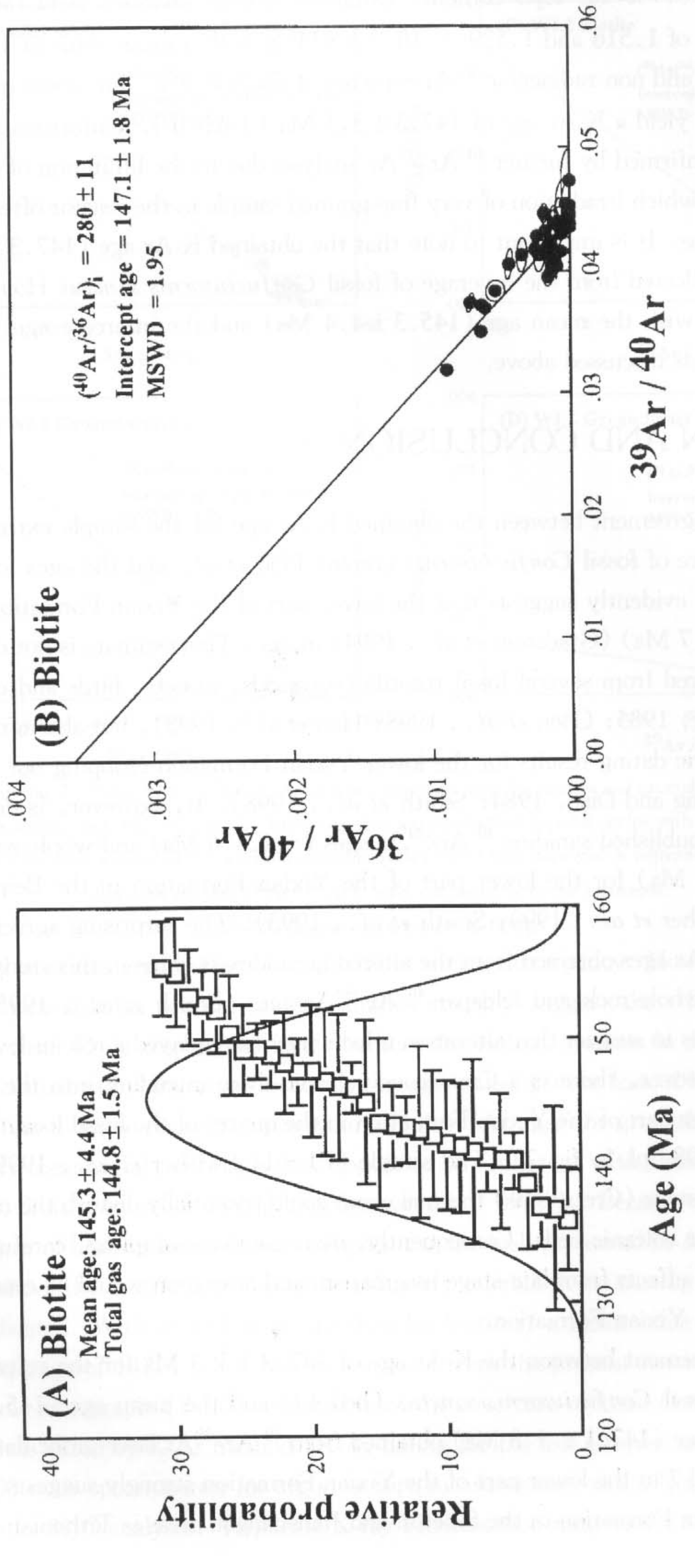
ation reaction or excess argon effects) might cause such a discrepancy. However, high L.O.I. contents and petrographic texture of the samples strongly suggest that the alteration effects would be the most likely responsible factor because the isotope systems in the samples could be significantly disturbed by alteration reactions through either gain or loss of K and/or Ar (Lo *et al*., 1994). As to these regards, these young $^{40}Ar/^{39}Ar$ ages for groundmass chips may not be geologically meaningful, although they appear to be consistent with those reported by previous studies (Smith *et al*., 1995; Swisher *et al*., 1999). Because of consistencies of $^{40}Ar/^{39}Ar$ ages of biotites between two samples and the well preserved K-Ar systems in the biotites, we believe the biotite ages would be relatively reliable in estimating the age of the volcanic bed indicated. With compiling all the data for biotites, a mean value of 145.3 ± 4.4 Ma and an intecept age of 147.1 ± 1.8 Ma are obtained from the present results (Text-fig. 4).

A volcanic ash sample (WL0) collected from the coverture of fossil *Confuciusornis sanctus* Hou *et al*. was dated by K-Ar method. K-Ar dating for the ash samples was performed by using a VG1200 mass spectrometer for argon isotope measurements and a Rigaku RIX2000 X-ray Fluorescence for K_2O analyses. Triplicate X-ray Fluorescence analyses for the ash sample give a mean value of 3.077% for K_2O content. Duplicate isotope analyses yield radiogenic argon ($^{40}Ar^*$) contents of 1.516 and 1.529 × 10^{-5} ccSTP/g with a mean value of 1.523 (0.015) × 10^{-5} ccSTP/g and non-radiogenic ^{40}Ar contents of about 8.9%. The mean contents of K_2O and $^{40}Ar^*$ would yield a K-Ar age of 147.3 ± 3.3 Ma (Table II). Unfortunately, this K-Ar age can not be confirmed by further $^{40}Ar/^{39}Ar$ analysis due to the limitation of the $^{40}Ar/^{39}Ar$ dating method in which irradiation of very fine-grained sample in the reactor often causes safety and recoil problems. It is important to note that the obtained K-Ar age (147.3 ± 3.3 Ma) for the ash sample collected from the coverage of fossil *Confuciusornis sanctus* Hou *et al*. is perfect in agreement with the mean age (145.3 ± 4.4 Ma) and the intercept age (147.1 ± 1.8 Ma) for biotites, as discussed above.

DISCUSSION AND CONCLUSION

The perfect agreement between the obtained K-Ar age for the sample extracted from the tuffaceous coverture of fossil *Confuciusornis sanctus* Hou *et al*. and the ages for biotite from the volcanic beds, evidently suggests that the lower part of the Yixian Formation is Tithonian (144.2 Ma – 150.7 Ma) (Gradstein *et al*., 1994) in age. This estimate is not only consistent with the age inferred from several fossil records (ostracods, insects, birds and compsognathid dinosaurs) (Zhang, 1985; Chen *et al*., 1998; Hou *et al*., 1995), but also agrees with some previous radiometric dating results for the lower Yixian Formation cropping out in other areas in NE China (Wang and Diao, 1984; Smith *et al*., 1998). It, however, is definitely much older than recent published sanidine $^{40}Ar/^{39}Ar$ ages (~124.6 Ma) and whole rock $^{40}Ar/^{39}Ar$ age (122.9 ± 0.3 Ma) for the lower part of the Yixian Formation in the Beipiao areas and Daxinfangzi (Swisher *et al*., 1999; Smith *et al*., 1995). The surprising agreement between the mean $^{40}Ar/^{39}Ar$ ages obtained from the altered groundmass chips in this study and the previously published whole-rock and feldspar $^{40}Ar/^{39}Ar$ ages (Smith *et al*., 1995; Swisher *et al*., 1999) leads us to suspect that alteration effects may have played a role in lowering the radiogenic age. Moreover, there is a Cretaceous volcanic dyke intruding into the fossil-bearing horizon of the lower part of the Yixian Formation in the quarry of the fossil localities in Sihetun (Wang *et al*., 1998, pl.1, fig.2). The sample (P1 – 1, Swisher *et al*., 1999) is near the dyke and this late-stage (Cretaceous) thermal event could potentially disturb the radiogenic systems in the Jurassic volcanic beds. Consequently, more cautious sampling, careful examination of possible thermal effects from late-stage magmatism and alteration would be crucial for future work in dating the Yixian Formation.

The good agreement between the K-Ar age of 147.3 ± 3.3 Ma for the volcanic ash from the coverture of fossil *Confuciusornis sanctus* (bed 4). and the mean age (145.3 ± 4.4Ma) and the intercept age (147.1 ± 1.8 Ma) obtained from $^{40}Ar/^{39}Ar$ laser-probe dating of biotite grains from the bed 7 in the lower part of the Yixian Formation strongly suggests that the lower part of the Yixian Formation in the Sihetun and Jianshangou areas is Tithonian (144.2Ma –



Text-fig.4 Single-grain $^{40}Ar/^{39}Ar$ ages and age probability spectrum derived from laser totalfusion analysis of individual grains of biotite from WL1 and WL2 samples. Individual data are represented by black dots with 2σ internal error bars (after Lo *et al.*, 1999)

Table II Results of K-Ar dating analyses

XRF Analysis		Mass Spectrometry Analysis			K-Ar Age[£]
K_2O (%)		$^{40}Ar^*$ (ccSTP/g)		$^{40}Ar_{air}/^{40}Ar_{total}$	
3.075 3.086 3.070	Mean = 3.077 ± 0.07	1.529 (± 0.015) x 10^{-5} 1.516 (± 0.015) x 10^{-5}	Mean = 1.523(±0.015) x 10^{-5}	8.9 % 8.9 %	147.3± 0.3 Ma

£: K-Ar date is obtained by using the following equation and parameters:

$$t=\frac{1}{\lambda}\ln\left\{\frac{\left[{}^{40}Ar^*\right]}{{}^{40}K}\left(\frac{\lambda_\varepsilon}{\lambda}\right)+1\right\}$$

, where $\lambda_\varepsilon = 0.581\times10^{-10} yr^{-1}$; $\lambda = 5.543 \times 10^{-10} yr^{-1}$; $^{40}K/K = 0.01167$ atom % (Steiger and Jäger, 1977). All the errors are given in 1σ.

(after Lo *et al.*, 1999 with slight modification)

150.7 Ma) in age as *Compsognathus* and *Archaeopteryx* found in Bavaria. It is not difficult to imagine that by the time of late Jurassic some creatures with asymmetrical feathers (*Confuciusornis*, *Liaoxiornis* and *Liaoningornis*) flew in the air, while others (*Protarchaeopteryx*, *Caudipteryx*, and *Sinosauropteryx*) with symmetrical feathers on the arms and downy filaments covering their bodies run speedily in the Chinese "Jurassic Park".

ACKNOWLEDGMENTS: This work was financially supported by NSC, NSFC, and CAS. We thank Dr. G. S. Odin for his kindness in providing the standard, and Prof. Zhang Mee-mann for critical comments and suggestions.

REFERENCES

Baksi A K, Archibald D A, Farrar E, 1996. Intercalibration of $^{40}Ar/^{39}Ar$ dating standards. Chem. Geol., **129**:307 – 324.

Chen P -J, Dong Z -M, Zhen S -N, 1998. An exceptionally well-preserved theropod dinosaur from the Yixian Formation of China. Nature, **391**: 147 – 152.

Chiappe L M, 1995. The first 85 million years of avian evolution. Nature, **378**: 349 – 354.

Dong Z M, 1993. Early Cretaceous dinosaur faunas in China: an introduction. Can. J. Earth Sci., **30**: 2096 – 2100.

Hou L -H, Zhou Z -H, Martin L D, Feduccia A, 1995. A beaked bird from the Jurassic of China, Nature, **377**:616 – 618.

Ji Q, Currie P J, Norell M A, Ji S -A, 1998. Two feathered dinosaurs from northeastern China. Nature, **393**: 753 – 761.

Li W -B, Liu Z -S, 1994. The Cretaceous palynofloras and their bearing on stratigraphic correlation in China. Cretaceous Res., **15**:333 – 365.

Lo C -H, Onstott TC, Chen C -H, Lee T, 1994. An assessment of $^{40}Ar/^{39}Ar$ dating for the whole-rock samples from the Luzon Arc near Taiwan. Chem. Geol. (Isotope Geosci. Sect.) **114**:157 – 178.

Lo C -H, Chen, P -J, Tsou T -Y, Sun S -S and Lee C -Y, 1999. Age of *Sinosauropteryx* and *Confuciusornis* – $^{40}Ar/^{39}Ar$ laser single-grain and K-Ar dating of the Yixian Formation, NE China. Geochimica, **28**(4), 405 – 409 (In Chinese with English abstract).

Padian K, Chiappe L M, 1998. The origin of birds and their flight. Scientific American, **278**(2):28 – 37.

Padian K, 1998. When is a bird not a bird? Nature, **393**:729.

Smith J B, You H -L, Dodson P, 1998. in the Dinofest Symposium, Abstracts (eds. Wolberg, D. L. *et al.*) 55 (Academy of Natural Sciences, Philadelphia).

Smith P E, Evensen N M, York D, Chang M M, Jin F, Li J L, Cumbaa S, Russell D, 1995: Dates and rates in ancient lakes:

$^{40}Ar-^{39}Ar$ evidence for an early Cretaceous age for the Jehol Group, northeast China, Can. J. Earth Sci., **32**:1426–1431.

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

Unwin D M, 1998. Feathers, filaments and theropod dinosaurs. Nature, **391**:119–120.

Wang X -L, Wang Y -Q, Wang Y, Xu X, Tang Z -L, Zhang F -C, Hu Y -M, Gu G and Hao Z -L, 1998. Stratigraphic sequence and vertebrate-bearing beds of the lower part of the Yixian Formation in Sihetun and neighbouring area, western Liaoning, China. Vertebrata Palasiatica, **36**(2): 81–101. (in Chinese with English Summary).

Wang D -F, Diao N -C, 1984. Geochronology of Jura-Cretaceous volcanics in west Liaoning, China. Scientific papers on geology for international exchange. 5. Geological Publishing House, Beijing. 1–12.

Xu X, Tang Z -L, Wang X -L, 1999. A therizinosauroid dinosaur with integumentary structures from China. Nature, 399, 350–354.

Xu Z, 1990. Mesozoic volcanism and volcanogenic iron-ore deposits in eastern China. GSA Special Paper, 237, 46pp.

York D, 1969. Least-squares fitting of a straight line with correlated errors. Earth Planet. Sci. Lett., **5**:320–324.

Zhang L, 1985. Nonmarine ostracod faunas of late Mesozoic in W. Liaoning. In: Mesozoic Stratigraphy and Palaeontology of western Liaoning, 2, Geological Publishing House, Beijing. 1–200.

Appendix: Results of $^{40}Ar/^{39}Ar$ laser single-grain fusion experiments.

No.	Atmos(%)	$^{36}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$	$^{40}Ar/^{36}Ar$	Age (Ma)
				WL1 Biotite			
1102	21.22	0.19183E-01	0.87063E-02	0.44919E-01	0.26737E+02	0.13938E+04	136.2 ± 3.9
1104	6.94	0.54938E-02	0.35608E-02	0.40771E-01	0.23402E+02	0.42596E+04	140.7 ± 2.1
1202	7.40	0.59968E-02	0.24111E-05	0.38171E-01	0.23985E+02	0.39997E+04	143.4 ± 3.0
1204	1.93	0.15750E-02	0.38382E-05	0.33084E-01	0.24083E+02	0.15291E+05	152.1 ± 3.0
1402	3.17	0.26240E-02	0.17717E-03	0.42702E-01	0.24469E+02	0.93249E+04	152.5 ± 2.6
1404	3.29	0.26872E-02	0.41967E-02	0.37126E-01	0.24121E+02	0.89761E+04	150.3 ± 4.5
1406	2.79	0.23400E-02	0.77583E-02	0.36362E-01	0.24792E+02	0.10595E+05	155.0 ± 4.1
1408	5.19	0.40629E-02	0.19359E-05	0.38382E-01	0.23179E+02	0.57050E+04	141.9 ± 4.9
1602	10.19	0.83637E-02	0.38670E-01	0.43410E-01	0.24250E+02	0.28994E+04	140.7 ± 5.1
1604	.01	0.42019E-05	0.42019E-05	0.35552E-01	0.22135E+02	0.52680E+07	142.9 ± 6.5
1606	.01	0.63849E-05	0.63849E-05	0.30313E-01	0.22996E+02	0.36016E+07	148.2 ± 3.8
1702	26.27	0.27861E-01	0.19382E-01	0.48543E-01	0.31365E+02	0.11258E+04	149.1 ± 3.4
1703	18.96	0.18292E-01	0.99795E-02	0.49448E-01	0.28536E+02	0.15600E+04	149.1 ± 2.1
1704	4.07	0.32522E-02	0.29648E-02	0.41306E-01	0.23629E+02	0.72655E+04	146.2 ± 1.9
1705	4.61	0.37748E-02	0.14184E-02	0.40118E-01	0.24210E+02	0.64134E+04	148.8 ± 2.4
1706	1.81	0.14223E-02	0.24006E-05	0.39131E-01	0.23300E+02	0.16382E+05	147.5 ± 2.5
1707	15.88	0.14003E-01	0.27150E-01	0.42675E-01	0.26076E+02	0.18622E+04	141.7 ± 4.8
1708	4.66	0.39933E-02	0.26477E-05	0.41186E-01	0.25333E+02	0.63437E+04	155.4 ± 3.6
1709	3.84	0.32099E-02	0.12083E-02	0.39116E-01	0.24756E+02	0.77124E+04	153.2 ± 3.6

J-value = 0.0037280 ± 0.000035170
Mean Age = 147.1 ± 5.5 Ma
Total Gas Age = 146.8 ± 1.5 Ma

No.	Atmos(%)	$^{36}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$	$^{40}Ar/^{36}Ar$	Age (Ma)
				WL2 Biotite			
2002	18.84	0.17122E-01	0.10661E-05	0.46568E-01	0.26887E+02	0.15704E+04	141.0 ± 2.6
2003	6.44	0.52742E-02	0.16861E-05	0.40897E-01	0.24240E+02	0.45961E+04	146.3 ± 5.4
2004	5.47	0.41487E-02	0.12260E-05	0.36648E-01	0.22444E+02	0.54099E+04	137.2 ± 2.9
2005	0.00	0.37522E-05	0.37522E-05	0.34578E-01	0.22876E+02	0.60968E+07	147.5 ± 5.0
2006	4.82	0.38954E-02	0.29018E-02	0.44432E-01	0.23905E+02	0.61366E+04	146.7 ± 5.5
2102	18.11	0.16574E-01	0.84257E-02	0.44119E-01	0.27065E+02	0.16330E+04	143.1 ± 2.6
2103	3.35	0.25873E-02	0.97135E-02	0.35728E-01	0.22858E+02	0.88348E+04	142.6 ± 5.0
2104	12.97	0.10824E-01	0.19410E-01	0.38394E-01	0.24686E+02	0.22806E+04	138.9 ± 4.9
2202	.01	0.68176E-05	0.68176E-05	0.42275E-01	0.22498E+02	0.33000E+07	145.1 ± 6.2
2203	0.00	0.22184E-05	0.22184E-05	0.41782E-01	0.21191E+02	0.95522E+07	137.0 ± 7.7
2204	.76	0.56975E-03	0.36868E-05	0.41576E-01	0.22056E+02	0.38712E+05	141.3 ± 7.1
2205	2.31	0.17806E-02	0.14466E-05	0.39191E-01	0.22784E+02	0.12796E+05	143.6 ± 6.4

J-value = 0.0037280 ± 0.000035170
Mean Age = 142.5 ± 3.6 Ma
Total Gas Age = 142.2 ± 1.9 Ma

No.	Atmos(%)	$^{36}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$	$^{40}Ar/^{36}Ar$	Age (Ma)
				WL1 Groundmass chip			
202	37.24	0.39119E-01	0.13210E+00	0.35058E-01	0.31043E+02	0.79355E+03	126.4 ± 6.7
203	5.94	0.43081E-02	0.77605E-01	0.14195E-01	0.21353E+02	0.49564E+04	130.1 ± 3.7
216	3.30	0.23126E-02	0.38370E-01	0.14001E-01	0.20681E+02	0.89425E+04	129.6 ± 2.0
523	12.00	0.84789E-02	0.30852E-01	0.13652E-01	0.20885E+02	0.24632E+04	119.4 ± 4.1
505	4.32	0.28887E-02	0.44977E-01	0.15356E-01	0.19690E+02	0.68163E+04	122.3 ± 3.6
516	1.33	0.89544E-03	0.15212E-01	0.11590E-01	0.19896E+02	0.22220E+05	127.3 ± 2.3
507	1.73	0.11219E-02	0.22903E-01	0.10124E-01	0.19041E+02	0.16972E+05	121.5 ± 5.9

J-value = 0.0037280 ± 0.000035170
Mean Age = 125.2 ± 4.2 Ma
Total gas age = 125.1 ± 1.8 Ma

WL2 Groundmass chip

827	9.96	0.66817E-02	0.29573E-01	0.13555E-01	0.19831E+02	0.29680E+04	116.1	± 1.2
809	.91	0.57524E-03	0.16939E-01	0.11922E-01	0.18663E+02	0.32444E+05	120.1	± 1.2
810	-.01	0.40172E-05	0.31474E-01	0.12444E-01	0.18224E+02	0.45366E+07	118.4	± 2.1
811	.04	0.29543E-04	0.11750E-01	0.12115E-01	0.18421E+02	0.62351E+06	119.6	± 1.2
812	0.00	0.62826E-06	0.95985E-02	0.11392E-01	0.18899E+02	0.30082E+08	122.7	± 1.2
902	1.22	0.78232E-03	0.31081E-01	0.14031E-01	0.18843E+02	0.24086E+05	120.9	± 1.4
903	2.09	0.13452E-02	0.30975E-01	0.13219E-01	0.18951E+02	0.14088E+05	120.5	± 1.4
904	1.73	0.11156E-02	0.18844E-01	0.12374E-01	0.19036E+02	0.17063E+05	121.5	± 1.5
905	1.61	0.11073E-02	0.92592E-01	0.13120E-01	0.19947E+02	0.18015E+05	127.2	± 2.0

J-value = 0.0037280 ± 0.000035170
Mean Age = 120.8 ± 3.1 Ma
Total gas age = 120.0 ± 1.1 Ma

Note:

J-value: Weighted mean of one fusion of irradiation standard LP-6 Biotite, having a K-Ar age of 127.8 ± 0.7 Ma (Baksi *et al.*, 1996).

The date is obtained by using the following equations:

$$\text{Date} = \frac{1}{\lambda}\ln\left(1 + J\frac{{}^{40}Ar^*}{{}^{39}Ar_K}\right), \text{ and}$$

$$\frac{{}^{40}Ar^*}{{}^{39}Ar_K} = \frac{\left[{}^{40}Ar/{}^{39}Ar\right]_m - 295.5\left[{}^{36}Ar/{}^{39}Ar\right]_m + 295.5\left[{}^{36}Ar/{}^{37}Ar\right]_{Ca}\left[{}^{37}Ar/{}^{39}Ar\right]_m}{1-\left[{}^{39}Ar/{}^{37}Ar\right]_{Ca}\left[{}^{37}Ar/{}^{39}Ar\right]_m} - \left[\frac{{}^{40}Ar}{{}^{39}Ar}\right]_K$$

where $[\ ]_{Ca}$ and $[\ ]_K$ = isotope ratios of argon extracted from irradiated calcium and potassium salts (values cited in the text) and $[\ ]_m$ = isotope ratio of argon extracted from irradiated unknown.

Age (Ma)=the date calculated using the following decay constants: $\lambda_\varepsilon = 0.581\times10^{-10}yr^{-1}$;

$\lambda_\beta = 4.962\times10^{-10}\ yr^{-1}$; $\lambda = 5.543\times10^{-10}\ yr^{-1}$; $^{40}K/K = 0.01167$ atom % (Steiger and Jäger, 1977).

Mean age is calculated by the mean of all obtained apparent age; whereas, the total gas age is calculated from the sum total gas from all analyses.

The quoted error is one standard deviation and the error estimate doesn't include those for the irradiation monitor and interference correction parameters.