Newly Discovered Tuff in the Lower Shaximiao Formation in Yunyang, Chongqing, Southwestern China and Its Constraint on the Burial Age of the Yunyang Dinosaur Fauna

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Research Article

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**Newly Discovered Tuff in the Lower Shaximiao Formation in
Yunyang, Chongqing, Southwestern China and Its Constraint on the
Burial Age of the Yunyang Dinosaur Fauna**

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Abstract

The Shaximiao Formation is one of the important Mesozoic burial horizons of dinosaur fossils in the Sichuan Basin. Although a large number of research results on the stratigraphic age of the Shaximiao Formation have been published, the age and division of the Shaximiao Formation are still controversial. To a certain extent, this affects the precise constraints on the burial age of the dinosaur fauna in Yunyang, Chongqing. In this study, the newly discovered tuff intercalation in the Lower Shaximiao Formation in Pu'an Township, Yunyang County, Chongqing City, was taken as the research object, and its lithology and formation age were determined using thin section identification, X-ray diffraction (XRD), scanning electron microscopy (SEM), and U-Pb zircon dating. The field observations and thin section microscopic characteristics of the rocks reveal that the clay rock intercalation has a typical sedimentary tuff structure, which is altered lithic tuff. The SEM imaging and XRD results indicate that it has a typical tuff mineral composition. The U-Pb zircon dating shows that the weighted average age of the newly discovered tuff is 174.8 ± 2.4 Ma, and the burial age of the dinosaur fossils is estimated to be 174.7 ± 2.4 Ma based on the sedimentation rate and the thickness of the stratum.

Key words: Sichuan Basin; Shaximiao Formation; Yunyang Dinosaur Fauna; Tuff; Burial Age

1. Introduction

Since 2016, a large number of dinosaur fossils have been found in the Xintiangou Formation and the Lower Shaximiao Formation in the village of Laojun, Pu'an Township, Yunyang County, Chongqing City (Li et al., 2019; Tan et al., 2019, 2020; Dai et al., 2020a, 2020b; Hao et al., 2017), which further expands the distribution range of the Jurassic dinosaur fossils in the Sichuan Basin, China. Previous studies of the stratigraphic ages of the Xintiangou and Shaximiao formations in the Sichuan Basin have conducted a great deal of work, and the opinions on the stratigraphic age of Xintiangou Formation are quite consistent, that is, the Xintiangou Formation was deposited in the Middle Jurassic (Xie et al., 1982; Compilation Group of Terrestrial Mesozoic Stratigraphy and Paleontology in Sichuan Basin, 1982). However, the age and division of the Shaximiao Formation are still somewhat controversial. The Shaximiao Formation is divided into two lithologic sections, i.e., the Upper Shaximiao Formation and the Lower Shaximiao Formation (Zhang, 2017), the naming of which is more in line with the international stratigraphic nomenclature standard (Yang, 2014; Zhang, 2017). The Lower Shaximiao Formation is generally considered to have been deposited in the Middle Jurassic (Wang et al., 2010), and some paleontologists believe that the Upper Shaximiao Formation was also deposited in the Middle Jurassic (Compilation Group of Terrestrial Mesozoic Stratigraphy and Paleontology in Sichuan Basin, 1982; Sun, 1996; Wang et al., 2010). However, some vertebrate paleontologists believe that it was deposited in the Upper Jurassic (Zhao et al., 1965; Dong, 1980; Wang et al.,

2003). Recently, Huang summarized previous data and proposed that the Lower Shaximiao Formation can be divided into the Middle-Upper Jurassic Batongian-Oxfordian, and the Upper Shaximiao Formation can be divided into the Oxfordian-Qinmolian (Huang, 2019). There are also several differences in the relatively precise geological ages reported for the Shaximiao Formation, including 167 Ma, 172 Ma (Electron Spin Resonance) (Zong et al., 1997), 172–167 Ma, 178–169 Ma (ESR) (Gou et al., 2000), 163 ± 3 Ma (the youngest U-Pb zircon age for the detrital rocks) (Li et al., 2010), 160 ± 4 Ma (weighted average age of the detrital rocks) (Luo et al., 2014), 158 ± 7 Ma (weighted average age of the detrital rocks) (Qian et al., 2016), and 159 ± 2 Ma (U-Pb weighted average age of the detrital rocks) (Wang et al., 2018). These results indicate that the existing data cannot effectively constrain the sedimentary age of the Shaximiao Formation, nor can it provide precise burial age constraints for the Yunyang dinosaur fauna found in the Lower Shaximiao Formation in Yunyang, Chongqing, southwestern China.

Due to the lack of large-scale volcanic activity in the Sichuan Basin, there are few reports of tuff. Huang concluded that the claystone of the P/T Boundary in the Zhongliangshan area, Chongqing, was the product of the alteration of volcanic material (Huang, 1992; Zhang et al., 2005). According to Zhang et al., felsic volcanic ash is present in the clay rocks of Middle Jurassic Upper Shaximiao Formation in Wanzhou, and its source may be related to the Tethys volcanic activity (Zhang et al., 2005). Ran et al. conducted U-Pb isotopic dating on the volcanic intercalations in the Xujiache Formation in western Sichuan and obtained a weighted

average age of 214.7 ± 1.6 Ma (Ran et al., 2016). Due to the regional characteristics of the distribution and evolution of terrestrial organisms, it is difficult to compare these fossils with the European marine stage standard fossils, and the isotopic chronology lacks reliable dating materials to accurately restrict the age. In this study, U-Pb zircon isotopic dating was carried out on newly discovered tuff intercalations in the strata underlying the Lower Shaximiao Formation in Yunyang, Chongqing. The ages of the Lower Shaximiao Formation and the burial age of the Yunyang dinosaur fauna were determined.

2. Materials and methods

The tuff intercalation found in this study is located in the Lower Shaximiao Formation, Pu'an Township, Yunyang County, Chongqing City, and it is about 21 m below the dinosaur burial horizon and 210 m above the bottom of the Shaximiao Formation ($30^{\circ}50'42.23''$ N; $108^{\circ}55'22.70''$ E) (Fig. 1). The tuff intercalation is mainly clay, with a thickness of about 8 cm, and is exposed in the clastic rocks. The rock is grayish green and soft (Fig. 2).

Fig.1. Geographic and geologic maps showing the location of the study area. (a) The geographic position of Chongqing city. (b) The geographic position of the study area. (c) Geologic map of the study area.

Fig.2. Field characteristics of the tuff interlayer in the Lower Shaximaio Formation, Yunyang, Chongqing, China. (a) Partial outcrop of the Lower Shaximaio Formation. (b) The tuff interlayer within the Lower Shaximaio Formation. (c) The field characteristic of the tuff.

In order to further determine the lithology and age, we have carried out a series of tests and analysis on the samples. The most ideal block samples HP02-32 were selected for thin section preparation, and then pulverized tuff samples from the fraction $< 2 \mu\text{m}$ were analyzed to determine their total mineral compositions using X-ray diffraction (XRD) at the Chengdu University of Technology, meanwhile the mineral composition of the tuff was analyzed using scanning electron microscopy (SEM).

In order to avoid the influence of the surrounding clastic rocks on the experimental results, in this study, relatively fresh and pure tuff samples were selected for the U-Pb zircon dating. In addition, in order to ensure the randomness of the experiment, the HP02-32 samples were divided into four samples and were sent to the same laboratory for testing. The zircon sorting, target preparation, and testing were conducted by Beijing Zircon Navigation Technology Co., Ltd. (China). The sample and data processing used methods were previously described by Zhang et al. (Zhang et al., 2019).

3. Results

3.1. Petrography

Under the microscope, the rock exhibits an obvious crystal chip tuff structure, which is composed of crystal chips, tuff grade glass chips, and volcanic dust. Melted harbor like quartz (Figs. 3a, b), rock debris (Figs. 3c, d), explosive crystal chips (Fig. 3e), arc-shaped semi plastic glass chips, and tearing mica (Fig. 3f) were observed. The volcanic ash is closely accumulated in the form of dust spots, and it exhibits

complete extinction under an orthogonal microscope. A small amount of the tephra exhibits devitrification, indicating weak optical properties. However, the particles are too small to be further resolved.

Fig.3. Microphotograph (+) of the tuff in the Lower Shaximiao Formation, Yungyang, Chongqing, China. (a) Macroscopic features of quartz. (b) Corrosion pits and corrosion harbour of quartz. (c) Pyroclastic rock fragment. (d) Rock detritus. (e) Burst angular crystal fragment. (f) Cambered semi-plastic vitric fragment and tearing mica.

The microscopic characteristics of the samples reveal that they have undergone a certain degree of alteration. Moreover, they are different from the typical lithic crystalline tuff studied by other scholars (Xu et al., 2019). However, they are somewhat similar to the characteristics of sedimentary tuff (Tang, 2020). Therefore,

in this study, this tuff is defined as an altered clastic tuff.

3.2. X-ray diffraction (XRD) analysis

The mineral compositions obtained from the XRD analyses are presented in Table 1. Representative XRD diagrams are shown in Fig. 4. The tuff samples are dominated by clay minerals (58–62%), quartz (21–22%), and plagioclase (17–19%). It is worth noting that the XRD results show that bentonite exists in the samples.

The volcanic ash produced during a volcanic eruption can be transported and distributed at a distance from the crater by wind, water, and other media (Ruddiman et al., 1972; Brown et al., 2012; Qiu et al., 2014). In sedimentary environments, volcanic ash (tephra) usually alters to clay minerals (e.g., smectite and illite) during diagenesis (Liao et al., 2016; Hong et al., 2017, 2019), and these devitrified volcanic ash fall beds are usually referred to as K-bentonites (Hong et al., 2019).

Table 1 Mineral compositions from the XRD analysis results

Sample	Mineral compositions (wt%)
HP02-32-1	clay minerals (illite/smectite) 62; quartz 21; plagioclase 17
HP02-32-2	clay minerals (illite/smectite) 58; quartz 22; plagioclase 19

Fig. 4. Representative XRD patterns of the Lower Shaximiao Formation tuff.
I/S: illite/smectite; Q: quartz; and Pl: plagioclase.

3.3. Scanning electron microscopy analysis

Under the scanning electron microscope, lamellar illite (Fig. 5a) and kaolinite (Fig. 5b) with an incomplete crystal morphology were observed. The boundary between the feldspar and matrix in the thin section is clear, and fine lines similar to cleavage or bicrystals were observed at the fracture surfaces. The fine grains are transverse grains corresponding to the long axis direction (Fig. 5c) and prismatic laumontite (Fig. 5d). The results of the scanning electron microscopy and X-ray diffraction are basically consistent, and the samples may be intermediate felsic tuff.

Fig. 5. Scanning electron microscope (SEM) imaging characteristics of the Lower Shaximiao Formation tuff in Yunyang, Chongqing (All of the images are backscattered electron images, BSED.).

3.4. *U-Pb zircon geochronology*

The cathodoluminescence (CL) images of the zircons (Fig. 6) show that most of the zircons exhibit relatively consistent morphological characteristics, i.e., complete zircon grains, straight edges, a high degree of automorphism, and mostly long columnar shapes, which are obviously different from those of general detrital zircons. The zircons studied were 90–180 μm long, 35–90 μm wide, and have length to width ratios of 2:1 to 3:1. Most of the zircons had obvious magmatic oscillatory zonation structures with uniform and small widths. The Th/U ratios of the zircons ranged from 0.35 to 1.3, with an average of 0.60, indicating that the zircons are of magmatic

origin (Andersen, 2002; Belousova, 2002).

A total of 44 zircons were selected for the U-Pb isotopic dating. After deducting the lower concordance zircon age data, 34 sets of data (concordance > 90%) were used. The data shows that the minimum age of the zircons was 167 Ma, and the maximum age was 1851 Ma, with two peak ages of ~170 Ma and ~230 Ma. The dominant peak age was ~170 Ma (sample number 16) (Figs. 6, 7). The weighted average age was 174.8 ± 2.4 Ma (N =16, MSWD=5.0). According to the latest geological time scale, the age of the tuff is near the boundary between the Early Jurassic and the Middle Jurassic. The U-Pb zircon ages exhibit a distribution pattern consistent with detrital zircon ages, which may be because some clastic rocks were mixed into the volcanic ash during diagenesis.

Fig. 6. CL image of zircons from the tuff in Lower Shaximiao Formation, Yungyang, Chongqing

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Fig. 7. Zircon U-Pb concordant age of the tuff in the Lower Shaximiao Formation, Yunyang, Chongqing, China.

4. Discussion

The Shaximiao Formation is one of the important burial horizons for Mesozoic dinosaur fossils in the Sichuan Basin. Previous discussions of the age of the dinosaur fossil burial horizon have mainly been based on regional lithologic correlations (Hou et al., 1976), dinosaur fossil species (Zhao, 1965), and invertebrate fossil assemblage (Wang et al., 2005), additionally, some scholars have tried to constrain the fossil burial age through detrital zircon U-Pb dating of the underlying strata (Wang et al., 2018). In this study, we also attempted to use the sporopollen assemblage and U-Pb zircon dating of the clastic rocks to constrain the burial age of the fossils. Spore and pollen samples were collected from the Shaximiao Formation in Pu'an Township, Yunyang, Chongqing. The lithology of the samples was purplish red silty mudstone. Only two fern spores, *Deltoidospora* and *Baculatisporites*, were identified in the 20 sporopollen samples. The results show that it is difficult to determine the burial age of the dinosaur fossils based on the sporopollen assemblages in the study area due to the lack of pollen in the Lower Shaximiao

Formation. U-Pb zircon dating of clastic rock sample (Sample HP02-54, discussed in another paper) from beneath the fossil burial horizon in the Lower Shaximiao Formation in the study area shows that the samples have five age ranges of ~160–180Ma, ~240–260 Ma, ~420–450 Ma, ~1730–1900 Ma, and 2400–2600 Ma. The six youngest zircons were selected to calculate the weighted average age of 169 ± 0.65 Ma (N = 6, MSWD = 2.05). This age is younger than that of the tuff.

The U-Pb age of the zircons from the tuff effectively constrain the burial age of dinosaur fossils (Luo et al., 1999; Jiang et al., 2010; Wang et al., 2020). Therefore, the discovery of this sedimentary tuff interlayer in the study area provides new material and ideas for effectively constraining the age of the Shaximiao Formation and for determining the burial age of the Yunyang dinosaur fauna. Therefore, we believe that the U-Pb zircon age of the sedimentary tuff can limit the burial age of the dinosaur fossils. The age of the Upper Shaximiao Formation is about 169 ± 0.68 Ma (Sample HP02-361, discussed in another paper), and the thickness between the two layers is about 1050 m. The calculated sedimentation rate is about 210 m/Ma. The bottom of the Lower Shaximiao Formation is about 210 m below the tuff interlayer. The burial horizon of the Yunyang dinosaur fauna is about 21 m above the tuff interlayer. It is inferred that the lower age limit of the Shaximiao Formation in Yunyang, Chongqing, is 175.8 ± 2.4 Ma, and the burial age of the dinosaur fossils is 174.7 ± 2.4 Ma.

5. Conclusions

Based on the petrographic, SEM, XRD, and U-Pb zircon dating analyses of the newly discovered tuff in the Lower Shaximiao Formation, Yunyang, Chongqing, it is concluded that the tuff is a lithic crystalline tuff, with an average weighted U-Pb zircon age of 174.8 ± 2.4 Ma, which is near the boundary between the Lower Jurassic and the Middle Jurassic. Based on the deposition rate and thickness, the burial age of the dinosaur fossils is 174.7 ± 2.4 Ma.

List of abbreviations

ESR Electron Spin Resonance

XRD X-ray Diffraction

SEM Scanning Electron Microscopy

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Author contributions

Yuxuan Zhou lead the project, organize the paper. Wenguang Yang is in charge of writing and refining the paper. Hongliang Zhang is responsible for all plots, initial analysis and some writing. All other co-authors make equal contributions by wording discussions, comments and reading proof.

Availability of data and materials

All data and materials generated or analyzed during this study are included in this published paper

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.