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Chronological evidence for extension of the Jehol Biota into Southern China

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ABSTRACT

The fossils of the Cretaceous Jehol Biota are magnificent, exquisitely preserved and extraordinarily diverse. Strata that may be correlative with the classic Jehol localities are known over much of Central and Eastern China, as well as Korea, Japan, Mongolia and Siberia. It has been previously hypothesized based on fossil assemblages that the Jehol Biota progressively expanded from the classic Jehol area, with younger representatives covering progressively larger geographic ranges. It has been interpreted that the youngest Jehol Biota bearing layers are in the East Anhui province of South China. Here we present robust $^{40}Ar/^{39}Ar$ dates of 129.0 ± 0.2 Ma for one rhyolite sample from the lower Longwanshan Formation and 127.1 ± 1.3 Ma and 128.0 ± 0.9 Ma for two volcanic samples from the upper Honghuaqiao Formation from the outcrops of Jehol fossils in East Anhui. Our age results indicate that fossils from these formations are time-equivalent to the second phase fossils from the lower Yixian Formation in the western Liaoning, NE China, and the deposition of these beds is at least 6 Ma older than previously estimated. Therefore our results suggest that the hypothesis of the Jehol radiation and migration should be reevaluated.

1. Introduction

The Cretaceous Jehol Biota is widely distributed in Central and Eastern Asia (Fig. 1) (Grabau, 1928; Gu, 1962; Chen, 1988, 1999; Chang et al., 2003; Zhou et al., 2003). The discovery of the feathered dinosaur by a farmer in Sihetun village, Beipiao City, Liaoning, NE China has led to intense exploration efforts, and the fossils of the Jehol Biota are now known to include a diverse assemblage of plants, insects, frogs, salamanders, dinosaurs, pterosaurs, choristoderes, birds, mammals and freshwater invertebrates. These fossils often preserve articulated skeletons, soft tissues including skin, feathers, and claw sheaths, color patterns and stomach contents (Chen et al., 1998; Ji et al., 1998; Gao et al., 2000; Currie and Chen, 2001; Xu et al., 2001; Norell and Xu, 2005; Zhang et al., 2010). Because of the exceptional preservation of fossils, the Jehol Biota is regarded as one of the most important Mesozoic lagerstätten (Zhou and Wang, 2010), rivaling the much longer-known Solnhofen Lithographic Limestones and Posidonia Shales from the Jurassic of Europe (Fürsich et al., 2007), both of which represent brackish-water environments. Vertebrate fossils discovered from the Dabeigou, Yixian and Jiufotang Formations from the classic outcrops in NE China have influenced our understanding of the bird origins, the evolution of feathers and flights and the timing of placental mammal radiation. Although less studied than vertebrates, abundant invertebrate fossils, including insects, spiders, crustaceans, bivalves and gastropods, are commonly found from the Jehol related formations in NE China. The high diversity and abundance of the Jehol insects, particularly, provide a unique window to understand the insect evolution and its diversification in Mesozoic (Zhang and Zhang, 2003; Zhang et al., 2010).

In addition to their extensive distribution in NE China, other strata that may be correlative with the classic Jehol Biota have been identified extensively in Central and Eastern China, as well the Korean Peninsula, Japan, Mongolia, Kazakhstan and Siberia (Chen, 1988, 2003; Zhou et al., 2003; Li and Gao, 2007). However, the chronological constraints on these finds are poorly known (Chang et al., 2003). Furthermore, the detailed stratigraphic correlation between the classic Jehol outcrops and the less-studied localities has yet to merge. In the past three decades, fossils of the Jehol Biota, including mollusks, conchostracans, ostracods, insects, fish and plants, have been found from localities of SE China (Mateer and Chen, 1986; Garassino et al., 2002; Li, 2003; Chen et al., 2007). Here, we present new $^{40}Ar/^{39}Ar$ data for three volcanic samples from the purported Jehol localities in SE China. The data enable us to correlate these formations in detail with the classic Jehol strata and test the hypothesis of the Jehol radiation and migration.

2. Phases and distribution of the Jehol Biota

Based on paleontological studies, the Jehol Biota is divided into three developing stages and each phase of the Jehol Biota corresponds to the Daibeigou, Yixian and Jiufotang Formations near the classic outcrops in NE China (Fig. 1 and Table 1) (Chen, 1988, 1999; Zhou, 2006). Fossil abundance and taxic diversity from the first phase of the Jehol Biota are low. For example, many indicator taxa from the later phases,

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including dinosaurs, the fish *Lycoptera* and the ostracod *Cypridea*, are absent from the oldest phase in NE China. Deposits from the second phase record a high diversity of plants and animals, indicating a thriving ecosystem. Several groups characteristic of the Jehol Biota had distinctive radiations during this time interval (Ji et al., 2002; Luo et al., 2003, 2007; Hu et al., 2005; Zhou, 2006). For example, insects significantly increased the diversity up to more than 500 species in 100 families and 16 orders in this phase (Zhang and Zhang, 2003). At least 23 genera of birds have been identified from the second phase in NE China, indicating the largest radiation in the Mesozoic avian evolutionary history (Zhou, 2006). Fossils from the third phase show that most groups characteristic of the Jehol Biota persisted through geologic time, although the fossil assemblage from the third phase in NE China is distinct from the previous ones (Unwin et al., 2000; Wang and Zhou, 2003; Zhou et al., 2003).

The first phase of the Jehol Biota is geographically restricted to a relatively small area in NE China and Siberia. The second and the third phases are found over a wider area (Fig. 1). Although detailed geological, paleontological and geochronological studies for the sampling localities in SE China are only sparsely available, paleontologists generally accepted that fossils from the sampling localities represent the third phase of the Jehol Biota (Chen, 1988, 1999; Zhou, 2006). This progressively expanding area through geologic time has led to the hypothesis that the Jehol Biota initially evolved in a concentrated area and then spread laterally as either ecosystems or organismal distributions expanded.

3. Samples

Since the 1980s, a wide range of Jehol fossils have been unearthed from localities in SE China (Mateer and Chen, 1986; Garassino et al., 2002; Li, 2003; Chen et al., 2007), although these localities remain understudied relative to Jehol deposits from NE China. Volcanic rocks are common in less-studied localities across SE China making it possible to correlate to the classic outcrops of NE China through high-precision dating. Three samples for $^{40}Ar/^{39}Ar$ dating were collected from two fossil-bearing formations in different localities of Anhui Province. The sampling localities and their stratigraphic relationships are shown in Fig. 2.

The 312–592 m thick Longwanshan Formation of eastern Anhui and western Zhejiang mainly consists of conglomerate, siltstone, breccia, tuff and rhyolite (Bureau of Geological and Mineral Resources of Anhui, 1987; Bureau of Geological and Mineral Resources of Zhejiang, 1989). Limited radioisotopic studies suggested that the age of the Longwanshan Formation is 125–136 Ma (Wang and McDougall, 1980; Zhang, 2009). The large uncertainties of most of these data and the incomplete stratigraphic descriptions of the samples limit their value for high-resolution chronostratigraphy.

The 262 meter thick Honghuaqiao Formation in the Eastern Anhui, equivalent to the Longwanshan Formation and also called the Pengjiagou Formation or the Zhongfencun Formation in different basins, is mainly composed of conglomerate, siltstone, tuff, breccia and trachyandesite (Bureau of Geological and Mineral Resources of Anhui, 1987). Until now radioisotopic ages for the Honghuaqiao Formation have not been reported.

4. $^{40}Ar/^{39}Ar$ geochronology

Sample preparation and analysis were conducted at AGES (Argon Geochronology for the Earth Sciences) at Lamont-Doherty Earth Observatory of Columbia University. Fresh plagioclases from HHQ09-2 and HHQ09-3, and sanidines from LWS09-1 are suitable for $^{40}Ar/^{39}Ar$

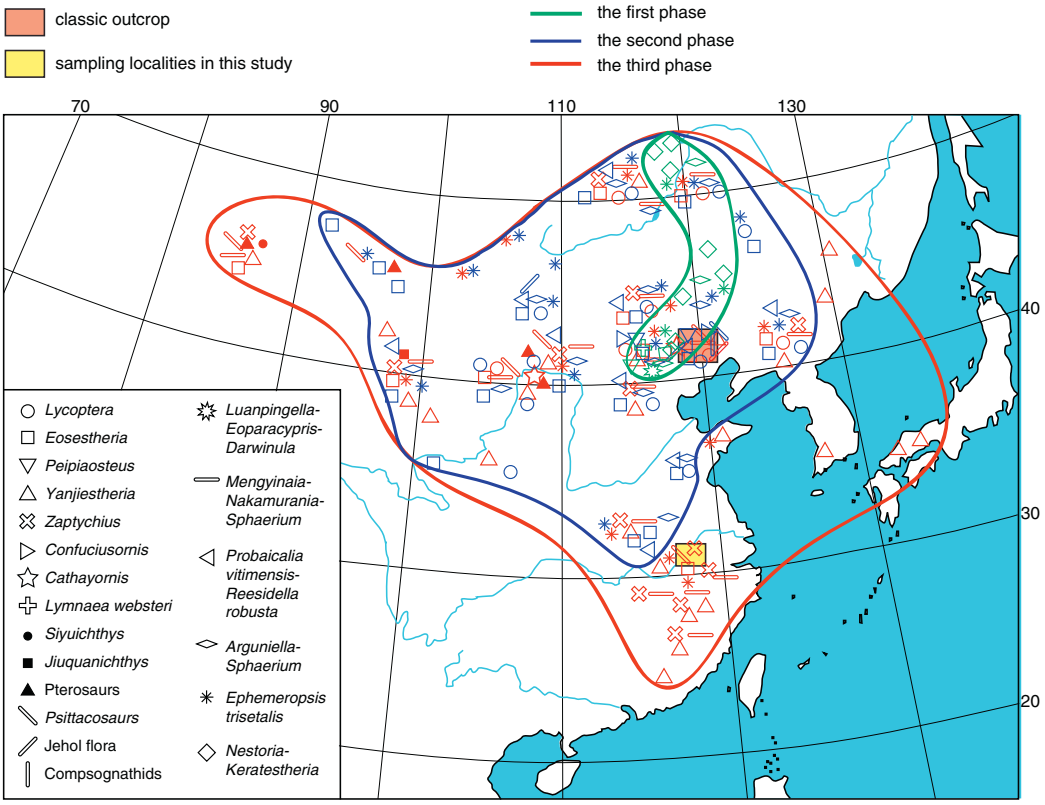

Fig. 1. The freshwater and terrestrial Jehol Biota, defined as the characteristic *Eosestheria–Ephemeropsis–Lycoptera* assemblage (Grabau, 1928), was widely distributed in East and Central Asia. Evidence indicated that each Jehol fossil-bearing formation has preserved a distinct assemblage of invertebrate and vertebrate fossils. Based on major invertebrate groups, the Jehol Biota is divided into three developing stages. A hypothesis demonstrated that the later phases of the Jehol Biota had wider geographic distributions (Chen, 1988, 1999). Our geochronology work enables us to test the timing and the duration of three phases of the Jehol radiation.
(After Chen, 1999).