Palaeogeography, Palaeoclimatology, Palaeoecology 427 (2015) 89–99

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

# The Chinese Pompeii? Death and destruction of dinosaurs in the Early Cretaceous of Lujiatun, NE China

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ARTICLE INFO

*Article history:*
Received 3 September 2014
Received in revised form 19 March 2015
Accepted 20 March 2015
Available online 28 March 2015

*Keywords:*
Dinosaur
Cretaceous
Jehol Biota
Liaoning
Lahar
Taphonomy

ABSTRACT

The Lujiatun Unit (Yixian Formation) yields some of the most spectacular vertebrate fossils of the Jehol Group (Lower Cretaceous) of NE China. Specimens are preserved both articulated and three-dimensional, unlike the majority of Jehol fossils, which are near two-dimensional compression fossils. The site has been referred to as the 'Chinese Pompeii' because the dinosaurs and other animals were assumed to have been killed and buried by hot, airborne volcanic debris and ash in a single event; this has yet to be confirmed. Field and laboratory evidence for the sedimentological context of the fossils from the Lujiatun Unit is described in detail, and used to assess whether the fossil remains correspond to a single depositional event and whether this event was the direct result of volcanic activity. Fossils of the Lujiatun Unit occur in several horizons of volcaniclastic sediments that represent multiple depositional events. Petrological analysis shows that the fossil-bearing sediments were remobilised and deposited by water. The Lujiatun dinosaurs and other fossils were therefore not killed by a single airborne volcanic ash, but in multiple flood events with a high load of volcaniclastic debris.



## 1. Introduction

The Jehol biotas from NE China offer an unparalleled window into Early Cretaceous terrestrial ecosystems, yielding highly abundant, exceptionally preserved fossils (Zhou et al., 2003; Benton et al., 2008). The most common Jehol fossils include plants, insects, aquatic invertebrates, fishes, salamanders, and feathered dinosaurs (Zhou et al., 2003), early birds (Zhou and Zhang, 2007), and other taxa linked to the Cretaceous terrestrial revolution (Lloyd et al., 2008). These fossils occur in sediments of the Jehol Group, and are typically preserved, as flattened, near-two-dimensional, compression fossils, in laminated fine-grained lacustrine deposits (Zhou et al., 2003; Benton et al., 2008; Pan et al., 2013).

The lowest part of the Jehol Group is the Yixian Formation; its most basal division, the Lujiatun Unit (Fig. 1), is known for its unusual fossil preservation. In contrast to other fossils from the Jehol Group, specimens from Lujiatun lack non-biomineralised tissues, and are, instead, partially or fully articulated three-dimensional skeletons hosted within volcaniclastic sediments (Zhao et al., 2007; Benton et al., 2008). The faunal composition of the Lujiatun Unit is also distinct from that of the remainder of the Jehol Group, comprising only dinosaurs, mammals and reptiles (McKenna et al., 2006; Evans et al., 2007; Zhao et al., 2007). The fossil assemblage is dominated by the ceratopsian dinosaur *Psittacosaurus*, the ontogeny and population biology of which have been studied in detail (Erickson et al., 2009; Zhao et al., 2013, 2014). A semi-arid climate during deposition of the Jehol Group has been proposed on the basis of plant fossils and sedimentology (Fürsich et al., 2007; Jiang and Sha, 2007). However, subsequent analysis of stable isotope ratios from dinosaur fossils suggests that a cool temperate climate would have been prevalent (Amiot et al., 2015).

The fossiliferous Lujiatun sediments have been referred to as the 'Chinese Pompeii' because of the suggestion that the dinosaurs and other fossil vertebrates were killed (Zhao et al., 2007; Jiang et al., 2014) and even transported (Jiang et al., 2014) by volcanic debris flows (lahars), suggesting a mode of preservation akin to the historical catastrophe at Pompeii.

A particular problem for study of the Lujiatun specimens is that many lack information on their precise stratigraphic context, often as a result of illegal excavation (Du, 2004). Recent work reporting on the taphonomy and sedimentology of a specimen containing several *Psittacosaurus* from the Lujiatun Unit has reiterated the need for

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http://dx.doi.org/10.1016/j.palaeo.2015.03.037

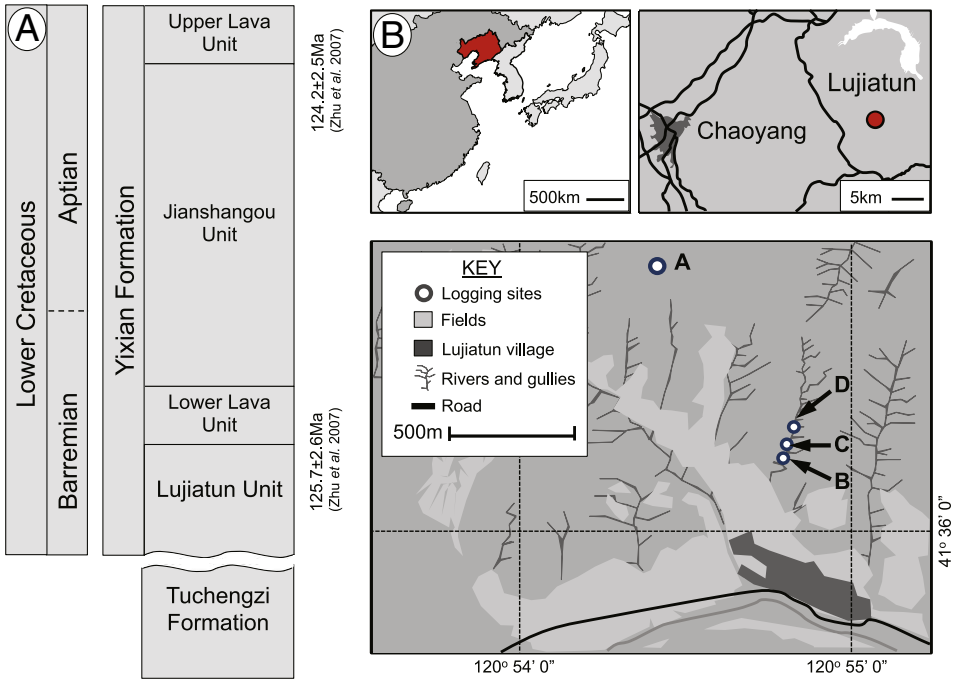


**Fig. 1.** The Lujiatun Unit, part of the Jehol Group, in NE China. A. Stratigraphic context of the Lujiatun Unit with $^{40}Ar/^{39}Ar$ ages of the Lower and Upper Lava Units (Zhu et al. (2007). B. Location maps for of sites logged (A–D) around Lujiatun and position of Lujiatun in Liaoning Province (highlighted), NE China.

stratigraphic context of specimens in order to properly assess the taphonomy of the unit as a whole (Hedrick et al., 2014). Therefore, identification and analysis of the fossiliferous horizons within the Lujiatun Unit is crucial to testing the 'Chinese Pompeii' hypothesis and understanding the sequence of events that led to such a distinctive mode of preservation. Critically, no study has yet provided a field or stratigraphic context for fossils from the Lujiatun Unit; further, it has yet to be confirmed whether any fossils supposedly from Lujiatun (especially those sourced illegally), actually originate from the Lujiatun Unit.

Here, the first account of the sedimentology of the Lujiatun Unit is presented. Using data from the field and from laboratory analysis of sediments from Lujiatun and from museum specimens of Lujiatun fossils, the stratigraphic position of the fossils within the logged succession is investigated, and the hypothesis of whether the dinosaurs, reptiles and mammals truly were overwhelmed and transported by volcanic debris flows is tested.

*Repository abbreviations* — IVPP, Institute of Vertebrate Paleontology and Paleoanthropology, Beijing; DMNH, Dalian Museum of Natural History.

## 2. Geological setting

The deposits of the Jehol Group are distributed around the confluence of Liaoning, Hebei and Inner Mongolia provinces, in north-eastern China (Benton et al., 2008). The Jehol Group unconformably overlies the Jurassic–Early Cretaceous Tuchengzi Formation. The Lujiatun Unit is a regional horizon within the Jehol Group (Fig. 1), occurring at the base of the succession, and underlying the Lower Lava Unit. Where it is absent, the Lower Lava Unit and even Jianshangou Unit, overlie the Tuchengzi Formation (Hethke et al., 2013). The Lower Lava Unit provides an ideal marker for the top of the Lujiatun Unit; it is traceable over an area measuring 4 km by 8 km, the unit ranges in thickness from 0.7–17 m in distal portions, to 200–300 m in the proximal area in the northwest, close to the presumed volcanic source (Jiang et al., 2011).

The Jehol Group encompasses, in stratigraphic order, the Yixian Formation (125–120 Ma), Jiufotang Formation, and Fuxin Formation (Pan et al., 2013). The group is late Hauterivian to early Aptian in age (Zhou et al., 2003; Benton et al., 2008). Current estimates for the age of the Lujiatun Unit are based on radiometric dates from the overlying Lower Lava Unit, and from tuffs within the Lujiatun Unit, and range from 124.9 Ma (Yang et al., 2007; Jiang et al., 2011) to 123.2 Ma (He et al., 2006; Jiang et al., 2011).

The fossils from the Jehol Biota have been researched extensively (Xu and Norell, 2004; Hu et al., 2005; Dong et al., 2013), but surprisingly little is known about the sedimentological context or taphonomy of fossils from the Lujiatun Unit (Zhao et al., 2007). Studies to date have provided a broad classification of the facies within the Lujiatun Unit, described the context of the unit within the regional geology of the area (Jiang and Sha, 2007; Jiang et al., 2011) and analysed the matrix of two Lujiatun specimens, one a cluster of *Psittacosaurus lujiatunensis* juveniles (Zhao et al., 2007), the second another assemblage of predominantly juvenile *Psittacosaurus* (Hedrick et al., 2014).

The Lujiatun Unit has been repeatedly described as a series of extensive fossiliferous tuffs, which show little to no stratification, but do display lateral variation in thickness (Zhou et al., 2003; He et al., 2006). A more thorough analysis of the area revealed that the Lujiatun Unit additionally consists of sheetflow, streamflow, sheetflood, debris flow and lahar deposits (Jiang and Sha, 2007; Jiang et al., 2012). The spatial distribution of the Lujiatun Unit and overlying Lower Lava Unit, in particular their consistent thinning southward (Jiang et al., 2011) and eastward (Jiang and Sha, 2007) suggests that they comprise a volcaniclastic, alluvial apron with a shield volcano at its centre (Jiang et al., 2011). In the Sihetun–Huanbanjigou area, this alluvial apron was deposited along the northern edge of a NW–SE trending basin, with the volcanic centre at the northwesternmost edge (Jiang et al., 2011). Whereas this study focuses upon Lujiatun village, the richest site for fossils in the Lujiatun Unit, earlier sedimentological accounts are based on more western locations (e.g. Jiang and Sha, 2007, 2011) and thus are not relevant to the unique mode of preservation of the Lujiatun fauna.

In a petrological analysis of the matrix of a cluster of articulated juvenile *P. lujiatunensis* (IVPP V14341), Zhao et al. (2007) suggested that the fossiliferous horizon within the Lujiatun Unit is composed predominantly of remobilised volcanic material that had undergone several cycles of transport and deposition. IVPP V14341 shows no evidence of mixing of bones between individuals; this plus a lack of bioturbation, suggests that there was little to no time between death and burial for