

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



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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 volcanoclastic 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 volcanoclastic debris.

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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 volcanoclastic 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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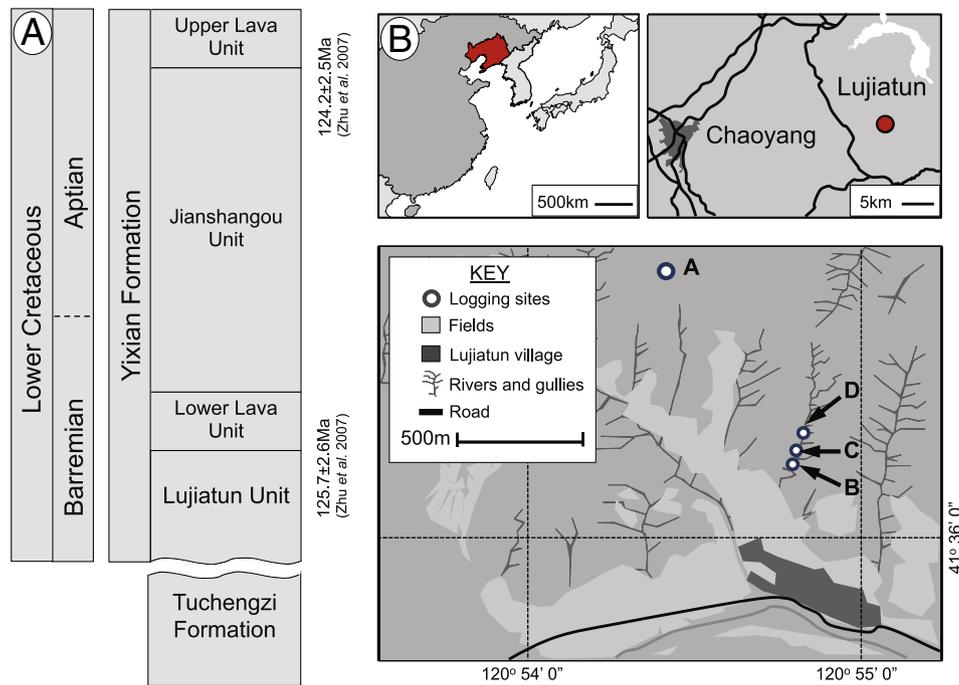


Fig. 1. The Lujiatun Unit, part of the Jehol Group, in NE China. A. Stratigraphic context of the Lujiatun Unit with $^{40}\text{Ar}/^{39}\text{Ar}$ ages of the Lower and Upper Lava Units (Zhu et al. (2007)). B. Location maps for sites logged (A–D) around Lujiatun and position of Lujiatun in Liaoning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

disruption of the carcasses via scavenging (Zhao et al., 2007). The host sediment was considered to comprise a high-density cohesive flow and not a turbulent hydraulic flow or aeolian deposit, on the basis of its high clay content, poor size sorting, massive texture and matrix-supported grains (Zhao et al., 2007). This list of characters supports a previous hypothesis that the entire Lujiatun succession represents a single catastrophic depositional event, in this case identified as a lahar (Wang and Zhou, 2003; Zhao et al., 2007). In a second study on a different cluster of predominantly juvenile *Psittacosaurus* (DMNH D2156), Hedrick et al. (2014) noted that the sediment appears to have been formed by a rapidly deposited volcanoclastic flow, which they interpreted as a lahar or fluvial deposit on the basis of its clay-rich matrix, and the concurrence of the preferred orientation of specimens and the prevailing flow direction. Though the matrix of DMNH D2156 is rich in volcanic products, a pyroclastic flow origin was rejected by Hedrick et al. (2014), based upon the lack of charring or modification to bone microstructure of the *Psittacosaurus*, expected from exposure to intense heat in a pyroclastic flow (Jiang et al., 2014). The burial of animals in the Lujiatun Unit by a catastrophic volcanoclastic flow has been the standard view, reiterated through the popular conception of Lujiatun as the ‘Chinese Pompeii’. This hypothesis was supported by Jiang et al. (2014), who further suggested that all terrestrial Jehol fossils, not just those at Lujiatun, had been killed by volcanoclastic flows, and that the fossils had been transported by those flows to the site of deposition.

Other studies, however, have proposed alternatives to this ‘Chinese Pompeii’ model. Some authors have invoked multiple massive catastrophic high-energy depositional events (Jiang and Sha, 2007), whilst others have argued for burial in volcanic debris by a flooding event, or entombment by the collapse of burrows (Meng et al., 2004). It is clear that there is no consensus as to whether or not these events were linked to volcanism, and how the animals died and became buried. In addition, the sedimentary matrix of some fossils includes mudstone lenses (Evans et al., 2007) and other heterogeneities such as burrow mottling (Meng et al., 2004), suggesting that the genesis of the Lujiatun Unit may be more complex than a single catastrophic volcanoclastic burial event.

3. Methods

The present work is based primarily on data from two field trips made in 2013, but also includes data from specimens at IVPP (including earlier observations by Zhao et al., 2007). The Lujiatun Unit was logged at four sites near to Lujiatun village, Beipiao, Liaoning Province (41°35′57.3714″ N, 120°54′45.0822″ E) (Figs. 1, 2). An extensive section (Fig. 3A) was logged 1.4 km to the northwest of the village; samples were collected from individual beds where possible; larger sedimentary packages composed of multiple beds, which share a similar lithology, were sampled every 0.2 m. Three logs (Fig. 3B–D) were made 0.43 km to the north of the village, along a transect of 135 m (Fig. 1B).

These logging locations were selected, and the exact horizons from which dinosaur specimens had been recovered were confirmed by three means.

- (1) The matrix of two fossils at IVPP that were thought to have originated from the Lujiatun Unit were sampled, so that the fossil matrix could be compared with rock samples taken in the field and keyed to the logs. Samples were retrieved from IVPP V14341, a cluster of juvenile *Psittacosaurus* (Zhao et al., 2007), and another separate single adult *Psittacosaurus* IVPP V14748.
- (2) Signs of excavation were observed at several points close to the sites of logs A–C, where specimens had been excavated previously, and these indicated fossiliferous levels (Fig. 2B–C). At one of these excavations exposed vertebrate fossil remains were identified in situ.
- (3) In 2007, MJB had visited the localities in the company of IVPP palaeontologists Zhou Zhonghe and Zhang Fucheng, and they

used their existing knowledge to identify the sites of logs B–D as typical of where the fossils were found (Fig. 2A–B). Further, one of us (QZ) has worked extensively on the local fossils (e.g. Zhao et al., 2007). Further, because of the intense activity over many years by illegal excavators, QZ interviewed those informants, and a local collector also identified the locality of log A as a source of dinosaur specimens, on the second field trip (Fig. 2C–E).

Prior to thin sectioning, rock samples from the field and those removed from the *Psittacosaurus* slabs at IVPP were dehydrated at 30–40 °C in an oven for 12 h. Samples were subsequently embedded in Epo-fix under vacuum at room temperature and cut using a Buehler ISOMET low speed saw equipped with a diamond wafering blade. Cut surfaces were re-impregnated with Epo-thin, polished and fixed to a frosted glass slide using a further layer of Epo-thin under vacuum, then ground and polished down to a thickness of 30 µm using oil-based lubricants to avoid compromising the integrity of the mud-dominated sediments.

Slides were analysed using a Nikon Eclipse LV100D–U stereomicroscope with NIS Elements software to calculate sediment composition and grain size. Offcuts from the manufacture of slides were polished, sputter-coated with carbon, and examined using a Hitachi S3500N variable-pressure scanning electron microscope equipped with an EDAX Genesis energy dispersive spectrometer (EDS). Rocks and sediments were classified according to the schemes in Hallsworth and Knox (1999).

4. Sedimentary succession

Field observations confirmed the position of the Lujiatun Unit beneath the extrusive vesicular trachyandesites of the Lower Lava Unit (Jiang et al., 2011) and above the underlying green sandstones of the Tuchengzi Formation (Zheng et al., 2001; Chen et al., 2006).

The Lower Lava Unit at the top of each log is a clear stratigraphic marker, whereas each log begins at a different level within the unit; so the sedimentary log is described from top to bottom. The four logs vary in thickness from 10–19 m and show significant lateral variation. The following sequence of sediment packages was identified beneath the Lower Lava Unit; not all units are present in all sections (from top to bottom): variegated sequence of sandstones, upper grey siltstones, pink tuffaceous sandstones and lower tuffaceous siltstones (Fig. 3). The lowest part of the Lujiatun Unit was obscured by debris and vegetation, but its basal contact was inferred by the first appearance of distinctive green sandstones characteristic of the upper part of the Tuchengzi Formation (Chen et al., 2006).

Below the Lower Lava Unit, a variegated sequence of upper sandstones was identified in logs B–D (Fig. 3). This is absent in log A. These upper sandstone deposits appear to vary in thickness, with some pinching out laterally over 50 m (Fig. 3B–D).

4.1. Lower Lava Unit

The lower boundary of the Lower Lava Unit is in contact with different beds within the Lujiatun Unit at different sites; the underlying sediments at all sites exhibit a clear baked margin implying lateral variation in the thickness of beds between sections. The Lower Lava Unit, typically ca. 10–20 m thick, comprises olivine basalts, basaltic andesites, and trachyandesites (Jiang et al., 2011, 2012).

4.2. Upper grey siltstones (UGS)

The upper grey siltstones (UGS) underlie the variegated sandstones and comprise the majority of sections in logs A–C; they are not present in log D (Figs. 3A–C, 4C). The UGS is a ca. 7-m-thick

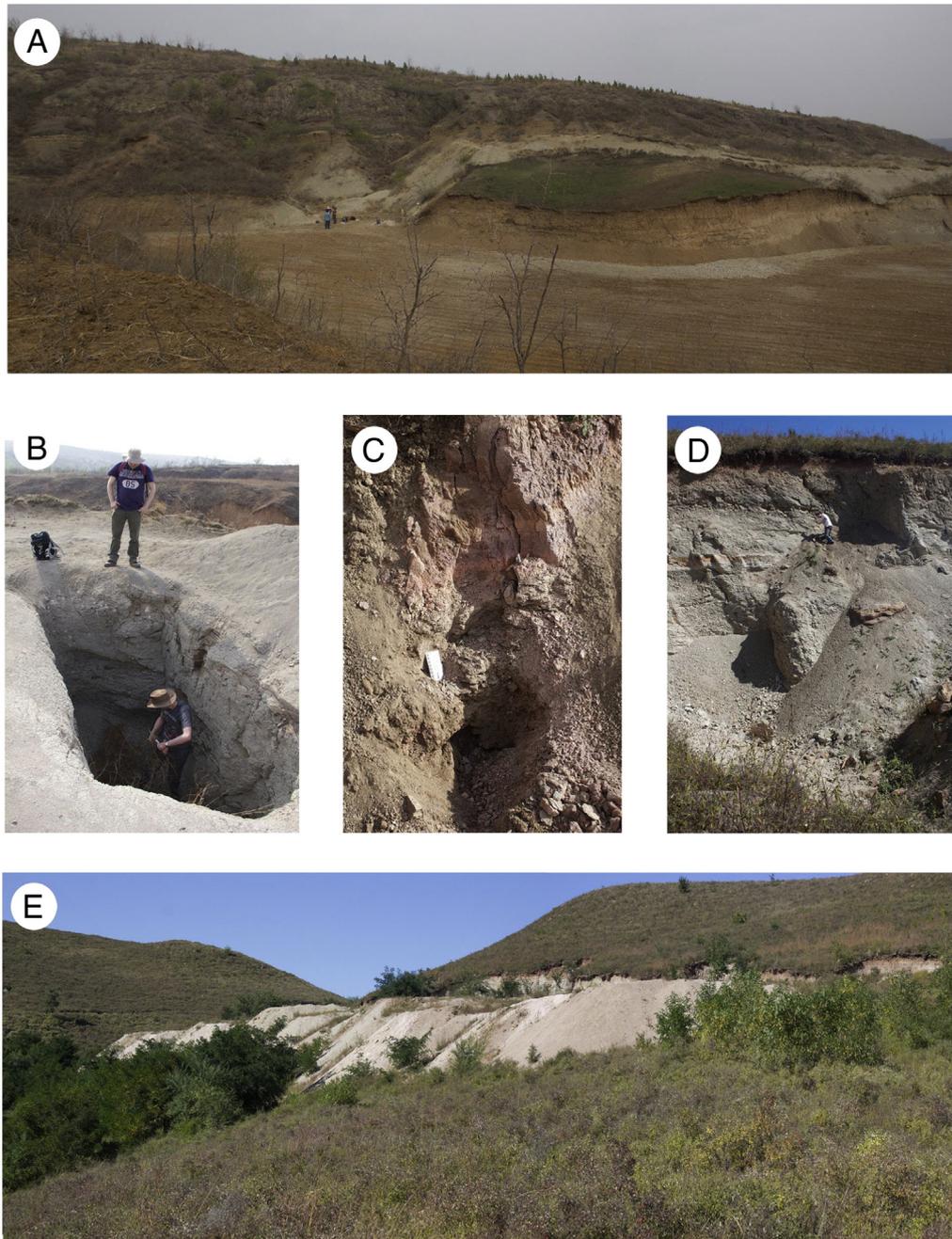


Fig. 2. Field sedimentology at the Lujiatun locality. A. Photograph of the site of log B showing the Lower Lava Unit capping the hills and the Upper Grey Siltstone at its base. B. Excavation into the Upper Grey Siltstone near to the site of log B. C. Several ~10 cm thick beds within the Pink Tuffaceous Sandstone at the base of log A, and at the bottom of the photograph the top bed of the Lower Tuffaceous Siltstones, the horizon to which excavations have been dug to (grain size card for scale 10 cm long). D. Photograph showing the site for log A and the extent of the Upper Grey Siltstones. E. The Lower Tuffaceous Siltstones at the base of log A. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

package of very fine-grained, tuffaceous muddy siltstones–sandstones, which show normal and reverse grading between beds. There is no evidence of sedimentary structures or bioturbation; subtle variations in grain size occur throughout (Fig. 3A). The package is dominated by silt and fine sand-sized grains composed of crystal, glassy ash at various stages of devitrification. In certain horizons, the volume of vitric ash is noticeably higher and can be distinguished by its bright orange–red coloration.

The UGS can be described as a moderately sorted, subangular to subrounded, tuffaceous, vitric–crystal sandy-siltstone to siltstone with very few lithics (<1% of total volume) (Fig. 4A). The crystal fraction is dominated by quartz (60–70% total clast volume) and plagioclase feldspar (35–25% of total clast volume), crystals of biotite vary considerably

in abundance between different horizons but can constitute up to 15% of total clast volume, and K-feldspars are also present but contribute less than 1% of total clast volume. Iron oxides can also be seen and exist both as rims around some crystals and as isolated accumulations. All grains are floating in a matrix of very fine silt grains and clay mostly derived from devitrified vitric shards.

Analysis of thin sections reveals elongate lenses of clay minerals with fiammé-like geometry. These most likely represent post-diagenetic alteration of vitric fragments that have deformed under the pressure of overlying sediment (Branny and Sparks, 1990). Well-rounded lithic fragments with conspicuous biotite inclusions are up to pebble and cobble size, and are distributed randomly throughout; they contribute less than 1% of the sediment by volume (Fig. 4A). Other minor components

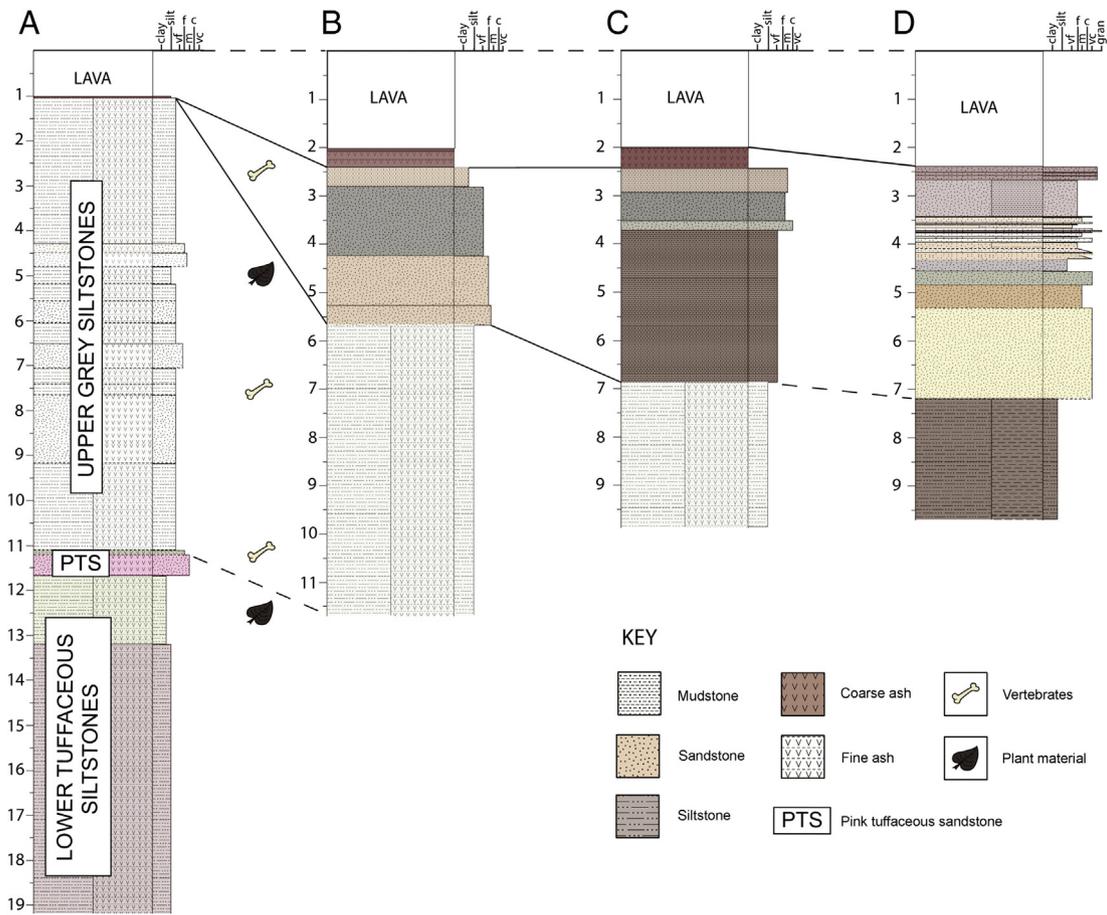


Fig. 3. Stratigraphic logs of the Lujiatun Unit. Logs A–D are capped by the andesitic lava of the Lower Lava Unit. Log A; articulated remains were found within the bed at the base of the Upper Grey Siltstones (UGS) as it grades into the Pink Tuffaceous Sandstones (PTS). Extensive excavations occur in both the Upper Grey Siltstones and Lower Tuffaceous Siltstones (LTS). Scales are in metres, and grain sizes follow Blair and McPherson (1999). Solid lines represent horizons traced between sections; dashed lines represent hypothesised relationships between horizons. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

of the UGS are small (2–3 cm diameter) fragments of carbonised wood; these are randomly distributed throughout the unit.

An isolated limb bone was recovered in log A approximately 3.45 m from the base of this package, and a partial tooth row was identified in thin section from a sample taken 2.45 m below the top of the package (Fig. 4A). These suggest that further isolated vertebrate remains are scattered throughout the package (Figs. 2B, 3B).

4.3. Pink tuffaceous sandstones (PTS)

Below the UGS package lie the 600 mm thick coarser pink tuffaceous sandstones (PTS). The PTS were found only in log A where they consist of five discrete beds (Figs. 2C, 3A, 4B,C). The PTS can be formally described as a poorly sorted angular to sub-angular, vitric-crystal tuffaceous sandstone. As with the overlying UGS, some vitric shards show distinctive orange-coloured rims, the crystal fraction is dominated by quartz (65% of total clast volume) and plagioclase feldspar (25% of total clast volume) with small amounts of biotite (<10% of total clast volume) and K-feldspars (<5% of total clast volume), the majority of crystals are monocrystalline, but others exist as crystal clusters. Lithics are also present, but constitute less than 1% of total volume. Clasts float in a clayey groundmass of devitrified volcanic glass and very fine silt-sized quartz and feldspar grains.

The top bed of the PTS is 100 mm thick and displays little internal structure and no evidence of bioturbation, but the boundary between the UGS and PTS is gradational and indistinct (Fig. 3A). This bed is a poorly sorted, medium-grained, greyish, orange–pink tuffaceous

sandstone (Fig. 4B–C). As with the UGS, there is abundant volcanic material in the vitreous and crystal fractions; the latter comprises predominantly fragmented plagioclase feldspar and quartz crystals with minor biotite crystals. Many vitric fragments are bright orange in colour in hand specimen (presumably due to oxidation) (Fig. 4B). Petrographic sections demonstrate that only the larger vitric fragments are oxidised. Coarse fragments of vitreous ash are common (Fig. 4C), and often exhibit distinctive concave to angular margins; larger fragments can contain vesicles up to 0.5 mm in diameter (Fig. 4B). Most vesicles are spherical, although elongated examples also occur within pumiceous clasts. Flattened clay pseudofiammè that represent weathered pumiceous fragments are also abundant. Most importantly, a partially articulated skeleton consisting of several ribs, pelvic bones and a partial humerus was exposed within this bed (Fig. 4B).

The remainder of the PTS is a succession of deeper pink, poorly consolidated, coarser tuffaceous sandstones. These contain slightly less orange weathered vitric ash than the previous bed, but otherwise are a similar composition. No fossil material was recovered from the remainder of the PTS (Fig. 4C).

4.4. Lower tuffaceous siltstones

The lower tuffaceous siltstones (LTS) lie beneath the PTS, but detailed field characterisation of the gross structure of this unit was not possible as it is typically obscured by debris and vegetation. The LTS can be described as a moderately sorted, vitric-crystal, tuffaceous, muddy siltstone with angular to subangular grains of quartz (55%

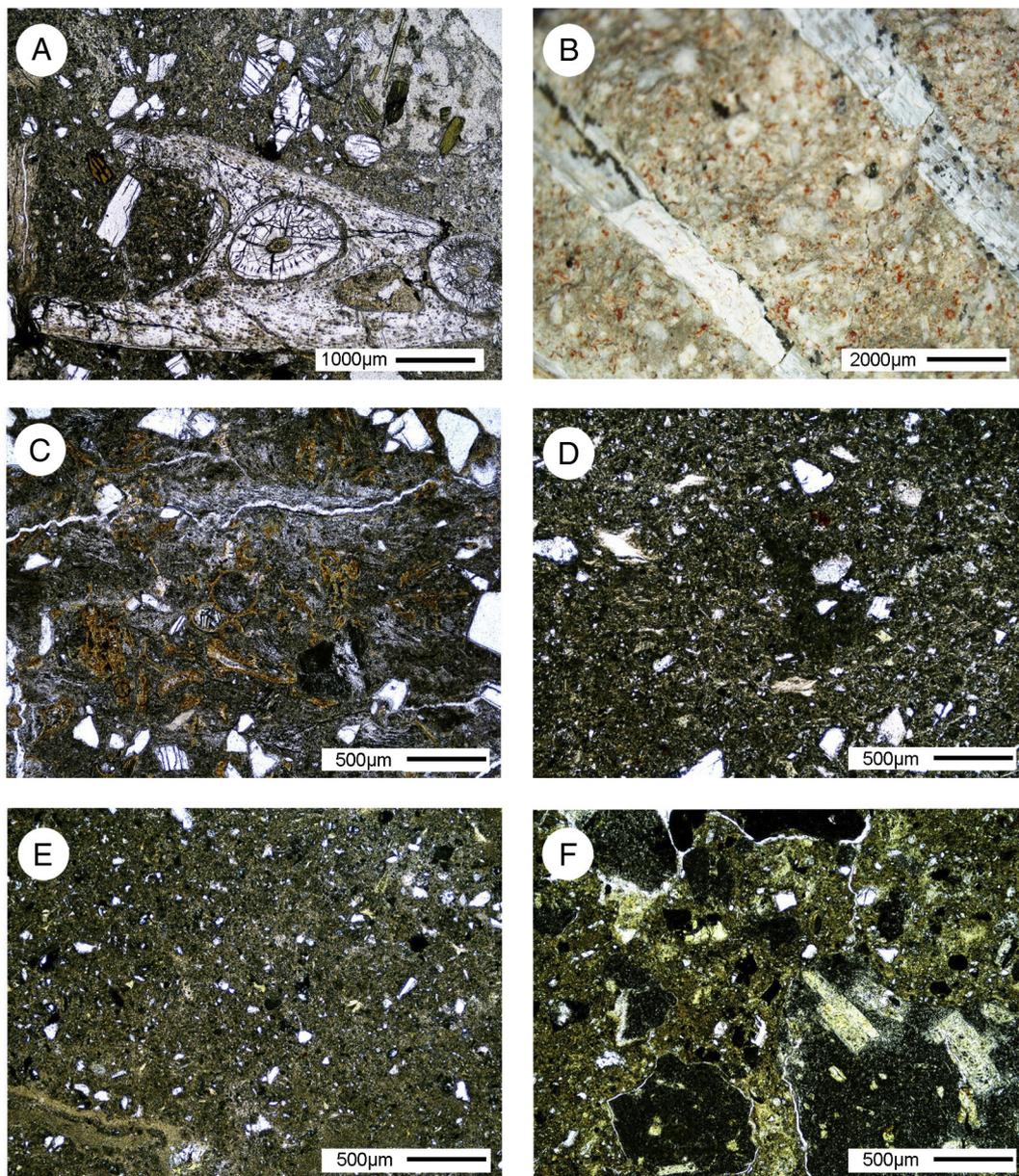


Fig. 4. The fossiliferous sediments and matrices of the Lujiatun Unit. A. Photomicrograph of Upper Grey Siltstone containing a partial tooth row in lower part of image and a biotite-rich volcanic rock fragment in top right of image; pseudo-fiammé, the result of alteration of vitric shard are visible on the left hand margin of the image. Scale bar equals 1000 μm . B. Close-up of articulated ribs within the Pink Tuffaceous Sandstone. Weathered orange vitric ash particles are visible in hand sample. Scale bar equals 2 mm. C. Photomicrograph of the Pink Tuffaceous Sandstone with orange coloured vitric ash, detailing large rounded vesicles and delicate vesicle walls. Scale bar equals 500 μm . D. Photomicrograph of sample from the Lower Tuffaceous Siltstone, showing several pseudo-fiammé. Scale bar equals 500 μm . E. Photomicrograph of the matrix of IVPP V14748. Scale bar equals 500 μm . F. Photomicrograph of the lahar matrix from IVPP V14341 (Zhao et al., 2007) showing volcanic rock fragment in the lower left hand corner of the image. Scale bar equals 500 μm . (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

of total clast volume), plagioclase feldspar (35% of total clast volume), biotite (>10% of total clast volume) and sparse volcanic rock fragments of larger biotite phenocrysts within an aphanitic groundmass. These clasts float within a matrix of very fine silt grains and devitrified volcanic glass (Fig. 4D). Accumulations of iron oxides are also relatively common compared to the overlying PTS.

A broad difference exists between the uppermost 1–2 m of the unit and the remainder, which are light olive grey and pale red in colour respectively (Figs. 2E, 3A). Despite the colour contrast, the texture and lithology of both units is similar to the UGS, i.e. the matrix is composed of weathered vitric–crystal ash. Rare small fragments (10–20 mm) of plant material occur. The LTS have a limited number of distinguishing features; unlike the overlying beds, the LTS contain a higher proportion of lithics (though still rare), and almost all volcanic glass components have been

totally altered to clay (Fig. 4D), and rarely show the characteristic orange rimmed vitric ash present in the upper part of the section.

No vertebrate fossil material was recovered in the LTS. This unit, however appears to be the horizon to which the main excavation pits were dug by locals, with evidence of recent activity.

5. Interpretation of the sedimentary log

In summary, the Lujiatun sections represent the upper reaches of a floodplain environment close to the edges of a basin that experienced multiple volcanic events such as ashfalls, lahars and pyroclastic flows. Various lines of evidence (see below) indicate that these volcanic deposits were subsequently remobilised in numerous unchannelised flows. These findings agree with those of Jiang and Sha (2007), Zhao

et al. (2007), and Hedrick et al. (2014), who identified a volcanoclastic origin for the Lujiatun Unit, associated with the remobilisation of volcanic material through lahars.

5.1. Lower Lava Unit

The various igneous rocks comprising the Lower Lava Unit are interpreted as the products of a shield volcano (Jiang et al., 2011, 2012) that was located to the northwest of the Lujiatun area, but perhaps less than 5 km away (Jiang et al., 2011).

5.2. Upper grey siltstones

The relative homogeneity of the UGS and the absence of channel structures indicate that these sediments originated in an unchannelled mass movement event. Successive graded intervals (normal and reversed) within the UGS indicate deposition occurred in multiple events. The silt-grade clastics suggest that the events were of low energy, only possessing sufficient energy to remobilise unconsolidated underlying sediment. Such a deposit could be generated in various ways. For example, the distal run-out portions of lahars and debris flows are known to form extensive, poorly sorted, mostly fine-grained volcanoclastic lateral deposits (Castruccio et al., 2010), and these have been recorded previously in the Lujiatun Unit (Jiang and Sha, 2007). Alternatively, the UGS could represent post-lahar deposits, which are often associated with high sedimentation rates and fine-grained, remobilised, poorly consolidated lahar sediment (Major et al., 2000; Major, 2003). These overspill-run out deposits can cover extensive areas reaching up to 22 km in length, from the source of the flow, to 1 km in width perpendicular to the direction of flow (Castruccio et al., 2010). The basal contacts of lahars and other debris flows are usually sharp, especially on shallow slopes and flat surfaces such as those in the distal reaches of a volcanic province (Fischer and Schmincke, 1984). However, the base of the UGS is gradational, which may indicate some other type of mass movement. The style of deposition of a lahar is typically non-erosional and can preserve pre-existing soil surfaces (Fischer and Schmincke, 1984), though the basal contacts of some lahars are locally erosive (Brantly and Waitt, 1988), potentially explaining the gradational contact between the lowest bed in the UGS and the underlying PTS.

An alternative depositional mechanism for the UGS is that they represent a series of sheetflood mass movements, a sedimentary feature known to be associated with volcanic deposits (Paik and Kim, 2006; Gernon et al., 2009) and that have been recorded previously at other outcrops of the Lujiatun Unit (Jiang and Sha, 2007). Sheetfloods progress downslope as uniform sheets of water and sediment slurries, the result of remobilisation of loose material by intense bursts of rainfall and lose momentum in alluvial areas where they deposit suspended and entrained sediment (Hogg, 1982). Early Cretaceous NE China has been considered to have experienced both an arid climate (Fürsich et al., 2007; Jiang and Sha, 2007) or cool temperate conditions (Amiot et al., 2015). However, both scenarios would have involved episodes of intense precipitation and so are compatible with the occurrence of sheetfloods. Channels can occur, leading to channelised flood deposits and, if the clay fraction is sufficiently abundant, potentially to mudflows or non-volcanically induced lahars (Hogg, 1982). However, it is notoriously difficult to distinguish pumiceous lahars and other mudflows from reworked pyroclastic flow and fall deposits, especially remobilised ignimbrites (Sparks, 1976; Fischer and Schmincke, 1984). The maximum distance travelled by sheetfloods is considerably lower than that for known lahars (Hogg, 1982). This has implications for the ability of a flow to entomb hundreds of animals, such as has been suggested at Lujiatun (Xu and Norell, 2006; Zhao et al., 2007). In spite of this, if pyroclastic material is being weathered over a large enough area, then a series of sheetfloods could lead to a repeated build-up of originally upslope material being deposited on top of older downslope sheetflood deposits. Considering the amount of material deposited in pyroclastic

flows and associated ash falls in general, a great amount of relatively unconsolidated sediment would have been available for remobilisation in the Lujiatun area. Though many sheetflood deposits are only a few centimetres in thickness (Hogg, 1982), single sheetflood events are also capable of forming beds 70–80 cm thick (Hubert and Hyde, 1982), consistent with the range of bed thicknesses at Lujiatun. Sheetfloods are often a response to intense seasonal bursts of rain, which would have been likely under either the semi-arid or cool temperate climates envisaged by different authors (Fürsich et al., 2007; Amiot et al., 2015). Repetition of these would generate the multiple stacked individual beds, although the similarity of the beds, and the absence of any other lithology, suggests a single depositional process, and that the series of depositional events was closely spaced in time (Hogg, 1982). This scenario is plausible given the ongoing volcanic activity in the Lujiatun area at the time (Jiang and Sha, 2007; Jiang et al., 2011). The variation in grain size and vitric–crystal ratios in the beds of the UGS could reflect differences in the precise nature of each eruption and co-occurring weather conditions (Parfitt and Wilson, 2008).

5.3. Pink tuffaceous sandstones

The grading of the PTS into the much finer grained, but otherwise broadly lithologically similar upper grey siltstone, suggests remobilisation of the uppermost parts of the PTS deposit (Fig. 3A). A distinct period of greater volcanic activity is suggested by the high abundance of coarse ash through the PTS compared to the PTS suggesting a decrease over time in the extent of volcanic activity (Fig. 4C). The predominance of smooth spherical vesicles within vitreous fragments of the PTS suggests a magmatic origin for the ash in all logged beds, as the vitreous fragments (Fig. 4B,C) are unlike the blocky shapes characteristic of a more phreatomagmatic eruption (Heiken, 1974). Pumiceous clasts represent regions of cooling magma that formed near the walls of the magma vent, whereas vitreous clasts with spherical vesicles originate in central vent regions where fluid forces are more equal (Heiken, 1974). The absence of deformed vesicles within the vitreous components indicates that the grain shape of vitreous particles was determined by the air bubbles within the magma, suggesting a melt of high viscosity, and pointing towards a rhyolitic–andesitic composition (Heiken, 1974). Magma composition of this type is not consistent with the hypothesis put forward by Jiang et al. (2011) that a shield volcano is the main source of eruptive and syneruptive deposits in the Lujiatun Unit (Heiken, 1974).

Based upon the abundance of poorly to moderately well-sorted, fine, angular crystal and vitric ash fragments, the near absence of lithic fragments, and the near absence of clay from a non-diagenetic origin, neither the PTS and the overlying UGS are representative of the matrix of IVPP V14341, shown by Zhao et al. (2007, Fig. 2). From this, two conclusions are drawn; firstly, the sediments in logs A–D are not deposits of cohesive lahars, and secondly the matrix of IVPP V14341 and the PTS and UGS represent separate depositional events. The relatively fine-grained matrix and small size of pyroclasts, together with the angular and fragmented nature of the ash, suggest rapid transport of material some distance away from the volcanic source. The poor sorting of the unit is noteworthy. This could result from the breakage of crystals through impact during transport, especially along fractures formed during rapid cooling. Pyroclastic ash fall deposits typically feature such ash fragments, but also large unfractured clasts, but these are characteristically well sorted, (except proximal to the volcanic vent, when larger pyroclasts, such as lapilli and bombs, can occur (Sparks, 1976; Parfitt and Wilson, 2008)). The PTS is therefore unlikely to comprise pyroclastic fall deposits. Both pyroclastic flow and pyroclastic surge deposits are poorly sorted (Fischer and Schmincke, 1984; Parfitt and Wilson, 2008); the latter are characteristically enriched in crystal and lithic fragments (Fischer and Schmincke, 1984) and can exhibit wavy or lenticular cross bedding and erosional bases. Pyroclastic flow deposits are also known to form discrete bedded intervals and distally, these deposits can exhibit subtle normal grading in their lower parts (Tucker, 2001)

that, when unwelded, can be expressed as compositional or colour changes (Fischer and Schmincke, 1984). The PTS contains abundant crystal fragments, but does not exhibit any of the other characteristic lithological features of pyroclastic surge deposits; it does, however show discrete bedding identifiable by clear colour changes and subtle grading internally; it is thus interpreted herein as a product of pyroclastic flows, specifically an ignimbrite.

Jiang and Sha (2007) identified volcanoclastic flows in the Lujiatun Unit, but did not consider these to represent ignimbrites because the deposits lacked grading and contained rounded pebbles. It is possible that there may have been some special and/or temporal variation in depositional processes but the evidence from this study confirms the importance of pyroclastic deposition.

An in situ partially articulated skeleton found within the PTS in log A (Fig. 3A) could have been overcome by such a pyroclastic flow, but the grading of the topmost bed of the PTS (in which the specimen is preserved), into the UGS suggests that this bed is formed by the reworking of previously deposited sediments. Therefore the animal may not have been buried within a pyroclastic flow but by a remobilisation of pyroclastic flow deposits. However, extensive weathering of the specimen means that it cannot be assessed whether it had been initially buried by a remobilisation of older sediments or itself remobilised from older pyroclastic deposits. The series of pyroclastic deposits reinterpreted by the PTS are an obvious potential source for the series of remobilised event beds represented by the UGS.

5.4. Lower tuffaceous siltstones

The distinctive light olive grey and pale red coloration of the LTS is likely a weathering effect, and is attributed to the weathering of iron oxide detrital grains (McBride, 1974). Although the sedimentology of this unit was difficult to study in the field, petrological analysis shows that its lithology is broadly similar to that of the UGS, and likely the result of similar depositional processes. Therefore, it is predicted that additional volcanoclastic flows and ash falls occur below the LTS and are the source of the ash within the latter.

In summary, sedimentological and petrological data support a scenario for the genesis of the Lujiatun beds consistent with reported fossil evidence, whereby various members of a terrestrial ecosystem were killed by a series of events depositing primary and remobilised volcanic material in ignimbrites and distal lahars/sheetfloods, respectively (Jiang and Sha, 2007). Significantly, data presented herein reveals that the animals were not killed and deposited in a single cataclysm, as had been suggested (Wang and Zhou, 2003; Zhao et al., 2007; Hedrick et al., 2014).

6. Regional context

Both the pink tuffaceous sandstone and the matrix of IVPP V14341 indicate that volcanoclastic flows were a key depositional mechanism within the Lujiatun sequence. Differences between the two lithologies reflect their different origins, a pyroclastic flow and a lahar (Zhao et al., 2007), respectively, and potentially different source lithologies. Both IVPP V14341 and the PTS appear to have been deposited some distance from the source. Given that pyroclastic flows and lahars are capable of transporting debris several hundreds of kilometres along their course before losing the required energy to keep load in suspension (Sparks, 1976; Vallance, 2000), it remains possible that the relevant flows associated with IVPP V14341 and the PTS came from different volcanic centres. Jiang and Sha (2007) report a trend in the lateral thinning of syneruption deposits southward, but also more importantly westward. Whereas Jiang and Sha (2007) reported fine-grained lapillistones and sheetflood deposits several kilometres to the west of Lujiatun village, they also described coarser pebble- and boulder-dominated deposits (Jiang et al., 2012), which were not recorded by this study. The sediments in logs A–D show smaller grain size, and thus represent

lower energy flows. There is no evidence of multiple vents at this stage in the geological evolution of the area. Given a single source, it appears that the sections reported here are distal to both the flanks of the volcanic source itself and the volcanoclastic deposits it yielded (Fig. 5). Consistent with this, the eruptive and syneruption deposits continue to thin radially away from the volcanic centre identified by Jiang et al. (2011).

In the context of the volcanic evolution of the area, the ignimbrite and the highly viscous nature of the vitric ash point towards a period of intermediate–felsic explosive volcanism during deposition of the Lujiatun Unit. Subsequently, the laterally continuous basaltic and andesitic lavas of the Lower Lava Unit were formed by a shield volcano, which was eventually terminated by a post-Lujiatun period of intermediate explosive eruptions (Jiang et al., 2012). A volcanic centre showing major chemical changes in eruptive material and variation between the two conditions of low viscosity effusive basaltic lava and high viscosity explosive intermediate eruptions could more appropriately be classified as a stratovolcano rather than a shield volcano (Fischer and Schmincke, 1984). This was discussed by Jiang et al. (2011) who favoured an interpretation of the source as a shield volcano, based on the profile and lateral extent of the deposits of the Lujiatun and Lower Lava units.

7. Fossil matrices

The total number of fossil specimens available to study from the collections and recovered in the field is low, and therefore any additional evidence for the depositional context from these fossil specimens is tentative. In addition to those lithological characters reported by Zhao et al. (2007), the matrix of IVPP V14341 has a high clay content and lacks pumiceous vitreous fragments (Fig. 4F), both of which exclude an origin as a pyroclastic flow (Fischer and Schmincke, 1984). The matrix of IVPP V14748 also lacks pumiceous vitric ash fragments, characteristic of pyroclastic flow deposits, ash fall deposits (Fischer and Schmincke, 1984) and of the UGS and PTS, but more resembles the LTS, indicating similar depositional processes, although the matrix of IVPP V14341 is finer grained (Fig. 4A, C, E). It appears that the matrix of IVPP V14748 originates either from the LTS, or another series of sheetflood deposits with a similar source. Field and witness evidence of repeated excavations by illegal collectors into the UGS and LTS suggests the likely presence of good quality dinosaur skeletons in these horizons. Additionally, the higher fidelity of preservation of specimens in the UGS makes it unlikely that skeletal material was routinely reworked from the underlying PTS; most Lujiatun material is unlikely to originate from the latter. Further, it should be noted that the proposal that some Lujiatun Unit dinosaurs were preserved as partially articulated skeletons within the violent interior of a pyroclastic flow, such as the PTS, is at odds with most other cases in which fossils in volcanoclastic flow deposits generally consist of isolated remains (Siebe et al., 1999; McKenna et al., 2006; Antoine et al., 2012).

The majority of Lujiatun skeletons are nearly fully articulated, suggesting preservation in situ and this is probably a result of the high density and low energy of these distal volcanoclastic flows (Evans et al., 2007; Zhao et al., 2007). Fieldwork in the course of this study confirms that other specimens are less complete and less well articulated, suggesting that they have undergone some degree of disturbance and transport. The discovery of isolated bones in the field, and in thin sections suggests that these are not uncommon, possibly more so than hitherto realised, (Evans et al., 2007; Hedrick et al., 2014). The prevalence of nearly fully articulated specimens in museums and institutional collections is almost certainly a sampling bias, whereby collectors preferentially excavate and sell articulated specimens instead of individual elements (Benton et al., 2008). Nonetheless, the high abundance of articulated specimens indicates that the quality of fossil preservation in the Lujiatun Unit is unusual, and implies that the prevalent sedimentological conditions

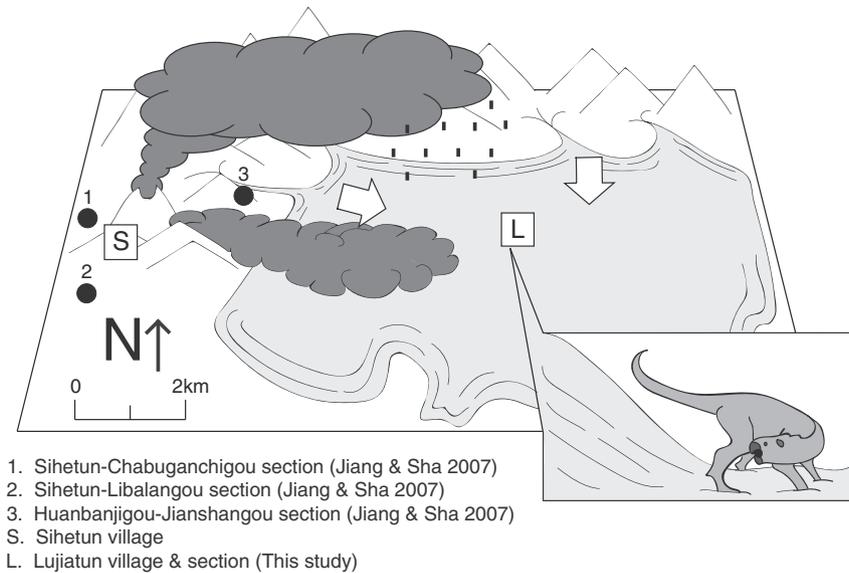


Fig. 5. Reconstruction of the depositional setting along the northern edge of a basin, based on this study and that by Jiang and Sha (2007). Light grey represents pyroclastic deposits, remobilised as sheetfloods; arrows indicate sense of motion. Dark grey clouds represent pyroclastic flows and ash clouds. Scale refers only to position of sites and volcanic centre, size and position of highlands at basin edge not to scale. Inset shows a *Psittacosaurus* being overwhelmed by a mass movement deposit.

were favourable. This is inconsistent with the suggestion that volcanic flows transported the Lujiatun fossils.

8. At-rest postures

Some of the articulated dinosaur skeletons from the Lujiatun Unit exhibit what has been described as a ‘sleeping posture’ (Xu and Norell, 2004; Wang et al., 2006; Gao et al., 2012). Here the term ‘at-rest’ is preferred to describe such postures, as they may also be adopted while an animal is at rest but alert; the terms ‘sleeping’ or ‘resting’ imply a behaviour that cannot be determined. The limbs of some Lujiatun specimens are not in ‘at rest’ positions: some specimens show other evidence for transportation, including considerable disarticulation (Evans et al., 2007).

Volcaniclastic flow deposits from other localities worldwide typically contain fossil material that is poorly articulated and fragmented (Siebe et al., 1999; McKenna et al., 2006; Antoine et al., 2012). The lahar hypothesis for the formation of Lujiatun fossil matrices has been challenged by some on the grounds that the at-rest postures of Lujiatun fossils would be unlikely to be maintained during even low-energy lahar events (Gao et al., 2012). Although lahars are capable of transporting large clasts, boulders and entire man-made structures (Antoine et al., 2012), at gradients below 10° their erosional potential is greatly diminished; soil surfaces and vegetation can be preserved underneath a flow (Fischer and Schmincke, 1984). The relatively high degree of articulation of the Lujiatun dinosaur skeletons and the absence of large clasts in the sedimentary matrix (Fischer and Schmincke, 1984) suggest that the fossiliferous localities were in low-gradient regions relatively distal to the source of the flows (Zhao et al., 2007). A lahar hypothesis cannot be excluded on the basis of the postures exhibited by the Lujiatun dinosaurs, although on sedimentological criteria this origin is less likely than other mass movement deposits (see above).

Death by asphyxiation from volcanic gases (Wang et al., 2006) is consistent with the widespread and repeated occurrence of volcanic episodes during the Early Cretaceous of NE China (Jiang and Sha, 2007; Jiang et al., 2011, 2012). Toxic volcanic gases have been invoked as the cause of death for taxa preserved in other Jehol beds (Guo et al., 2003). In particular, this killing mechanism could generate the at-rest postures of some Lujiatun taxa (although a mode of burial that preserves the posture is required). For example, the post-mortem at-rest postures documented in humans in volcanically active areas have

been claimed to be the result of asphyxia via mass CO₂ release from nearby lakes (Kling et al., 1987; but see Hansell and Oppenheimer, 2004). Within ash sediments from the Jianshangou Unit of the Jehol Group (Fig. 1), the concentration of volatiles within phenocrysts correlates positively with the abundance of fossiliferous beds (Guo et al., 2003). These volatiles are hypothesised to originate either via precipitation from volcanic plumes or adsorption onto the surfaces of tephra (Guo et al., 2003). The introduction of various poisonous eruption products into the environment through gas release, volatile-contaminated tephra, or water could be responsible for the death of the animals in the Lujiatun Unit, and their at-rest postures. Not all of the fossiliferous horizons of the Lujiatun Unit, however, are related to volcanic activity and only some of the Lujiatun vertebrate fossils show resting postures (Zhao et al., 2007). It is therefore unnecessary to evoke the release of toxic volcanic volatiles/gases as a death mechanism for all fossils from the succession. The death positions of the Lujiatun vertebrates within lahars and sheetfloods more likely represent burial in situ by the flow.

If the classic ‘Pompeii’ model were correct, the fossils should be preserved in various postures, as is the case for humans and dogs at Pompeii. Although some animals would perhaps hunker down and die in a curled-up and at-rest or defensive posture (or even be overcome while asleep), others would attempt to flee and thus show signs of being in motion. Some fossil localities show animals remaining in situ and presumably being buried alive (especially aeolian deposits showing animals brooding on a nest e.g., Norell et al., 1995) though this would seem less likely as a response to a low-energy waterborne deposit than a sandstorm. If the sediment has been redeposited by water, there should also be a wider range of skeletal postures, some animals lying on their backs or sides, for example, and in particular limbs would be extended rather than flexed (Faux and Padian, 2007). It is possible that the current flows lacked sufficient energy to shift the carcasses, but were strong enough to rework the sediments. At most, it is envisaged that the sheetflood and/or lahar flows lined the carcasses up in stable positions, but did not move them or disturb their protective positions.

Dinosaurs from Lujiatun that show at-rest positions have also been interpreted as having taken shelter within burrows, which were subsequently infilled (Xu and Norell, 2004; Gao et al., 2012). The burial of the DMNH D2156 *Psittacosaurus* in burrows was also considered one of several plausible hypotheses by Meng et al. (2004). However, such claims require stronger evidence than simply their having a curled or

head-down posture; claims of burrow collapse by Meng et al. (2004) were later rejected, by Hedrick et al. (2014) who claimed that the sedimentary textures that would have supported this concept were absent. In the case of unequivocal examples of fossil vertebrates preserved in burrows the burrow walls are distinct and visible as distinct sharply curved margins that cross-cut bedding; there can be scratch marks on the inside walls of the burrow (Groenewald et al., 2001; Varricchio et al., 2007; Krapovickas et al., 2013). None of these features were observed in the field, or associated with museum specimens.

The preservation of at-rest postures in Lujiatun vertebrates occurred above ground as the animals were rapidly buried in situ by a variety of cohesive flow mechanisms (lahars, sheetfloods). Otherwise, the relationship between the mode of deposition of the Lujiatun beds and the posture of the preserved vertebrates is enigmatic. It is possible, but unlikely, that the animals were covered in situ while alive, having failed to flee or adopting a defensive posture – animals in the process of being covered would be expected to move or at least adopt an alternate posture. It seems more likely that these animals had already died in a non-violent manner; volcanic gassing may have been involved. Additional specimens may well demonstrate the frequency of at-rest postures at Lujiatun, and data from modern burial events of vertebrates in lahars and sheetfloods would be especially valuable.

9. Conclusions

Here, the first systematic description of the sedimentology of the fossiliferous deposits of the Lujiatun Unit is presented and related to the exceptional preservation of the Lujiatun fossils. This study shows that multiple fossiliferous horizons exist within the Lujiatun Unit. In the region of Lujiatun village, most articulated remains are derived from a limited number of beds that represent a series of sheetflood deposits of remobilised pyroclastic material onto the upper reaches of a floodplain. The matrix of IVPP V14341 (Fig. 4F) is unlike any of the deposits encountered at Lujiatun village, which suggests that more than a single depositional event was responsible for the burial of the Lujiatun fossils. Field evidence shows that some depositional events occurred as a prolonged pulse of activity. Other fossiliferous horizons, such as the pink tuffaceous sandstones, represent either the remobilisation of partially articulated remains from sheetfloods and lahars or in situ burial of remains within a pyroclastic flow.

The absence of channelised facies, as noted by Jiang and Sha (2007) in more proximal areas, indicates that the sediments close to Lujiatun village lay further from the volcanic source than those studied by Jiang and Sha (2007); they most likely represent unchannelised sheetflood deposits. Critically, widespread evidence for sheetfloods indicates that the dense tuffaceous flows that killed the Lujiatun dinosaurs, and other animals, were not necessarily associated with primary volcanic events/eruptions. This study emphasises the need to elucidate the depositional history of a succession prior to interpreting the taphonomy of any associated fossils. The results of this study will provide a basis for understanding the taphonomy of all fossils from the Lujiatun Unit, and will provide a framework for further investigations into the taphonomy of the Jehol biota as a whole.

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