Cretaceous Research 36 (2012) 96–105

Contents lists available at SciVerse ScienceDirect

Cretaceous Research

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

Sedimentary laminations in the lacustrine Jianshangou Bed of the Yixian Formation at Sihetun, western Liaoning, China

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ARTICLE INFO

Article history:
Received 31 August 2011
Accepted in revised form 8 February 2012
Available online 29 February 2012

Keywords:
Early Cretaceous
Yixian Formation
Varves
Western Liaoning

ABSTRACT

Extremely fine sedimentary laminations of the lacustrine Early Cretaceous Yixian Formation were studied in the excavated Sihetun Fossil Museum section in western Liaoning, China. The section consists mainly of mudstones, shales and layers of volcanic ash. The mudstones and shales are composed of siliciclastic and organic-rich laminae. Most of the laminations are varves that record seasonal climatic changes. Varve thickness measurements show that the sedimentation rate for the majority of the mudstones and shales was 0.2–0.7 mm/year. Quiet, anoxic lacustrine bottom waters were critical for the preservation of the laminations.

1. Introduction

Seasonal climatic changes may lead to a regular change in sediment composition and, thus, to the formation of sedimentary laminations (O'Sullivan, 1983; Saarnisto, 1986; Anderson and Dean, 1988; Kemp, 1996; Petterson, 1996; Ojala et al., 2000). Lacustrine sedimentary laminations record abundant palaeoenvironmental information (e.g., Brüchmann and Negendank, 2004; Mingram et al., 2004; Bostick et al., 2005; Schettler et al., 2006; Trachsel et al., 2008) and continuous varve successions have been used for time calibration (e.g., Ridge, 1990; Lamoureux, 2001; Stanton et al., 2010). Some sedimentary laminations are cyclical in nature and many are known to have been driven by solar (e.g., sunspot) cycles (Anderson and Koopmans, 1963; Williams and Sonett, 1985; Olsen, 1986; Halfman and Johnson, 1988; Olsen and Kent, 1996; Park and Fürsich, 2001; Haltia-Hovi et al., 2007).

In western Liaoning, northeast China, the lowest formation of the Early Cretaceous Jehol Group, the Yixian Formation, yields fossils of the Jehol Biota, including early angiosperms and feathered dinosaurs (Chang et al., 2003; Zhou et al., 2003; Sha, 2007), and contains finely laminated lacustrine rocks. Although the taxonomy of the Jehol Biota (e.g., Chang et al., 2003), the strata (Sha, 2007; Sha et al., 2007) and the radiometric age (Yang et al., 2007; Zhu et al., 2007; Chang et al., 2009) of Yixian Formation have been well studied, there have been few analyses of the sedimentary lamination (Liu et al., 2002; Fürsich et al., 2007). In this paper, the characteristics, origin, and environmental significance of the laminations in the Sihetun Fossil Museum section are described and discussed.

2. Material and methods

The Yixian Formation of the Jehol Group is mainly Barremian in age (Sha, 2007; Sha et al., 2007, Fig. 1A). It consists essentially of four fossil-bearing sedimentary units, the Jianshangou, Zhuanchengzi, Dakangpu and Jingangshan beds, which are sandwiched between volcanic rocks (Chen et al., 2005, Fig. 1B). The Jianshangou Bed, the lowest of the four units (Fig. 1B), contains two fossil-bearing levels (Fig. 1C). An excavated section (Fig. 2C) of the lower of these two beds is exposed adjacent to the Sihetun Fossil Museum (Fig. 2B) on the western hill by Sihetun Village (41°35′ 20.2″ N, 120°47′ 35.7″E), Shangyuan Town, Beipiao County, Liaoning Province (Fig. 2A). The section represents a period of lacustrine deposition and contains numerous fossils of the Jehol Biota. It consists mainly of mudstones, shales, layers of volcanic ash and sandstones (Fig. 1D, E), and is sandwiched between an overlying olivine basalt and underlying vesicular andesite or vesicular basaltic andesite (Zhang et al., 2004, Fig. 1D).

During 2008 we collected fresh rock samples and fossils from the Sihetun Fossil Museum section through a total thickness of 7.43 m. The rocks of the lower part (4.61 m) of the succession were sampled continuously but sampling of the remainder was selective

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0195-6671/$ – see front matter
doi:10.1016/j.cretres.2012.02.010

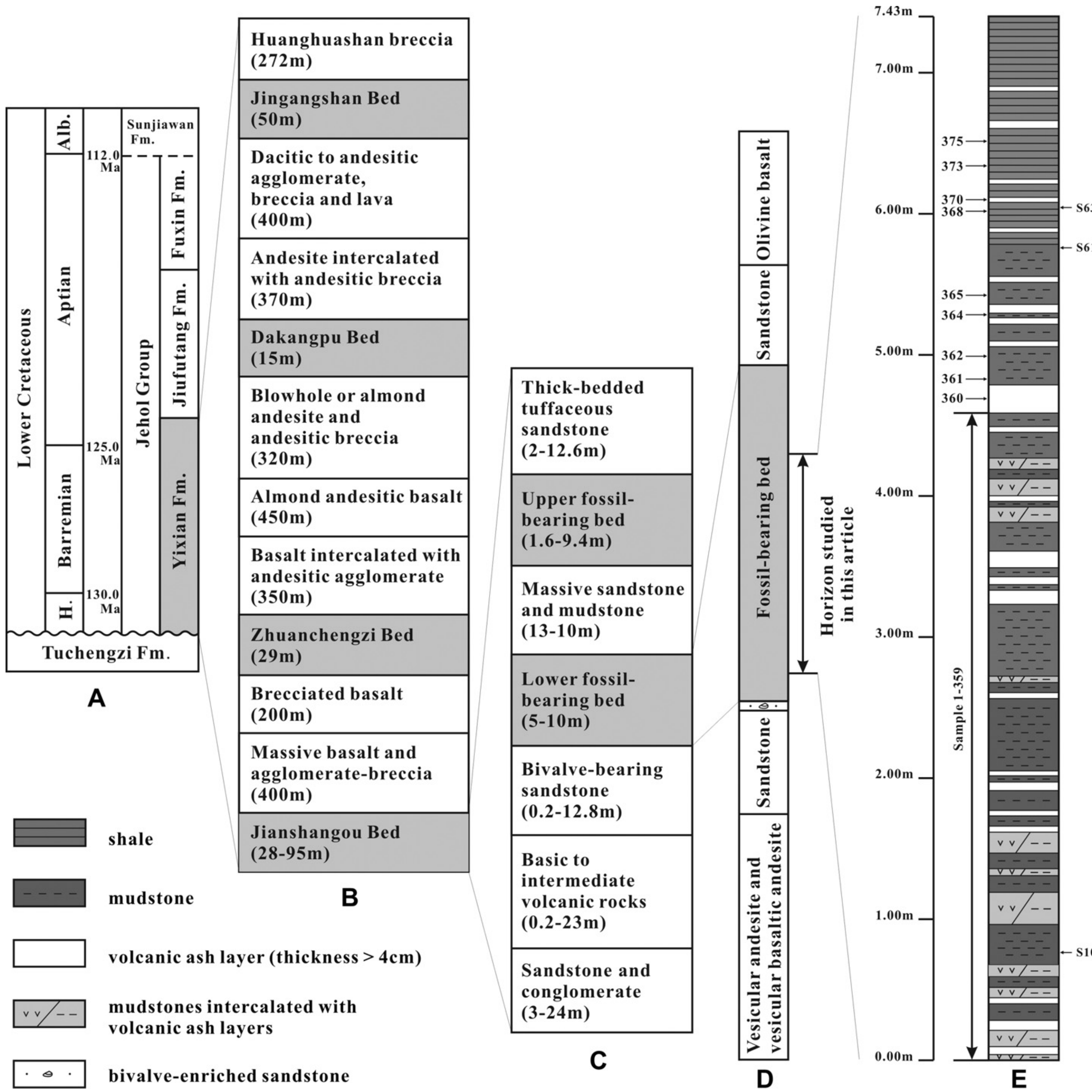

Fig. 1. Subdivision of the Jehol Group (A), Yixian Formation (B), and Jianshangou Bed (C), based on Sha (2007), Sha et al. (2007), Chen et al. (2005), Wang et al. (1998), and the stratigraphic log of the excavated Sihetun Fossil Museum section (D, E).

(Fig. 2C). In the laboratory the rock specimens were cut vertical to bedding and polished. The polished sections were scanned and a series of digital images obtained (Figs. 3, 4). In addition, 57 thin sections were prepared from typical rock samples. These were also scanned so that a digital image record of each was obtained. The thin sections were studied under petrographic, fluorescence, reflectance and scanning electron microscopes, and by energy dispersive spectroscopy (EDS). In addition, 74 rock samples (at intervals of 10 cm) were analyzed for total organic carbon (TOC) and palynofacies.

3. Definitions

Because there are no common classification of fine-grained siliciclastic sediments and sedimentary rocks, some important terms used in this article are defined as follows: (1) mudstone: siliciclastic sedimentary rock consisting primarily of particles smaller than 1/16 mm; (2) shale: a fissile mudstone; (3) sedimentary lamination (Fig. 5): a bedding structure formed from the rhythmic change of different fine layers (so-called laminae); the thickness of the layers is usually less than 1 cm and the basic unit of

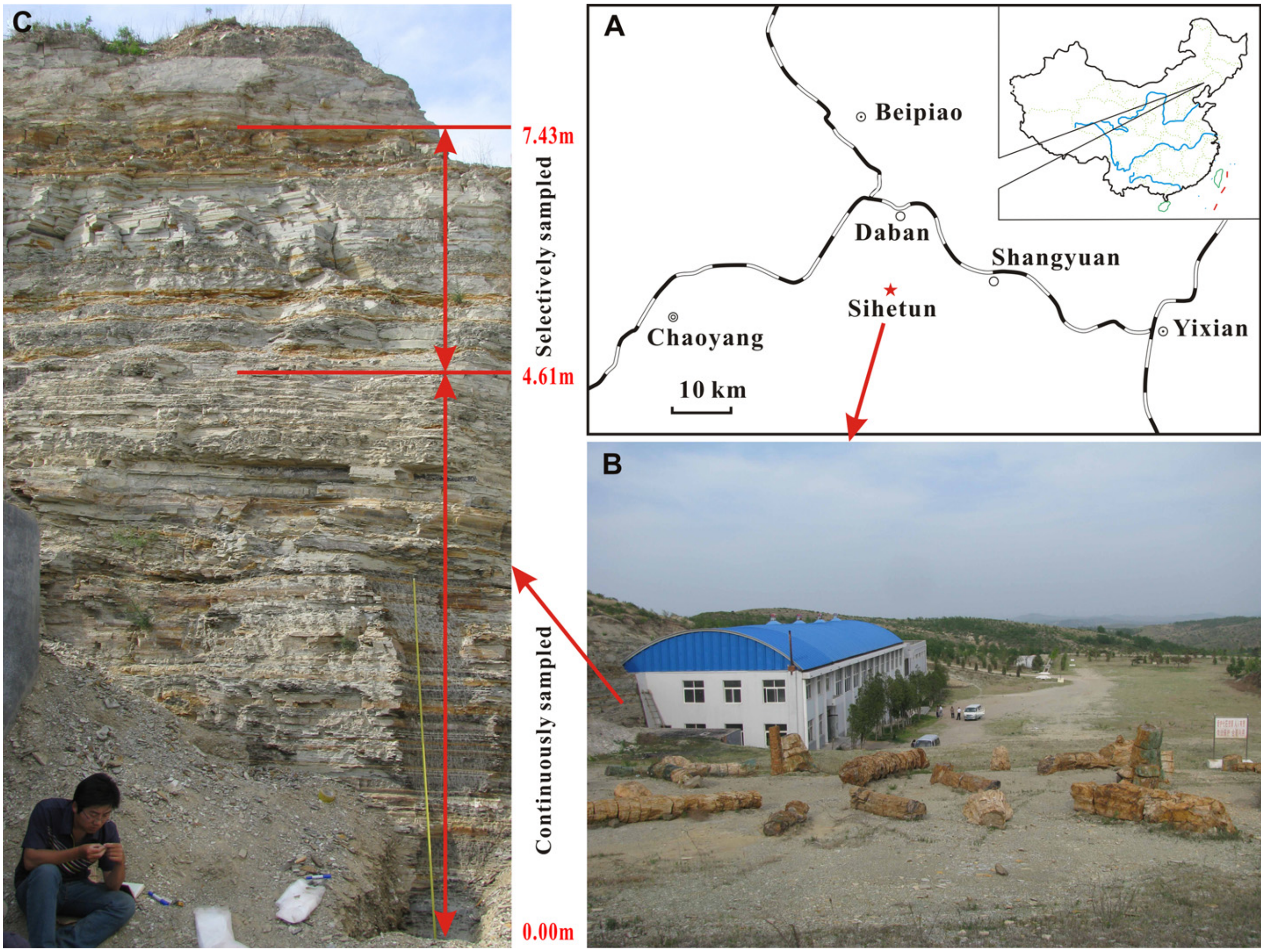

Fig. 2. Locations of A, Sihetun Village (red asterisk), B Sihetun Fossil Museum and C, the excavated Sihetun Fossil Museum section. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

lamination consists of two (couplet), three (triplet) or more laminae; (4) varve: a lamination formed in a single year.

4. The laminations

The excavated Sihetun Fossil Museum section consists of three types of rock: mudstone, shale and volcanic ash. The mudstones can be classified as black, grey, and pale grey–greenish grey. The shale is mainly pale grey–greenish grey. Sedimentary laminations are well developed in the shale and most of the mudstones. All of the laminations are siliciclastic–organic-rich, with variations depending on rock type. The basic unit is usually a siliciclastic lamina and an organic-rich lamina. The siliciclastic laminae consist mainly of clay minerals and some silt-sized quartz and feldspar. The organic-rich laminae mainly comprise organic matter and clay minerals. Silt-sized quartz and feldspars may also be present, but they are less common than in the siliciclastic laminae. The features of the laminations in different rocks are described as follows.

4.1. Black mudstone

Lamination is not very well developed in the black mudstones (e.g., samples 47–58, 67 and 68 in Fig. 3) (Fig. 6A1). The thickness of the siliciclastic and organic-rich laminae is not very regular. The former are usually very thin, only a few tens of micrometres (Fig. 6B1, C1). The thickness of the organic-rich laminae varies, ranging from a few tens (minority) to hundreds (majority) of micrometres (Fig. 6B1, C1). Large amounts of silt-sized (3.9–62.5 μm) quartz and feldspar debris (a few fall into very fine sand grade, i.e., 62.5–125 μm) are scattered through both the siliciclastic and organic-rich laminae (Fig. 6B1). The latter are mostly composed of clay and organic matter arranged in a filamentous network (Fig. 6C2).

4.2. Grey, pale grey–greenish grey mudstone

Most of the grey (e.g., samples 193–197 in Fig. 3) and pale grey–greenish grey (e.g., samples 199–221 in Fig. 3) mudstone exhibit beautiful siliciclastic–organic-rich lamination (Fig. 6A2, B2). The basic unit usually consists of three laminae, a lower siliciclastic lamina and an upper organic-rich lamina with a transition lamina in between (Fig. 7A), although occasionally the transition lamina is not obvious (Fig. 6C3). The thickness of most of these triplets fluctuates between 0.2 and 0.7 mm (Figs. 6B2, 7A). The contact faces between different laminae are not very clear (Fig. 7A). Occasionally, a siliciclastic lamina gradually merges into an organic-rich lamina (Fig. 7A). The content of silt-sized quartz and feldspar debris

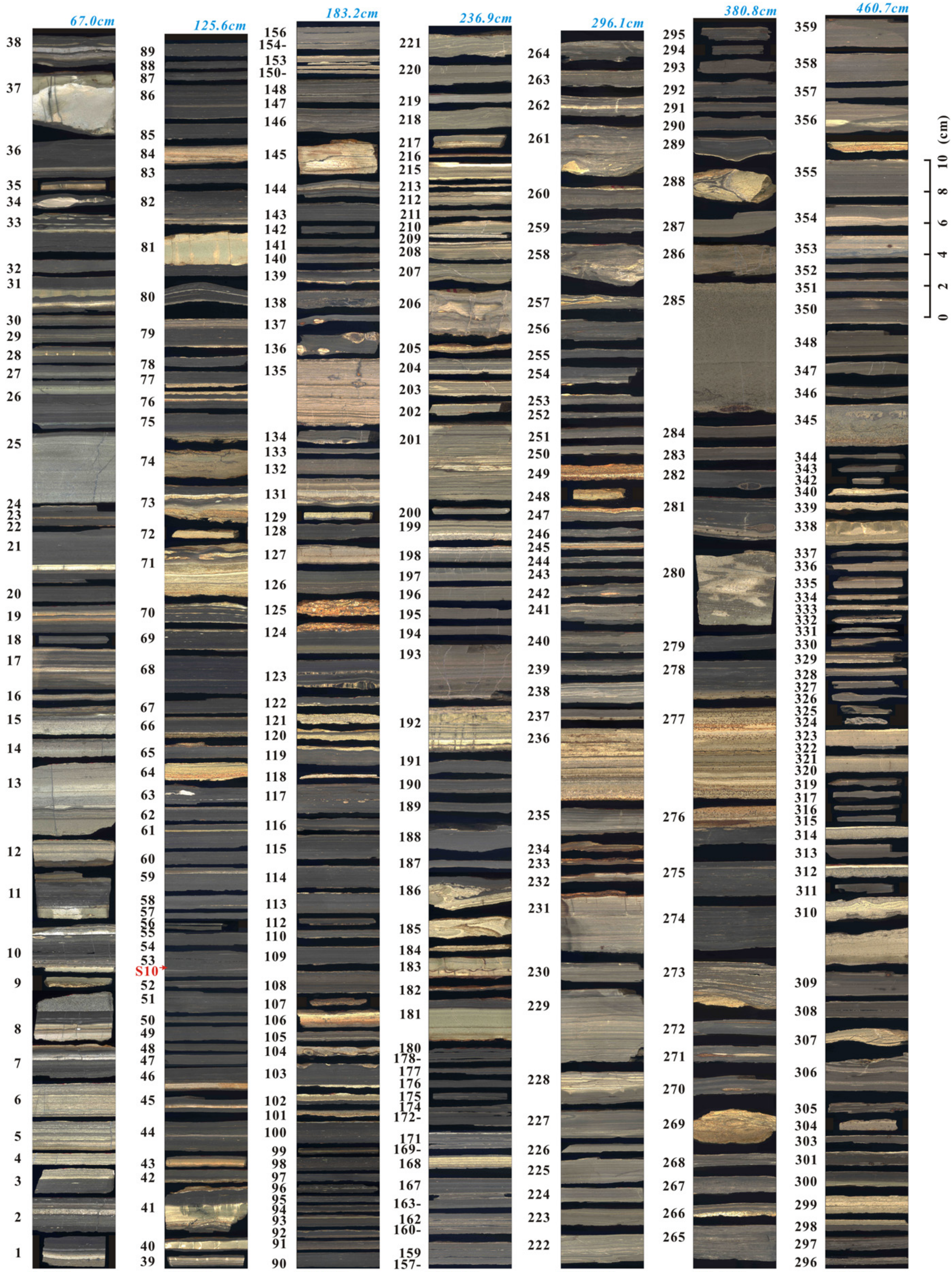

Fig. 3. Continuous rock samples (1–359) from the lower 4.61 m of the excavated Sihetun Fossil Museum section. The polished sections of the rock samples were scanned in stratigraphic order and the digital images set against a black background.

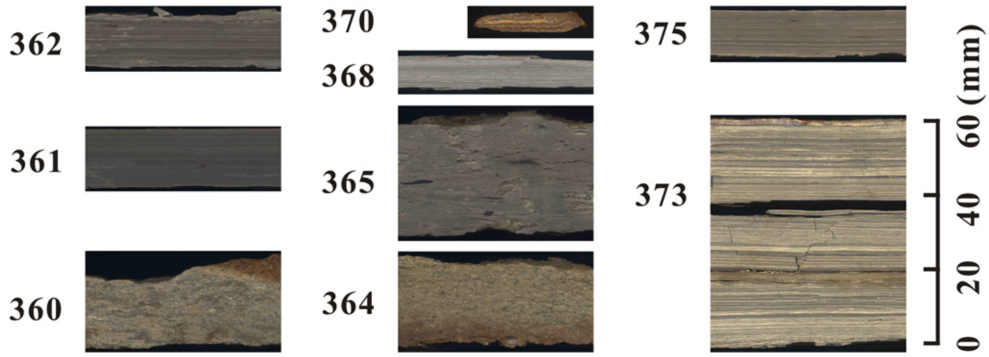

Fig. 4. Representative rock samples from the upper 2.82 m of the excavated Sihetun Fossil Museum section. The position of these samples in the section is indicated on the stratigraphic log in Fig. 1E.

is less than in black mudstone (Fig. 6B2). Most of this debris occurs in layers in the siliciclastic lamina but a small amount is irregularly distributed as in black mudstones (Fig. 6B2). When examined under a fluorescence microscope the organic matter in the organic-rich and transition laminae does not show a filamentous network (Fig. 6C4).

4.3. Shale

Shale (e.g., samples 368, 373, and 375 in Fig. 5) also exhibits beautiful siliciclastic–organic-rich lamination (Fig. 6A3, B3). The basic unit is composed of a lower siliciclastic lamina and an upper organic-rich lamina (Fig. 7B). The thickness of most couplets fluctuates between 0.2 and 0.5 mm (Figs. 6B3, 7B). The siliciclastic laminae are usually very thin, only a few tens of micrometres. The organic-rich laminae are much thicker, usually hundreds of micrometres (Figs. 6B3, 7B). The contact faces between the siliciclastic and organic-rich laminae are sharp (Fig. 6B3). When examined under a fluorescence microscope almost no organic matter is seen in the siliciclastic laminae whereas it is evenly distributed in the organic-rich laminae (Fig. 6C6). It is difficult to observe this feature under a petrographic microscope (Fig. 6C5). There is very little silt-sized quartz and feldspar debris in the shale (Fig. 6B3).

5. Origin of the laminations

The basic unit of the lamination usually consists of at least two different layers: siliciclastic, biogenic (e.g., diatoms, organic matter) or authigenic mineral (e.g., calcite). Siliciclastic–organic-rich, organic–carbonate and siliciclastic–evaporite are some of the common laminations in lacustrine sediments or sedimentary rocks (O'Sullivan, 1983; Anderson and Dean, 1988; Kemp, 1996). The majority of lacustrine sedimentary laminations are varves (O'Sullivan, 1983; Saarnisto, 1986; Petterson, 1996). Siliciclastic–organic-rich varves are very common in modern lacustrine sediments. Light-coloured siliciclastic laminae are formed usually during a post-winter thaw and/or wet spring and early summer when large quantitites of allochthonous minerogenic matter are transported into lakes by rivers and streams. Dark-coloured organic-rich laminae are usually formed from late summer onwards through the winter months when there is little allochthonous input of minerogenic matter and clay minerals and autochthonous organic matter settle out from a static water column (Petterson et al., 1993; Ojala et al., 2000; Tiljander et al., 2002; Haltia-Hovi et al., 2007; Stanton et al., 2010).

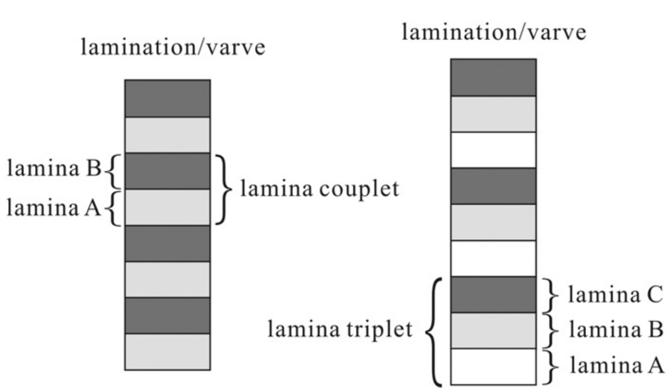

Fig. 5. Graphic illustration of the sedimentary lamination.

The siliciclastic–organic-rich lamination in Sihetun Fossil Museum section is very similar to the siliciclastic–organic-rich varves in modern lacustrine sediments. This suggests to us that, with the exception of the black mudstones, the majority of the siliciclastic–organic-rich laminations in the mudstones and shales are varves, and that the mode of formation in both is similar. Explanations for slight differences in the laminations encountered are as follows.

5.1. Black mudstone

There is no regular lamination in black mudstone (Fig. 6B1). The irregular distribution of siliciclastic laminae may be attributed to a lack of regular rainy seasons. There may have been one or more significant rain events in a single year. Since each siliciclastic lamina is likely to have been deposited during a wet period, several rain events in a single year will be reflected by several siliciclastic and organic-rich laminae. It is difficult to determine how many laminae were deposited in one year.

Palynofacies analyses show that the palynological matter in the organic-rich laminae is dominated by amorphous organic matter (AOM). There are also some pollen and spores, the assemblages being dominated by gymnospermous pollen, and larger land-plant fragments are occasionally encountered. Batten and Stead (2005) noted that AOM commonly has bacterial and algal components, and may be dominated by them. Viewed in thin-section, the organic matter forms a filamentous network (Fig. 6C2) that between the scattered silt-sized particles (Fig. 6C1, C2). These textures are similar to those of modern microbial mat fabrics (Noffke, 2010). Hence, the filamentous organic matter in the organic-rich laminae may be mainly derived from microbial mats (bacteria and/or benthic algae).

As described above, the thickness of siliciclastic laminae usually amounts to no more than a few tens of micrometres. These suggest

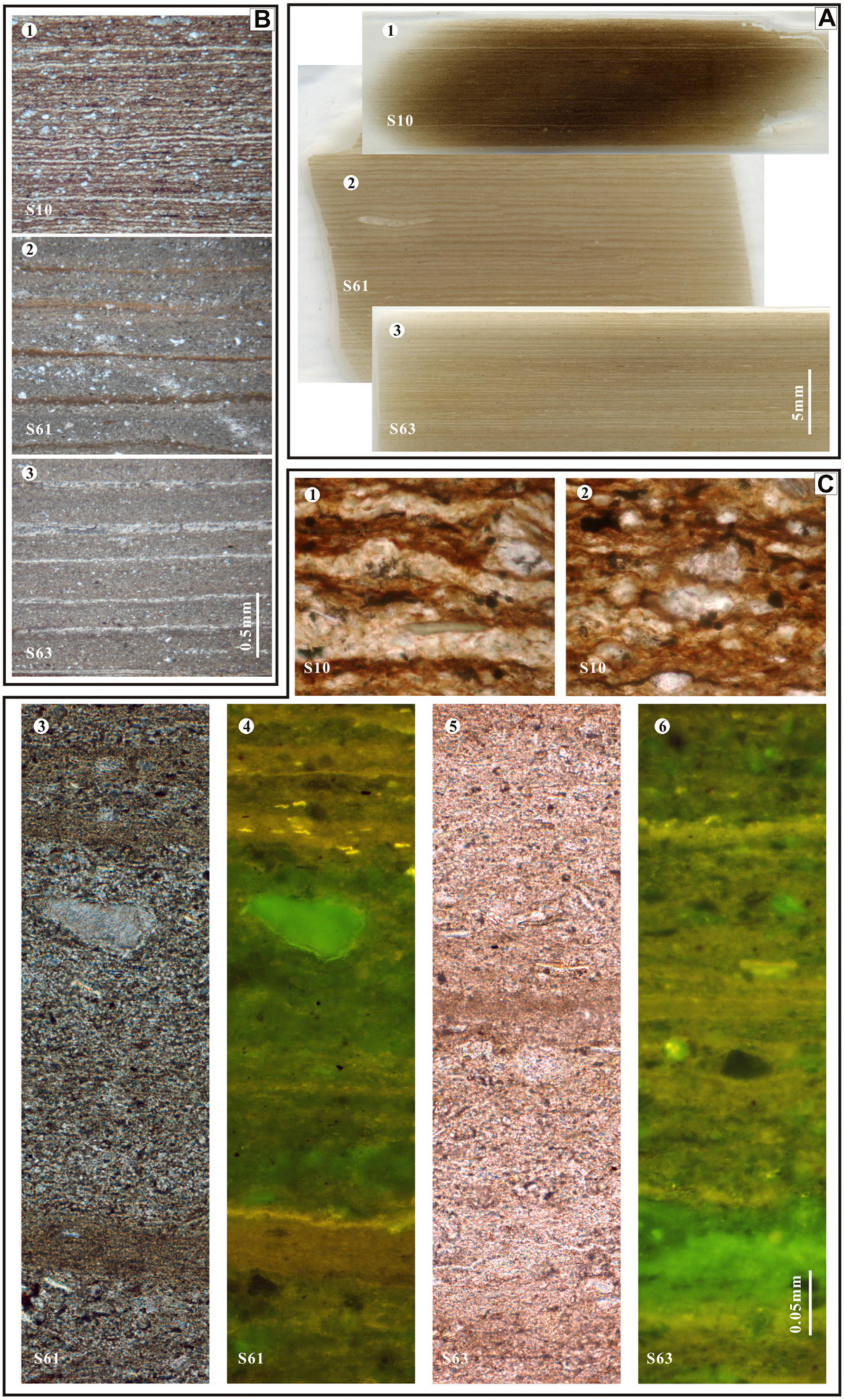

Fig. 6. Siliciclastic–organic-rich laminations in mudstones and shale. A, thin-sections of sample S10, S61, S63. B, C, photomicrographs of thin-sections. C1 and C2 are of different parts of sample S10. C3 and C4 are of the same part of sample S61; C5 and C6 are of the same part of sample S63. C4 and C6 are fluorescence photomicrographs; the yellow colour is emitted by sedimentary organic matter and the green colour is emitted by glue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

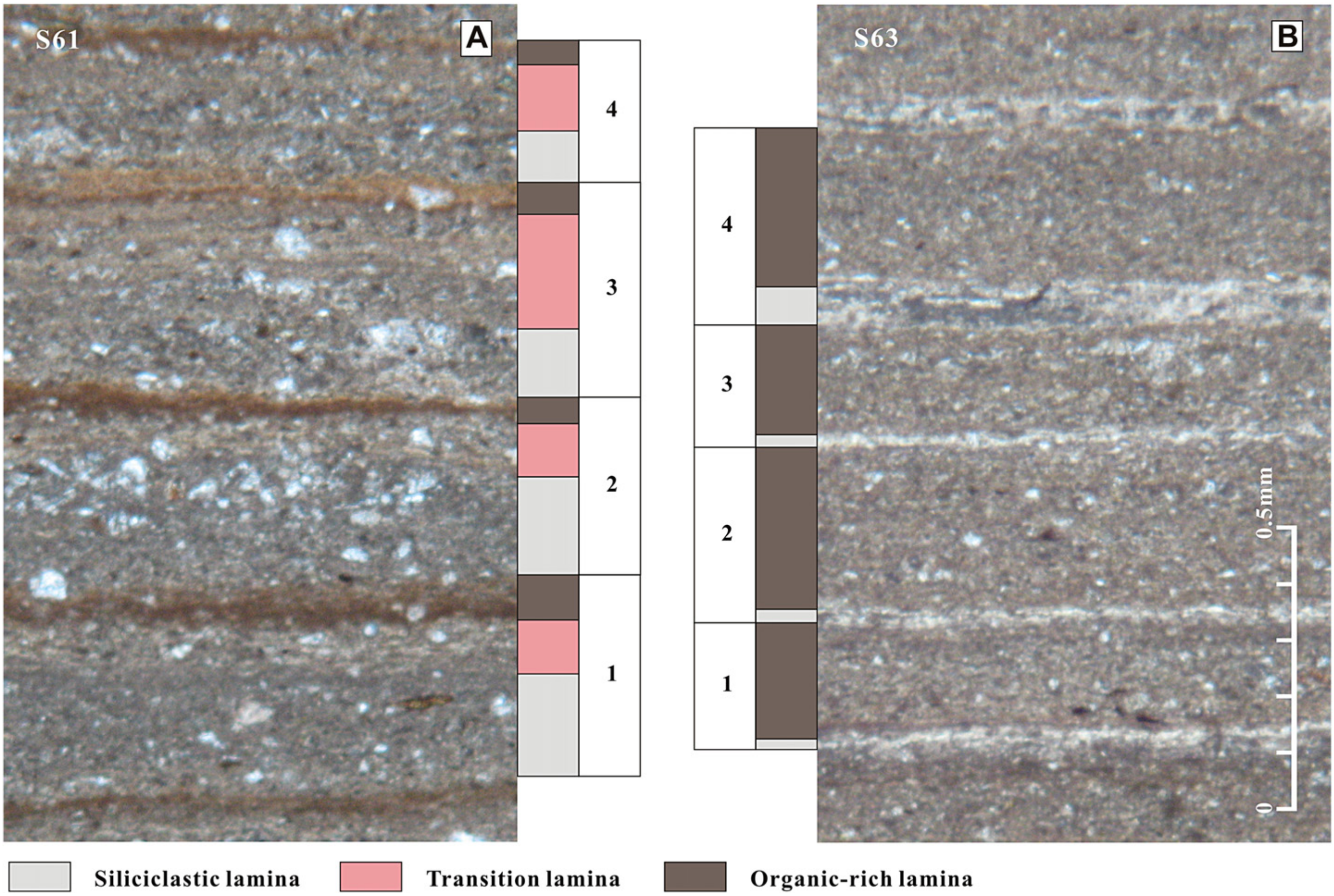

Fig. 7. The siliciclastic–organic-rich varves in A, grey mudstone and B, shale. Four basic units are plotted in each case.

that even after a significant rain event the in-flowing rivers had relatively low sediment loads. Cohen (2003) reported that such enter a lake usually as overflows (surface currents) and often develop into interflows (under currents) as they advance. There is, moreover, no erosion of fabrics resulting from underflows (turbidity currents) between different laminae. As a result, the terrigenous particles in siliciclastic laminae are considered to have been transported to the depositional site mainly by overflows and/or interflows.

Hence, the alternation of different laminae in black mudstone originated from background microbial growth and episodic burial of microbial mats by terrigenous siliciclastic particles. In addition, the large quantitites of silt-sized particles that are scattered through both the siliciclastic and organic-rich laminae were probably transported into the lake by wind because they do not occur in layers.

5.2. Grey and pale grey–greenish grey mudstones

We consider the rhythmic lamination in grey and pale grey–greenish grey mudstone to be varves (Fig. 7A). These were formed by seasonal changes in primary production and precipitation. The siliciclastic lamina at the base of the varve was deposited during the rainy season, probably in spring and early summer when the sedimentation rate of terrigenous debris was much greater than that of organic matter. The transition lamina in the middle part of the varve was probably deposited in the summer when some autochthonous organic matter and large amounts of allochthonous debris were deposited synchronously. The organic-rich lamina at the top of the varve probably accumulated from the late summer until the end of the following winter when the supply of the terrigenous debris was very low and the organic matter and clay particles settled out from the quiet water column. The gradual transition of the siliciclastic lamina to the organic-rich lamina reflects a gradual decrease in rainfall and a commensurate increase in autochthonous organic productivity.

The terrigenous particles were transported to the depositional site mainly by overflows and/or interflows. The organic matter is composed largely of AOM, which does not show a network structure when viewed in thin-section. These characters indicate that the organic matter was probably derived mainly from phytoplankton, with some gymnospermous pollen and a few land-plant fragments in association.

5.3. Shale

The rhythmic lamination in the shale also represents varves (Fig. 7B). The alternation of different laminae indicates fluctuations in fluvial discharge as a result of seasonal changes in precipitation. The siliciclastic lamina probably formed during a very short, rainy, spring to summer season and the organic-rich lamina probably reflects deposition during the rest of a year. The organic matter is distributed homogeneously in the organic-rich lamina (Fig. 6C6). This suggests that the sedimentation rate of the allochthonous debris and autochthonous organic matter was more or less constant during most of each year except in the rainy season.

The terrigenous particles were transported to depositional site mainly by overflows and/or interflows. The organic matter was mainly derived from phytoplankton. There are almost no pollen and spores or land-plant fragments.

6. Discussion

6.1. Colour of the rocks and sedimentary laminations

Mudstone and shale can be classified in two series, a red → purple → greenish grey series based on Fe^{3+}/Fe^{2+} and a greenish grey → grey → black series based on organic-carbon content (Potter et al., 1980). In effect, pigmentation is by Fe^{3+} in the first series, but by organic carbon in the second, once the Fe^{3+} has been converted to Fe^{2+} (Potter et al., 1980).

The pale grey–greenish grey → grey → black colour series of mudstone and shale in this study corresponds to the second series. The TOC content progressively decreases from black mudstone through grey mudstone to pale grey–greenish grey mudstone and shale. The TOC content of the black mudstone is highest, ranging from 3.2 to 5.3%. The TOC content of the grey mudstone ranges from 1.4 to 2.8% and that of the pale grey–greenish grey mudstone and shale from 0.4 to 1.4%. The colour of the mudstones and shale is, therefore, mainly controlled by the organic-carbon content.

The organic-carbon content is also the main controlling factor of the colour of the laminations. The siliciclastic laminae are usually pale because they contain little organic carbon, whereas the organic-rich laminae are usually dark because the content of organic carbon is relatively high.

6.2. Depositional environment

The existence of laminated sediment requires not only a regular change in sedimentary composition but also a quiet, anoxic depositional environment that will protect the laminated sediment fabric from bioturbation and hydrodynamic disturbance (O'Sullivan, 1983; Anderson and Dean, 1988; Kemp, 1996). Bottom water/sediment anoxia resulting from stratification will prevent colonization by benthic animals, and a quiet depositional environment means no hydrodynamic disturbance resulting from waves and currents. The morphometry of a lake basin is crucial for the preservation of lamination; e.g., laminated sediments are more readily preserved in deep than in shallow lakes (O'Sullivan, 1983).

The well-developed sedimentary laminations in the mudstones and shales in the Sihetun Fossil Museum section indicate that there was no bioturbation and hydrodynamic disturbance when the sediments were deposited. The lack of hydrodynamic disturbance was probably because the morphological features of the lake were suitable: it is thought to be a crater lake (Liu et al., 2002; Jiang et al., 2011). Crater lakes are often very deep with steep walls (Liu et al., 2002; Cohen, 2003), features that prevent disturbance of sediments from wind-driven waves and currents. There are also unlikely to have been any underflows to disturb the sediments once they had been deposited because rivers entered the lake mainly as overflows and interflows. The lack of bioturbation was probably because the water at the bottom of the lake was anoxic. Liu et al. (2002) thought the lake environment was predominantly anoxic because most maar lakes are meromictic with anoxic bottoms. Fürsich et al. (2007) considered it to be periodically anoxic as a result of seasonal changes in water temperature and oxygen consumption. Whether the lake bottom was permanently or seasonally anoxic, it was clearly not conducive to colonization and disturbance by benthic animals; rather it favoured the preservation of sedimentary lamination (Liu et al., 2002) and fossils (Liu et al., 2002; Zhou et al., 2003; Fürsich et al., 2007; Harding et al., 2009). In addition, large quantitites of small pyrite framboids, which are commonly formed in anoxic water columns (Wilkin et al., 1996), are present in the black mudstones. These also indicate anoxic conditions in the lake.

6.3. Sedimentation rate

The duration of the Yixian Formation has been estimated from radiometric dating of the associated volcanic rocks. Smith et al. (1995) thought the rate of sedimentation of the fossil-bearing beds was as high as 500–2000 m/myr (i.e., 0.5–2 mm/year). Zhu et al. (2007) suggested that the lacustrine sediments accumulated at a rate of no less than 2 cm/kyr (i.e., >0.02 mm/year). Chang et al. (2009) argued that the rate of accumulation of the fossil-bearing unit was 22–250 m/Ma (i.e., 0.022–0.25 mm/year).

As noted above, measurements show that the thickness of the varves ranges from 0.2 to 0.7 mm. These indicate that the sedimentation rate of the majority of the fossil-bearing mudstones and shale in the Sihetun Fossil Museum section is approximately 0.2–0.7 mm/year. Assuming such a sedimentation rate, it would have taken approximately 11,000–37,000 years for the 7.43-m-thick section to accumulate.

6.4. Lake evolution

Some authors have suggested that there were probably many small lakes in the Sihetun area (e.g., Liu et al., 2002), whereas others have inferred the presence of just one large lake (e.g. Li and Batten, 2007; Harding et al., 2009). We have not been able to determine how many lakes were involved or how large they were, but the characters of the sedimentary laminations in the section investigated indicate a gradual increase in lake area and water depth with time.

The lower part of the section is dominated by black mudstones that contain large quantities of silt-sized quartz and feldspar debris. This suggests that the depositional site was not far from shore, the silt-sized particles being easily transported there by water currents or wind. The existence of microbial mats indicates relatively shallow water with sunlight penetrating the lake floor. This suggests that the lake was relatively small and shallow at that time.

The middle part of the section is dominated by grey and pale grey–greenish grey mudstones. The content of silt-sized particles, especially the scattered particles, is less than in black mudstone, suggesting that the distance from shore had increased. Although overflows and interflows were still able to transport large quantities of silt-sized particles to the depositional site, it would have been more difficult for wind to transport large particles there. In addition, the organic matter is mainly derived from phytoplankton. The disappearance of the benthic microbial mats may have been a consequence of deepening water to the point at which sunlight could not reach the bottom of the lake.

The upper part of section is dominated by shales. The absence of terrigenous silt-sized particles in these suggests that the depositional site was far from the shore during a period of high lake level. As a result, large particles were rarely transported to the depositional site by either water currents or wind. The organic matter in the shales is also mainly derived from phytoplankton; almost no pollen and spores are present. The further offshore the deposit the fewer and smaller the land-plant products (spores, pollen grains and phytoclasts) (Batten and Stead, 2005); hence, the scarcity of pollen and spores also indicates that the depositional site was far from the shore.

6.5. Palaeoclimate

Palaeobotanical evidence indicates a seasonal climate in the area during the Early Cretaceous (Sun et al., 2001; Ding and Zhang, 2004; Ding et al., 2004; Li and Batten, 2007). Fürsich et al. (2007) thought that the seasonal fluctuations were related mainly to the hydrological cycle, a conclusion with which we agree. The alternation of siliciclastic and organic-rich laminae was mainly for this reason, but there were probably also seasonal fluctuations in temperature, which could have been an important cause of seasonal changes of lacustrine primary production. In addition, the scattered silt-sized particles in the mudstones indicate that there were often strong winds at that time.

7. Conclusions

The Sihetun Fossil Museum section is composed of mudstone, shale and volcanic ash layers. The siliciclastic–organic-rich laminations are well developed in the mudstone and shale, and apart from those in black mudstone, most are considered to be varves.

The colour of the mudstones and shale is determined by the content of organic carbon: the higher the content, the darker the colour of the rock. The colour of the different laminae is also controlled by the amount of organic carbon present.

The rate of sedimentation has been determined to be about 0.2–0.7 mm/year. It follows that the 7.43-m-thick Sihetun Fossil Museum succession represents deposition during approximately 11,000–37,000 years.

The well-developed laminations indicate a lack of bioturbation and hydrodynamic disturbance as a result of permanent or seasonal anoxia in the bottom water and the morphology of the lake. The characters of the sedimentary laminations in the section indicate both a seasonal climate and a gradual increase in lake area and water depth with time.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (91114201, 40632010). We thank professors Lizeng Bian and Yaosong Xue for their considerable help during the course of this study. We are grateful to Prof. F.T. Fürsich and an anonymous reviewer for their constructive suggestions and careful review of the manuscript, and Prof. D.J. Batten for improving the paper. We also appreciate Xiaogang Yao, Fabing Dong, Yanhong Pan and Yaqiong Wang for their help in the field.

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