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Stratigraphy, correlation, depositional environments, and cyclicity of the Early Cretaceous Yixian and ?Jurassic-Cretaceous Tuchengzi formations in the Sihetun area (NE China) based on three continuous cores

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A B S T R A C T

Three continuous cores acquired in the Sihetun area of Liaoning Province, famous for feathered non-avian dinosaurs of the Jehol Biota, reveal the stratigraphic and facies relationships of the divisions of the Early Cretaceous Yixian and underlying ?Jurassic-Early Cretaceous Tuchengzi formations. Based on these cores, we propose a modified lithostratigraphic nomenclature in the Sihetun Sub-basin in which the Yixian Formation is divided into three members: the Lujiatun Member, a fluvial and alluvial volcaniclastic sandstone and conglomerate, unconformably overlying the Tuchengzi Formation, with articulated tetrapods plausibly preserved in burrows; the Xiatulaigou Member, an extrusive basaltic flow and breccia comprising the only true lavas in the area; and the Jianshangou Member, a cyclical lacustrine mudstone containing a taphocoenosis of articulated compression fossils with soft tissue preservation including non-avian dinosaurs, birds, pterosaurs, mammals, fish, crustaceans, insects, mollusks, and plants. The latter, is divided into 4 units: the basal Dajianshanzi Bed, a shallow-water lacustrine unit with abundant mollusks and rooted zones; the Anjiagou Bed, the main tetrapod-bearing unit, consisting of microlaminated dark gray mudstones with many interbedded airfall ashes deposited in a meromictic lake; the Hengdaozi Bed comprised of thin and rhythmically to medium bedded light gray to tan mudstones and sandstones with few discrete ashes, famous for its diverse insects and plants, including early angiosperms deposited in alternating dysoxic and oxygenated bottom water; and the Huangbanjigou Bed, the most obviously cyclical of the units, with dark gray microlaminated intervals with articulated vertebrates alternating with more massive lighter colored mudstones and volcaniclastic sandstones deposited in lakes that oscillated in depth. Cyclicity in the Jianshangou Member is dominated by meter-scale cycles that may be paced by orbital variations. Unambiguous, relatively rapid, lateral facies changes within the Yixian Formation are suggestive of local relief, not the bottom of a giant flat-bottomed basin.

1. Introduction

Spectacular feathered proto-feathered and feathered non-avian dinosaurs, abundant birds, and articulated pterosaurs and mammals as well as early flowering plants and diverse insects of the Early Cretaceous age Konservat Lagerstätte, conventionally termed the Jehol Biota, have arguably revolutionized our understanding of Mesozoic continental ecosystems (Norell et al., 1995; Sun et al., 1998; Zhou et al., 2003; Meng et al., 2004; Benton et al., 2008; Pan et al., 2013; Xu et al., 2014). In particular, fossils, such as the proto-feathered theropod dinosaur *Sinosauropteryx* (Ji and Ji, 1996; Chen et al., 1998), have provided rigorous tests of phylogenetic hypotheses of bird-dinosaur relationships and the origin of feathers.

Many iconic representatives of this assemblage come from the Yixian Formation in the region around Sihetun, Beipiao, western Liaoning (Liaoxi area), northeastern China (Fig. 1), including *Sinosauropteryx*. They were collected from numerous quarries and multiple levels, some of which have now become geoparks and museums. However, placing the strata and their contained biotic remains in temporal order has been hampered by geographically disparate localities with generally poor exposure and deep weathering. These issues are compounded on the larger scale by the nominal juxtaposition of unit names from different basins not known to be

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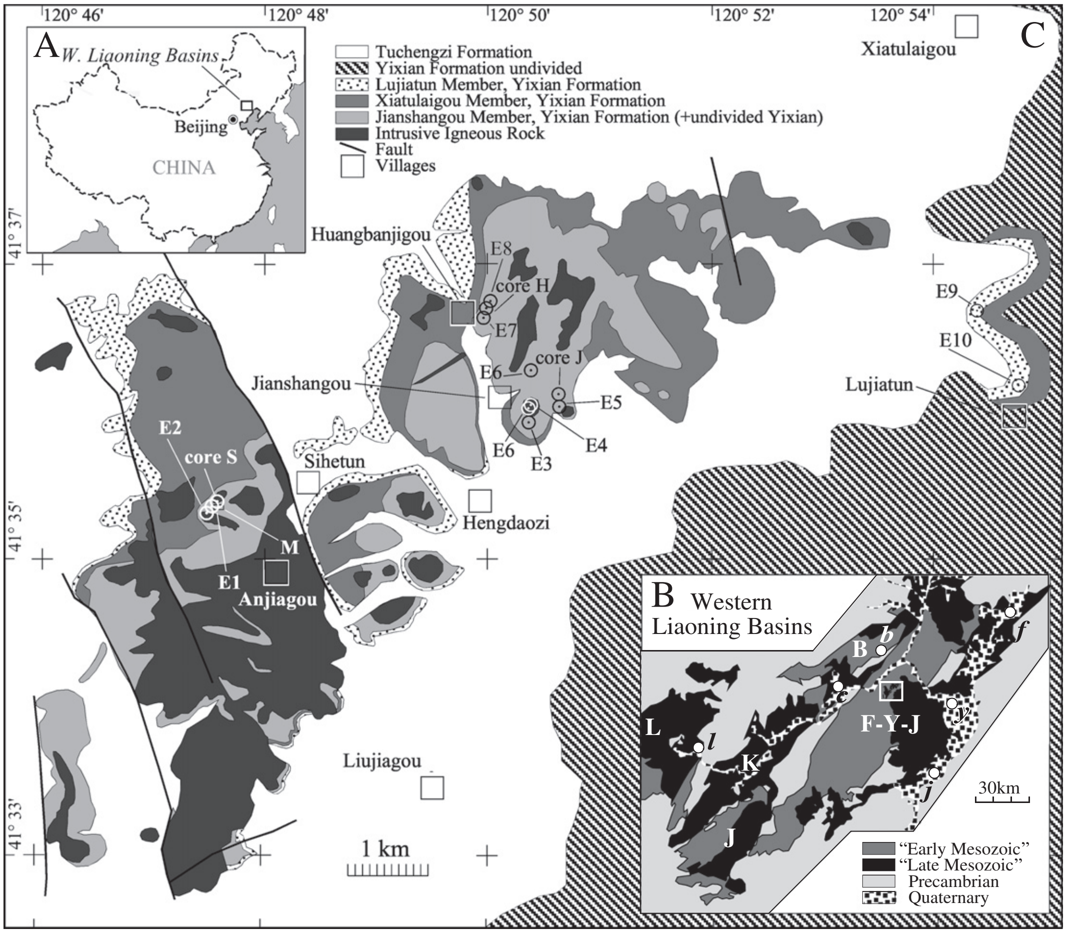

Fig. 1. Maps showing the location of cores and lithological units. A, Map of China showing the location of the Western Liaoning basins (W. Liaoning Basins) shown in detail in B. B, basins of western Liaoning Province (map adapted from Wang et al., 1989). "Early Mesozoic" includes Beipiao Formation (Jurassic), Haifanggou Formation (Jurassic), Lanqi Formation (Jurassic), and Tuchengzi Formation (?Jurassic–Early Cretaceous) while "Late Mesozoic" is comprised of the Yixian Formation. Abbreviations are: B, Beipiao Basin; *b*, Beipiao City; *c*. Chaoyang City; F-Y-J, Fuxin-Yixian-Jinzhou Basin (Yixian Basin in text); *f*, Fuxin City; J, Jianchang Basin; *j*, Jinzhou City; K, Kazuo-Chaoyang basin; L, Lingyuan Basin; *l*, Lingyuan City; *y*, Yixian City. C, Geologic map of the Sihetun Sub-basin and adjacent Yixian (Fuxin-Yixian-Jinzhou) Basin. Cores abbreviations are: core S, Sihetun no. 1; core H, Huangbanjigou no. 1; Core J, Jianshangou no. 1. Exposures are: E1, excavation of Zhang and Sha (2012); E2, West wall of Sihetun Museum excavations; E3, ditch Along Road to Dajianshanzi; E4, top of Dajianshanzi; E5, "turtle hill" excavations; E6, laminite exposure near top of Dajianshanzi; E7, Exposures of upper Hengdaozi Bed, the type section of the Huagbanjigou Bed, and undivided Yixian Formation on east side of hill at Huagbanjigou; E8, temporary exposures at the top of the hill at Huangbanjigou of undivided Yixian Formation; E9, type section of the Lujiatun Member; E10, section of the Lujiatun Member in Fig. 21; M, Sihetun Landscape Fossil Bird National Geopark museum and type section of the Anjiagou Bed within. "Early Mesozoic" includes the Jurassic Beipiao, Haifanggou, and Lanqi formations and its equivalents as well as the ?Jurassic-Early Cretaceous Tuchengzi Formation. "Late Mesozoic" includes Early Cretaceous Yixian, Jiufutang, and Fuxin formations. Map registered to GoogleEarth image.

in superposition anywhere, as well the persistence of a largely informal and contentious stratigraphic nomenclature.

These issues motivated continuous coring at three sites in the region around Sihetun. The hope was to see stratigraphic units with the various fossiliferous levels and famous biota in superposition and in an unweathered state. Here we describe the cores, their lateral correlation, and erect a revised lithostratigraphic nomenclature that clarifies the various fossil-bearing horizons in the Sihetun area and provides a foundation for further studies in the region.

1.1. Geological context

According to the regional synthesis of Li et al. (2012), the Fuxin-Yixian-Jinzhou Basin (Jiang and Sha, 2006), hereafter termed simply the Yixian Basin, developed within the Yinshan-Yanshan Orogen on the north edge of the North China block during a mid- to late Mesozoic phase (Yanshanian) of changing stress regimes (Yan et al., 2002), including extension, in what is now the Liaoxi area of Liaoning Province (Fig. 2). The consequent extensive igneous activity and crustal-scale deformation and thinning is termed the destruction (or deconstruction) of the North Chinese Craton (Li et al., 2012). The Yixian depositional basin formed as one of a now-disconnected series of basins bounded by major faults (Xu et al., 2000; Ren et al., 2002; Li et al., 2012) and transected by smaller faults, although how or if the smaller basins, such as the Yixian Basin, linked up with others during Mesozoic deposition is not clear.

The Yixian Basin contains a thick series of Jurassic and Cretaceous continental and volcanic rocks resting unconformably on Precambrian and Paleozoic age strata (Yan et al., 2002) (Fig. 3). As a whole, the Mesozoic strata have a complex nomenclatural history (Zhao et al., 2010; Jiang and Sha, 2006) that is largely outside the purview of this paper. Definitively Jurassic age strata have been assigned to the volcanic Xinglonggou Group, the coal-bearing fluvio-lacustrine Beipiao Group, the largely lacustrine Haifanggou and largely volcanic Lanqi formations. They are overlain by strata assigned to the fluvio-lacustrine Tuchengzi Formation that yields definitive Early Cretaceous ages (Chang et al., 2009) but may extend into the Jurassic (Xu et al., 2012). A regional unconformity separates the Tuchengzi from the overlying Early Cretaceous (130–122 Ma, Chang et al., 2009) lacustrine, fluvial and volcanic Jehol Group, which is based on the Jehol Series, first introduced by Grabau (1923). The basal formation of the Jehol Group is the Yixian Formation, which together with the underlying Tuchengzi Formation, are the main focus of this paper. The Yixian is conformably overlain by the Jiufotang

Fig. 2. Paleogeographic position of the Yixian Basin (Y). Map was prepared with GPlates (Boyden et al., 2011) using the poles in of Seton et al. (2012), consistent with the data and reconstructions in Kent et al. (2015). Note that this is a significantly different reconstruction that places the Yixian Basin at about 58° N, greater than 20° further north than shown by Enkin et al. (1992), which has generally been used by others (e.g., Zhou et al., 2003; Benton et al., 2008).

and Fuxin formations also in the Jehol Group, which in turn are overlain disconformably by the Sunjawan, and then unconformably by the Late Cretaceous age Daxingzhuang formations (Sha, 2007). Cenozoic age strata unconformably overlie the Yixian Basin sequence.

We use the term Sihetun Sub-basin to refer to the series of outcrop areas of Yixian Formation, near Sihetun itself and limited by the area shown by Jiang et al. (2011, Fig. 1) (Fig. 1), that are separated from the much larger area of contiguous Yixian Formation to the east. We do this to recognize the possibility that the stratigraphy in the Sihetun Sub-basin may not be the same as in the outcrop areas to the east, including the type area for the formation.

2. Material and methods

The three drill cores and adjacent outcrops described in this paper are from the western part of the Yixian Basin in the Sihetun Sub-basin, close to the Sihetun Landscape Fossil Bird National Geopark in Sihetun and several of the most important Yixian Formation localities (Fig. 1): 1) the Sihetun no. 1 core (41.589776°, 120.793713°) drilled in 2008 to a depth of 103 m to the immediate NE of the Sihetun Fossil Museum (Fig. 4A); 2) the Huangbanjigou no. 1 core (41.611806°, 120.833472°) drilled in 2014 to a depth of 200 m about 3.9 km NE from Sihetun no. 1 and to the immediate east of the eponymous village (Fig. 4); 3) the Jianshangou no. 1 (41.602000°, 120.844167°), also drilled in 2014 to a depth of 100 m (Fig. 4) about 1.4 km to the SE of Huangbanjigou no. 1, is named for the nearby village of Jianshangou that is 760 m WSW.

All three cores were drilled using diamond-impregnated mineral coring bits (Fig. 5) by the 3rd Geological Team of Liaoning Province. The Sihetun no. 1 core (Fig. 4) was conventionally cored, meaning the drill string was pulled up for each cored segment. Nominally 8.50 cm (PQ) diameter core was recovered from the upper 4 m of section, entirely within an igneous intrusion whereas the rest of the core was nominally 4.76 cm (NQ) diameter. The Huangbanjigou no. 1 and Jianshangou no. 1 (Fig. 4) cores were obtained using wireline coring, meaning only the core barrel was retrieved for each segment of core, whereas the drill string remained in place. Most of the core was HQ (nominally 6.35 cm) diameter core except for a few short intervals at the top of the Jianshangou no. 1 core that was 8.50 cm (PQ). Rock within 10 m of the surface is weathered and recovery in this interval was sometimes poor (<50%) especially in Huangbanjigou no. 1 and Jianshangou no. 1, but was better in Sihetun no. 1, which was spudded in igneous rock, although recovery was still poor in that upper interval. Recovery below 10 m was usually excellent and close to 100%.

Analysis of the cores was complemented by adjacent outcrops and exposures, which in fact were the source of so many spectacular Jehol Biota fossils, and these provided faunal and floral data that we could register to the cores. Exposures enclosed in the Sihetun Landscape Fossil Bird National Geopark museum (41.589154°, 120.793552°) comprise the type section of the new Anjiagou Bed, and exposures immediately to the south of the museum (41.588547°, 120.792177°) (Fig. 6A, B,) are parts of a larger excavation that include the type locality for *Sinosauropteryx*, the first non-avian dinosaur with feathers to be discovered (Chen et al., 1998). These excavations were initially the product of local farmers and then teams from the Institute of Vertebrate Paleontology and Paleoanthropology, Beijing (IVPP) during the late 1990s. The Huangbanjigou no. 1 core was spudded on the hill on the east side of the village (41.611806°, 120.833472°), rimmed by excavations largely for insects, fish, and plants, notably including the excavation that produced *Archaefructus* (Sun et al., 2002), a stem angiosperm. We were fortunate to be at this locality in 2012 when exposures of the basal laminites (Anjiagou Bed, this paper) of the Yixian Formation were still exposed (41.610876°, 120.831538; Fig. 6C) and in September 2015 during the very extensive excavations accompanying the development of the Beipiao Bird Fossils National Nature Reserve that wrapped around the northwest, southwest, and southeast sides of the hill on which the core was drilled (Figs. 6D,E, 7). Jianshangou no. 1 was spudded next to a road (at 41.602000°, 120.844167°) leading 150 m, NNW from a locality we call "turtle hill" (41.600667°, 120.844333°), riddled by tunnels dug by farmers largely for the abundant fossil turtles such as *Manchurochelys* (Ji, 1995). This hill is part of a series of hills that are between the Jianshangou and Dajianshangou (大尖山沟) valleys. Although we wanted to spud on the hill itself, that area was deemed unsuitable for drilling because of the unknown course of the extensive subterranean galleries dug for the turtles. Exposures at "turtle hill" and two adjacent sites - a pointed hill just east of Jianshanzi village termed Dajianshanzi – (41.600738°, 120.840023°; and "ditch along road to Dajianshanzi, 41.598779°, 120.839680°) (Figs. 6E, 8) proved invaluable in assessing the stratigraphy and local facies changes seen in Jianshanzi no. 1 relative to the other two cores. Outcrops and excavations at Lujiatun (41.603000°, 120.913167°), famous for having produced many spectacular 3-dimensional tetrapod skeletons such as the tiny theropod dinosaur *Mei long* and *Repenomamus robustus*, a mammal known to have eaten baby dinosaurs (Wang et al., 2001), were also examined for this study (Figs. 6F, 9).

Cores were measured, described, and photographed where they are housed at NIGPAS using conventional methods within the core boxes provided by the drillers both before and after being split. Depths were not marked on the cores themselves and therefore measurements were taken relative to the boxes and then corrected to fiducial tags, placed in the boxes by the drillers, indicating the run number and drilling depth. Core depth was then corrected to stratigraphic depth using the regression equation between the two depth series. The main corrections needed were for the upper parts of the cores where there was considerable core loss. Depth measurements within the text will be referred to by stratigraphic depth (SD) (which has been corrected by the above regression), and in parentheses, apparent core depth (ACD), which are the measurements we took on the core, not accounting for core loss. Stratal dip, as visible in outcrop, is very gentle in the Yixian Formation (<5°) and generally undetectable in the core of the

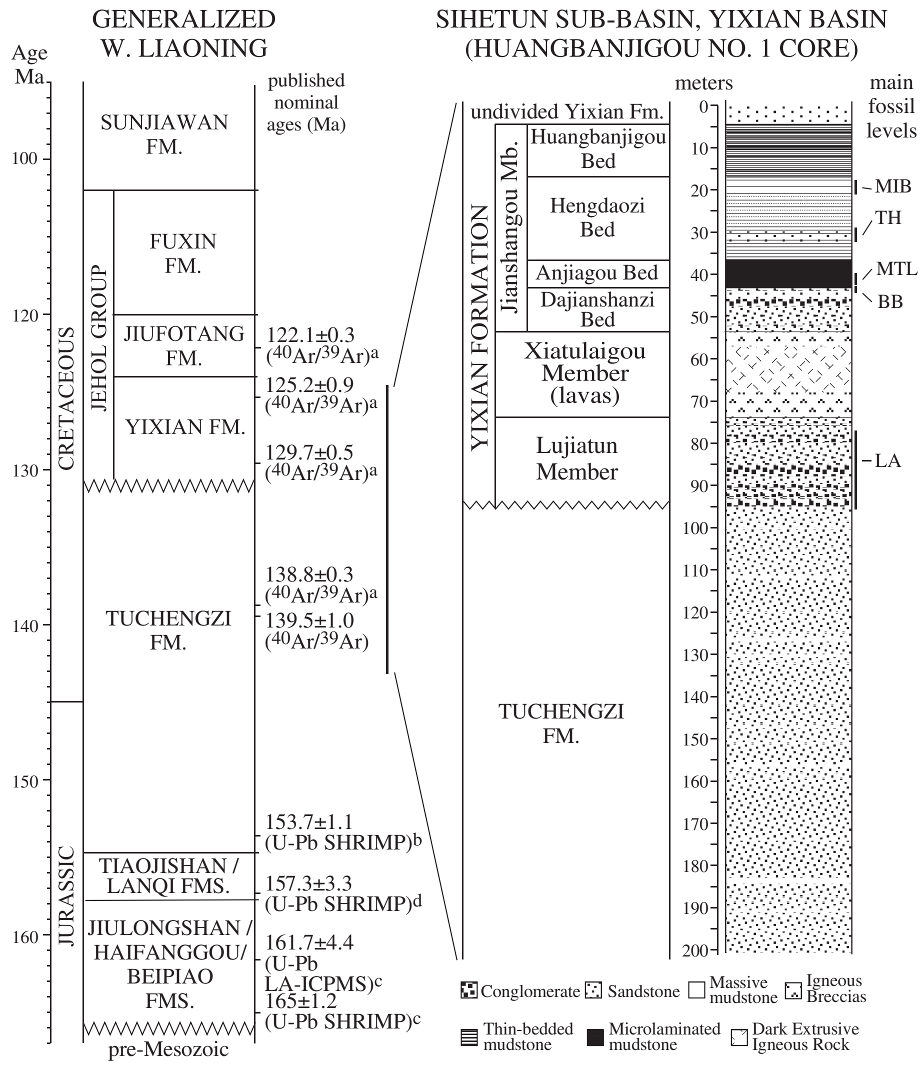

Fig. 3. Generalized Stratigraphy of the Mesozoic basins in western Liaoning and stratigraphy of the studied interval in the Sihetun Sub-basin of the Yixian Basin (Fuxin-Yixian-Jinzhou Basin), based on the Huangbanjigou no. 1 core. Nominal ages are from: a, Chang et al. (2009), b, Xu et al. (2012), c, Liu et al. (2006), d, Liu et al. (2012). These dates and the generalized section calibrated to them are shown for context and should not necessarily be taken as accurate representations of the true durations of the units. Abbreviations for main fossil levels are: MIB, main insect bed; TH, "turtle hill" (projected); MTK, main tetrapod level ("bird bed"); BB, "bivalve beds"; LA, Lujiatun Assemblage.

Tuchengzi Formation. In addition, core holes generally deviate into being perpendicular to bedding with depth, and because there was no survey of the drill holes conducted, there is no way to translate outcrop dips to the core. Therefore we made no attempt to correct to true stratigraphic depth. Regardless, any difference between true stratigraphic depth and core depth is likely to be very small.

Outcrops were measured with a tape measure in contiguous intervals of distinct lithology. For both cores and outcrops, measurements were entered in Microsoft Excel™ spread sheets with uniform properties (color, grain size, and a lamination index where applicable) as well as annotations describing distinctive properties, sample numbers and positions. Color and grain size were determined subjectively with a simple classification (red = 0, purple = 1, gray = 2, black = 3; clay = 0, mud = 1, silt = 2, fine sand = 3 to coarse conglomerate = 7). The lamination index is a subjective classification of sedimentary facies arranged in a series along an inferred relative water depth gradient from 0 (subaerial exposure, pervasively mudcracked) to 5 (deep water, microlaminated) equivalent to the "depth ranks" as described in Olsen and Kent (1996). Graphic logs were produced from Excel™ charts of the spreadsheet data imported as vector graphics into ACD Canvas™ graphics program.

3. Stratigraphic nomenclature

Although a complete review and revision of the lithostratigraphic nomenclature of the Jurassic and Cretaceous age strata of the Yixian Basin and Western Liaoning Province is beyond the scope of this paper, it is necessary to review the terminology we use for the lithostratigraphic units of rocks encountered in the cores (Fig. 10). We follow the International Code of Stratigraphic Nomenclature (ICSN) (Salvador, 1994; Murphy and Salvador, 1999) and raise the rank of several units traditionally called "beds" to formal member rank to allow the formal recognition of bed status for smaller-scale units.

Revision of the existing nomenclature is necessary because much of it is informal or uses the names of units representing subdivisions of the Yixian Formation that were established in strata very far away from the Sihetun area, in different basins, and not in observable superposition. In addition, probably due to the relatively poor natural outcrop in the area, stratigraphic studies of the Yixian Formation have tended to not discriminate between intrusive and extrusive dark igneous rocks. However, numerous excavations for fossils, particular those at Sihetun itself as well as the new cores, allows this to be remedied. This is extremely important because extrusive flows can be excellent stratigraphic markers,

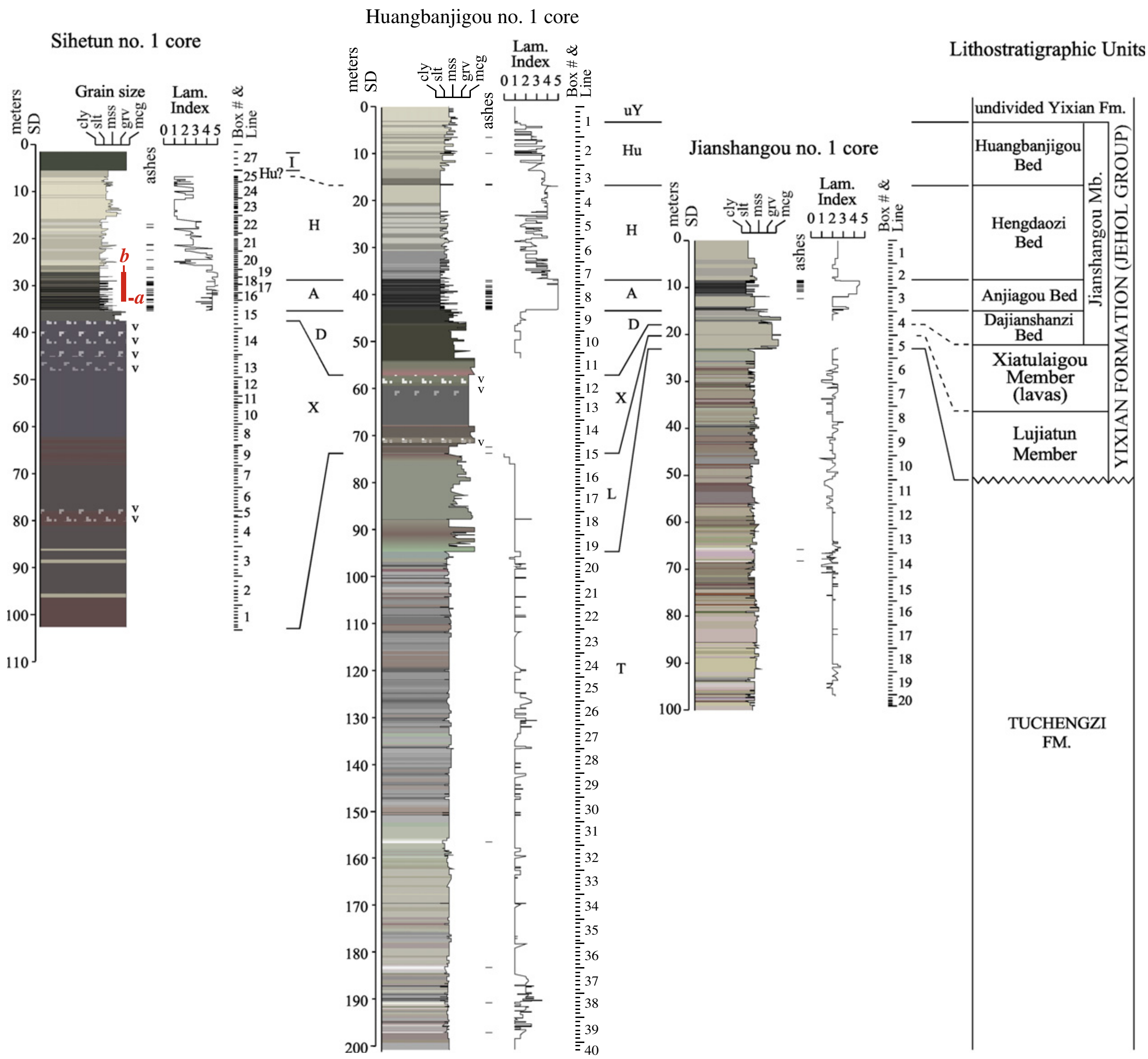

Fig. 4. Cores from the Sihetun area correlated at the base of the Anjiagou Member and to the same depth scale. Abbreviations are: A, Anjiagou Member; D, Dajianshanzi Bed; H, Hengdaozi Bed; Hu, Huangbanjigou Bed; I, Igneous Intrustion; L, Lujiatun Member; T, Tuchengzi Formation; v, vesicles in extrusive igneous rock of the Xiatulaigou Member; X, Xiatulaigou Member. Lam. Index, is the lamination index. *a*, tie interval between type section of Anjiagou Bed and Sihetun no. 1 core; *b*, correlative interval between Sihetun no. 1 core and type section – thick line represents Anjiagou Bed in type section and thin line is Hengdaozi Bed.

whereas the intrusive sheets are not and in fact are misleading if treated as extrusive. Historically, this has had a large effect on the complex nomenclatural history of the formation. The lack of discrimination between intrusive and extrusive igneous units has muddled attempts to correlate sections in different areas. This has been particularly true in comparisons between the eastern outcrops in areas near the town of Yixian, the type area, which has multiple extrusive flows of various compositions with relatively thin interbeds of sedimentary rocks, and the Sihetun area to the west which has only one extrusive interval of dark igneous rock but many intrusive sheets and plutons of similar looking rock injected into otherwise continuous sedimentary sequences. For example, a relatively recent summary of the nomenclatural history of the Yixian Formation by Zhao et al. (2010) treats all of the igneous intervals in the Sihetun area as volcanic, i.e., extrusive in origin. In contrast, Chiappe et al. (1999) regard all of the dark igneous rocks in the Sihetun area as intrusive. Li et al. (1998) does not discriminate between extrusive and intrusive, whereas Wang et al. (1998), Wang et al. (2004), and Chen et al. (2005) clearly differentiate in their sections between vesicular units and massive units and clearly show units we interpret as intrusive as such in their sections. Jiang et al. (2011) mixes intrusive and extrusive units, interpreting some intrusions as volcanic eruptive centers. Many of the sedimentary units in earlier papers are defined by boundaries that are in fact intrusive sheets (e.g., Zhao et al. (2010)) that intrude lithologically continuous sequences, greatly complicating a clear assessment of priority and synonymy). That said, we have not looked at all of the outcrops of igneous rocks in the Sihetun area, and it is possible there are younger flows that we have not identified.

Here we take a conservative approach and retain conventional nomenclature at the formation scale, raise bed names with priority to member rank where they correspond to defensible lithologic units, and propose new bed names for distinctive units that may be recognizable over a smaller area than the formations or members (Fig. 10).

3.1. Tuchengzi Formation

The Tuchengzi Formation (originally Tucheng Conglomerate) was named for coarse-grained sedimentary rocks in the Tuchengzi area in Beipiao County, Liaoning Province. The citation for the origin of this name is listed by Zhang (2009) as Rin (1942), but the actual use of the formation name in print appears to be Nishida (1942) in a preceding

Fig. 5. Coring rig of the 3rd Geological Team of Liaoning Province at the drilling site of the Huangbanjigou no. 1 core, looking northeast (27°) on the hill northeast side of the village of the same name. In the background is the crest of the hill comprised of undivided Yixian Formation sandstones.

short paper in the same volume.[1] Tuchengzi Formation is the name conventionally used for the greenish, gray, tan, purple and red clastic rocks and minor volcaniclastic strata present below the unconformity with the overlying Yixian Formation in the Sihetun area. We use that term here for the units encountered in the Huangbanjigou no, 1 and Jianshangou no. 1 core below the unconformity above the base of the Yixian (Figs. 4, 10). The exact relationship of the formation in the Sihetun area to the type area of the Tuchengzi Formation is not known, despite an overall lithological resemblance and homotaxial position.

3.2. Jehol Group

Grabau (1923, 1928) named the Jehol Series for strata containing what is now called the Jehol Biota. The name Jehol (热河) derives from the former Rehe Province, now largely divided between western Liaoning and Hebei provinces and Nei Mongol Autonomous Region. There has been a lack of agreement on what currently recognized formations should be included in the Jehol Group (Pan et al., 2012), but we use it as defined by Sha (2007) to contain the Yixian, Jiufotang, and Fuxin formations (Fig. 3).

3.2.1. Yixian Formation

The Yixian Formation, originally Yixian Volcanics, was named in the Zaocishan-Jingangshan area of Yixian County for the local “lower porphyry beds” (Muroi, 1940; Gu, 1962; Zhang, 2009). In its type area, the Yixian Formation consists of hundreds to thousands of meters of extrusive igneous sequences and thinner interbedded clastic rocks; however to the west in the region around Sihetun, extrusive igneous rocks are much less extensive and correlation of the two areas is hence uncertain. Chen et al. (1980) used the name Jianshan Bed, named for the Jianshangou area, as a subdivision of the lower Yixian Formation. Li et al. (1998) proposed the name Sihetun Formation as a replacement for what had been traditionally called the Yixian Formation in the Sihetun area, citing the lack of lithological similarity with the type area. Similarly, Chiappe et al. (1999) argued that the highly fossiliferous laminated units producing birds and non-avian dinosaurs in the Sihetun area should not be part of the Yixian Formation and instead recognized a new unit of equivalent rank, the Chaomidianzi Formation. Chen et al. (2005) points out that neither the Chaomidianzi nor Sihetun formation names have gained acceptance, and Yixian has very clear priority. We continue to use Yixian in the sense used by Chen et al. (1980) and many others for the formation overlying the Tuchengzi in the Sihetun area. Member-level divisions of the Yixian Formation we recognize in the Sihetun area are as follows (Fig. 10).

3.2.1.1. Lujiatun Member. Clastic and volcaniclastic strata above the unconformity with the Tuchengzi and below the crystalline igneous rock of the Xiatulaigou Member (see below) have been termed the Lujiatun bed or “beds”. The term was introduced as Lujiatun bed by Wang Xiaolin (2003, in Chang et al., 2003), corresponding to the “first member” of the Yixian Formation of Wang et al. (1998) and used as Lujiatun bed by Wang et al. (2004). We propose to raise the rank of this unit to the Lujiatun (陆家屯) Member of the Yixian Formation to correspond in rank to the other major divisions of the Yixian Formation in the Sihetun area. In English transliteration this name is a homonym of a Triassic age formation in a completely different area (Zhang, 2009), however in Chinese it is not a homonym and therefore this familiar and well-established name is available according to the ICSN.

Chiappe et al. (1999) and Ji (2002) used the name Sihetun Member for what Wang Xiaolin (in Chang et al., 2003) called the Lujiatun bed, but the name Sihetun was already used as a formation for a much more extensive of unit of formation rank by Li et al. (1998) (above). Use of Sihetun in such a massively restricted sense does not seem justified.

We propose to raise the rank of the Lujiatun bed to member and designate the type section as Section A (at ~41.611510°, 120.906468°) of Rogers et al. (2015) (Fig. 9). Reference sections include sites B–D of Rogers et al. (2015) and the Huangbanjigou no. 1 core from 69.1 m to 91.3 m core depth (72.4 M to 94.7 stratigraphic depth) (Fig. 4B, C). These outcrops lie to the immediate east of the Sihetun Sub-basin and are within the main outcrop area of the Yixian Formation.

3.2.1.2. Xiatulaigou Member. Perhaps the most mappable of all the units of the Yixian Formation in the Sihetun area is the lava flow sequence and associated welded breccias above the Lujiatun Member and below the Jianshangou Member (see Jiang et al., 2011) also termed the lower lava unit (e.g., Jiang et al., 2011). The name Xiatulaigou (下土来沟) bed (Fig. 10) was applied by Wang et al. (2004) to the dark vesicular igneous rock and immediately overlying “…laminated pebbly gray-green debris in coarse tuff” above the Lujiatun bed (here member) and below the Jianshangou bed (here Member), with the name deriving from outcrops in the Xiatulaigou area, Beipiao City, Chaoyang Prefecture, Liaoning Province (~41.643750°, 120.903933°) which is its type area (Fig. 1). We propose to restrict this unit to the crystalline dark igneous rock, which is often vesicular and associated welded breccia (basalt and basaltic andesite) (units 4–5, p. 441 of Wang et al., 2004), to avoid confusion with younger volcaniclastic units and conform to a strict

[1] Zhang (2009) gives only “Rin T, 1942, Jour. Geol. Soc. Japan, vol. 49” as the citation, but the only entry in that volume by that author is an abstract on rock units near Beipiao that would have included the Tuchengzi Formation, but the latter name is not used in that very short abstract. We have listed the complete citation for Rin (1942), as we understand it, in our references along with that of Nishida (1942) who does mention the unit by name. Kobayashi (1942) mentions that C. Rin has worked on a conglomerate in the Beipiao “coal-field” which is clearly in the stratigraphic position of the Tuchengzi Formation, but does not give a literature citation. Chokei and Tyokei are equivalent romanized spellings (orthographic variants) of the given name of the author with the family name of Rin (林朝棨), and therefore Kobayashi (1942) is referring to the same researcher, plausibly indicating that the formation name was not in use prior to 1942.

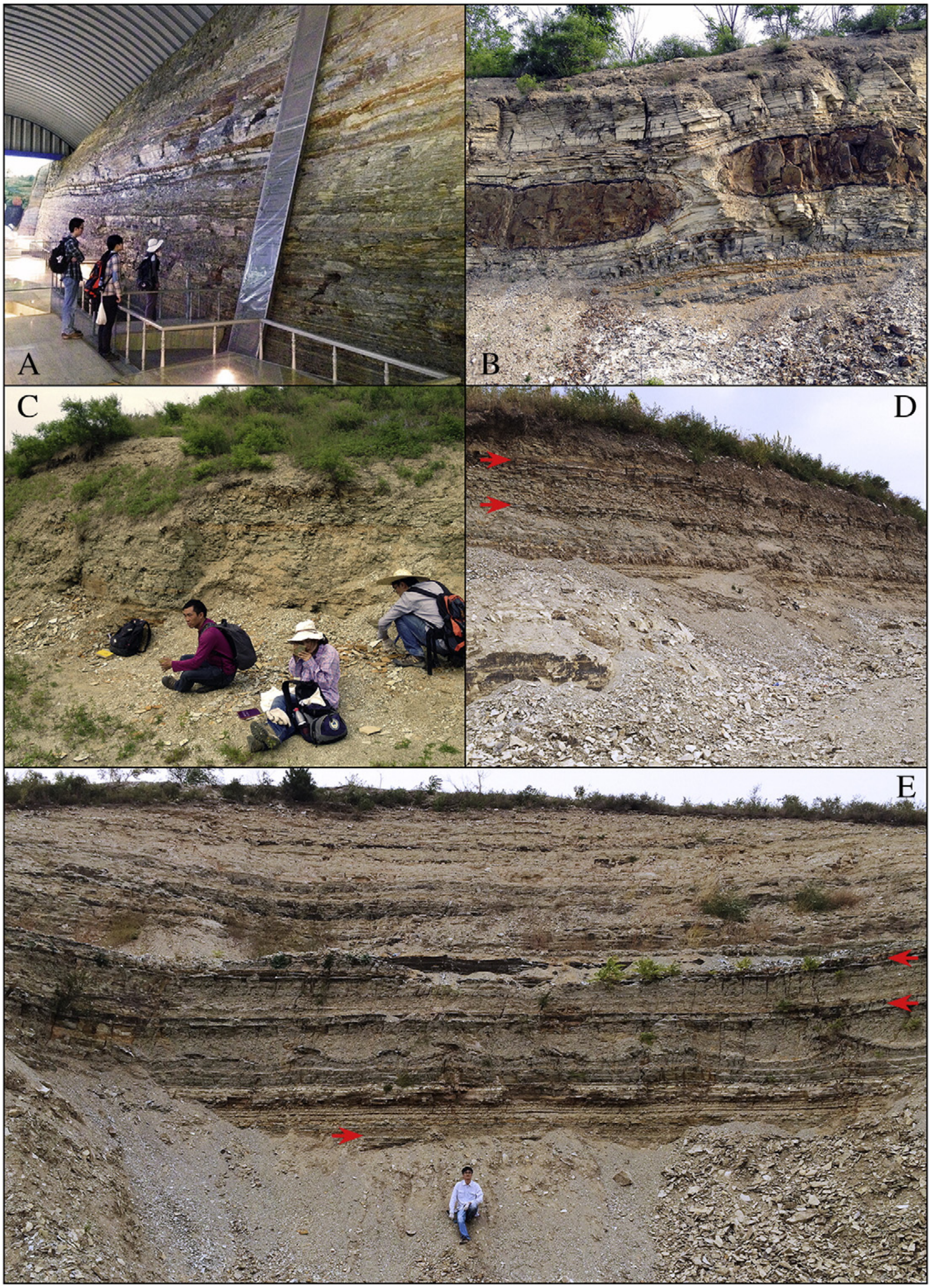

Fig. 6. Photographs of key exposures: A, exposures preserved within the Sihetun Landscape Fossil Bird National Geopark museum and type section of the Anjiagou Bed; B, south wall of excavations opposite museum showing two small intrusive sills, June 26, 2012; C, Exposure at Huangbanjigou of Anjiagou Bed, June 20, 2012, now covered; D, northwest side of exposures at Huangbanjigou, September 22, 2015 showing cyclicity in the Huangbanjigou Bed with the two red arrows corresponding to the upper two in E and in Fig. 7; E, southeast side of Huangbanjigou exposures comprising the type section of the Huangbanjigou Bed and showing the same cyclcity as in D and contact with the underlying Hengdaozi Bed (lowest red arrow), September 22, 2015, three red arrows correspond to those in the measured section of this exposure in Fig. 7.

lithological definition. Thus, we transfer the sedimentary part of the unit as previously defined to the Jianshangou Member. This is an extrusive lava flow interval, which we propose to raise to member rank in conformity to other major divisions of the Yixian in the larger Sihetun area. We designate the Huangbanjigou no. 1 core as a reference section (Fig. 4B). This unit corresponds to the "second member" of Wang et al. (1998).

The name Wumingshan Volcanics (无名山) was applied by Ji (2002) to what seems to be the same lava flow unit as the Xiatulaigou Member and might be considered to have priority. However, "Wumingshan" romanizes to "no-name-mountain", and we have been unable to find a geographic feature with this name within the Liaoxi area of Liaoning Province. Instead, it apparently derives from an igneous unit in the

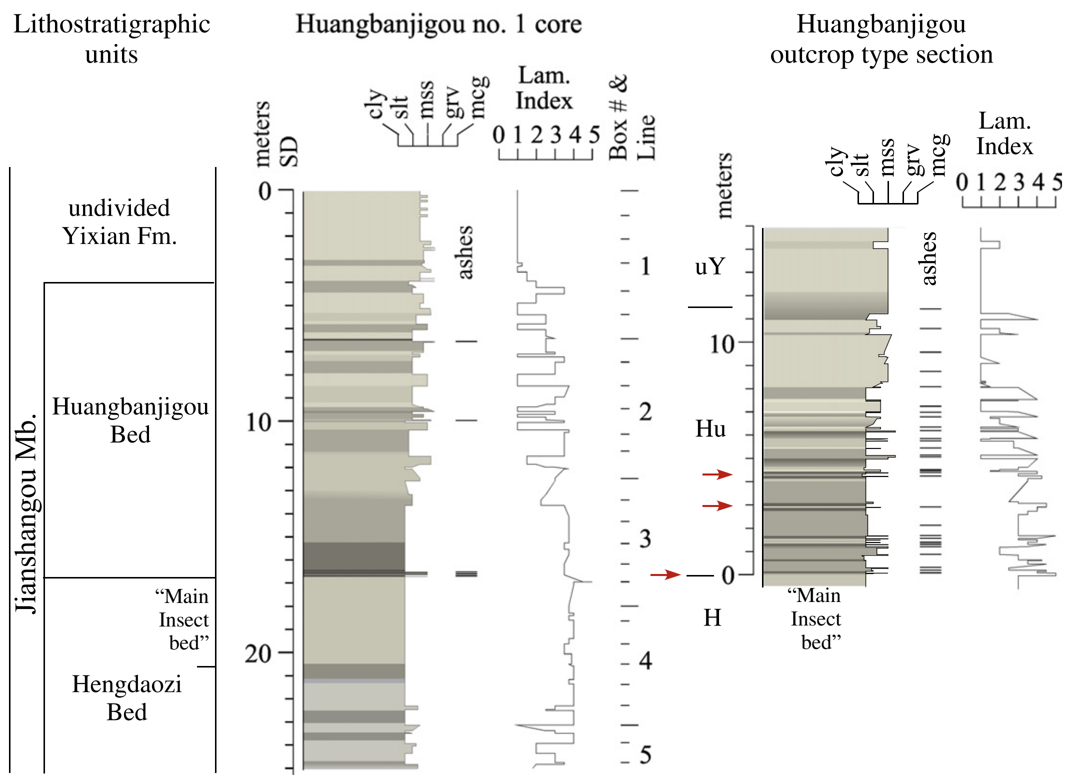

Fig. 7. Type section of Huangbanjigou Bed on southeast side of the Huangbanjigou exposures compared to the correlative part of the Huangbanjigou no. 1 core. Abbreviations are: H, Hengdaozi Bed; Hu, Huangbanjigou Bed; uY, undivided Yixian Formation. The three red arrows correspond to correlative levels in Fig. 6E and the upper two arrows correspond to the two in Fig. 6D. The lower red arrow also corresponds to the boundary between the Hengdaozi and Huangbanjigou beds.

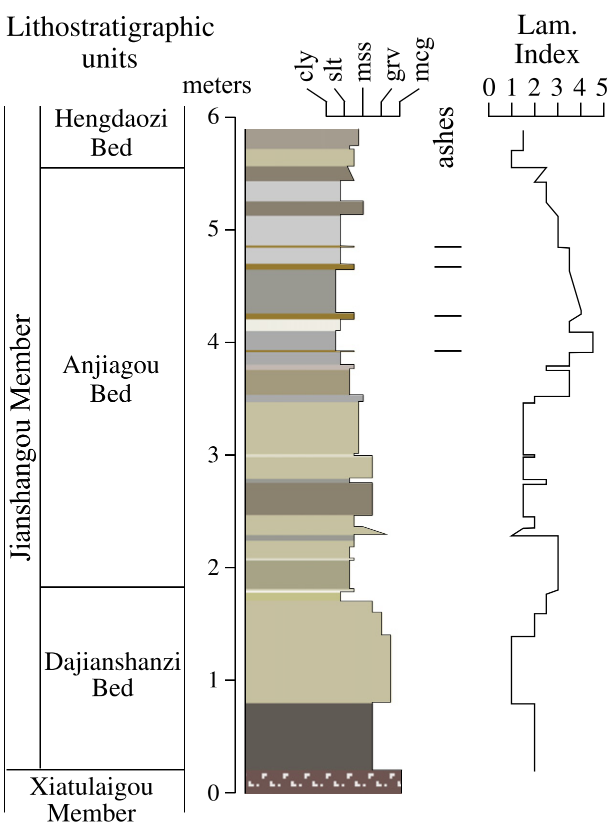

Fig. 8. Section of the Jianshangou Member in ditch along road to Dajianshanzi.

Luanping Basin 200 km to the west of Sihetun (Professor Yongqing Liu, pers. com., 2016). Ji (2002) also refers to it as an intrusive unit in reference to the Sihetun section (Ji et al., 2004, 2011), although its stratigraphic position appears clearly equivalent to the Xiatulaigou Member (Fig. 10), which is extrusive. We therefore do not use this name for the Sihetun area.

3.2.1.3. Jianshangou Member. As mentioned above, by 1963 and 1964 Chen (cited in Chen et al., 1980) was using the name Jianshan Bed, named for the Jianshangou area (~41.604701°, 120.840095°: Beipiao City, Chaoyang Prefecture, Liaoning Province), for the strata above the Tuchengzi Formation in the Sihetun Sub-basin. The Chaomidianzi (Chiappe et al., 1999) and Sihetun (Li et al., 1998) formations are clear junior synonyms of the Jianshangou bed of the Yixian Formation. We propose to restrict the Jianshangou bed to the strata between the Xiatulaigou Member and the overlying volcaniclastic beds that lack laminated mudstones as seen at Huangbanjigou (Figs. 4, 10) and formally designate it a member. Much of the Jianshangou Member consists of laminated mudstones with the characteristic and famous lacustrine Jehol Biota Lagerstätte (Chen et al., 2005; Zhou et al., 2003). Raising this unit to member rank permits further subdivision and parallel construction with the Lujiatun and Xiatulaigou members. Our use of the Jianshangou Member closely corresponds to the use of that name in Wang et al. (2004) except that we provide an upper boundary to the unit. We define the top of the Jianshangou Member as at the top of the locally highest laminated mudstone and siltstone bed that is proximal to other such underlying units. The Jianshangou Member is readily divisible into 4 distinctive units of bed-rank. These are summarized below (Fig. 4).

3.2.1.3.1. Dajianshanzi Bed (new). We propose the name Dajianshanzi Bed for the largely non-laminated, generally dark, often volcaniclastic, sedimentary strata conformably overlying the Xiatulaigou Member lavas and welded breccia and underlying the finely laminated mudstones of the Anjiagou Bed. Dajianshanzi (大尖山子) is name of the

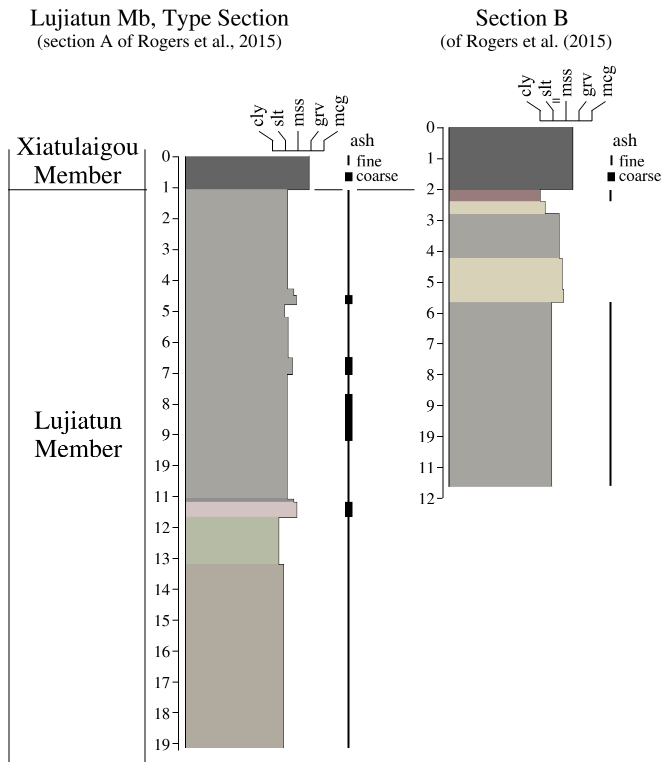

Fig. 9. Type section of the Lujiatun Member, adapted from Rogers et al. (2015). Location shown in Fig. 1.

steep, pointed hill (41.600667°, 120.840023°) (Figs. 1, 6) adjacent to Jianshangou, Beipiao City, Chaoyang Prefecture, Liaoning Province. The lower part of this bed is split off from the otherwise igneous Xiatulaigou Bed of Wang et al. (2004) as described above. The type section of this bed is in the Huangbanjigou no. 1 core from 43.2 m to 57.1 m. The upper part of this bed is generally rich in the bivalves *Arguniella ventricosa* and *Sphaerium anderssoni* (Pan et al., 2012), which are also present in the basal part of the overlying Anjiagou Bed (Fürsich and Pan, 2016).

3.2.1.3.2. Anjiagou Bed (new). We propose the name Anjiagou Bed for the largely dark gray (when unweathered) very microlaminated strata with abundant graded ash beds between the Dajianshanzi Bed and the overlying less finely laminated and lighter-colored Hengdaozi Bed (Fig. 4). The name Anjiagou Bed is derived from the village of Anjiagou (安家沟) (Beipiao City, Chaoyang Prefecture, Liaoning Province), 1.1 km southwest (41.581665°, 120.802154°) of the Sihetun Museum. We propose not to use the name Jiulongsong bed (Chiappe et al., 1999; Ji et al., 2004) that had been applied to these strata, despite its priority, because that name is derived from a location in Hebei Province that has an unknown relationship to strata in the Yixian Basin.

The Anjiagou Bed is famous for extraordinary articulated vertebrates preserving soft tissue, most famously non-avian dinosaurs such as the type specimen of *Sinosauropteryx prima* (Chen et al., 1998), the first proto-feathered dinosaur discovered, and abundant birds, especially *Confuciusornis sanctus* (Hou et al., 1995; Chiappe et al., 1999).

The exposure we designate the type section of the Anjiagou Bed is conserved in the main hall of the Sihetun Fossil Museum and adjacent exposures outside that preserve the east wall of the excavations conducted for vertebrate fossils in the 1990s. This section has been described by Wang et al. (1998), and Zhang and Sha (2012). The interval from 27.3–35.4 m SD (21.9–28.3 m ACD) in the Sihetun no. 1 core is designated a reference section of the Anjiagou Bed, as is the interval 36.8–43.3 m SD (32.8–39.4 ACD) in the Huangbanjigou no. 1 core.

3.2.1.3.3. Hengdaozi Bed. Chiappe et al. (1999) and Ji (2002) applied the name Hengdaozi Bed for the lighter colored and coarser, but still often laminated, strata above their Jiulongsong bed and our Anjiagou Bed and below our new Huangbanjigou Bed (Fig. 4). It has produced abundant and diverse insects (Ren et al., 2010) and important fossil plants such as *Archaefructus* (Sun et al., 1998). Hengdaozi (横道子), Beipiao City, Chaoyang Prefecture, Liaoning Province (41.589753°, 120.832161°) is a village about 2.4 km south of site of the Huangbanjigou no. 1 core and 3.2 km east of the Sihetun Fossil Museum. Although no type section was provided for this bed by Chiappe et al. (1999) and Ji (2002), its stratigraphic meaning and position is unambiguous, and therefore we designate the type section of this bed as the interval in the Huangbanjigou no. 1 core from 16.5 to 36.4 m. The upper part of the Hengdaozi Bed includes the "main insect bed" at

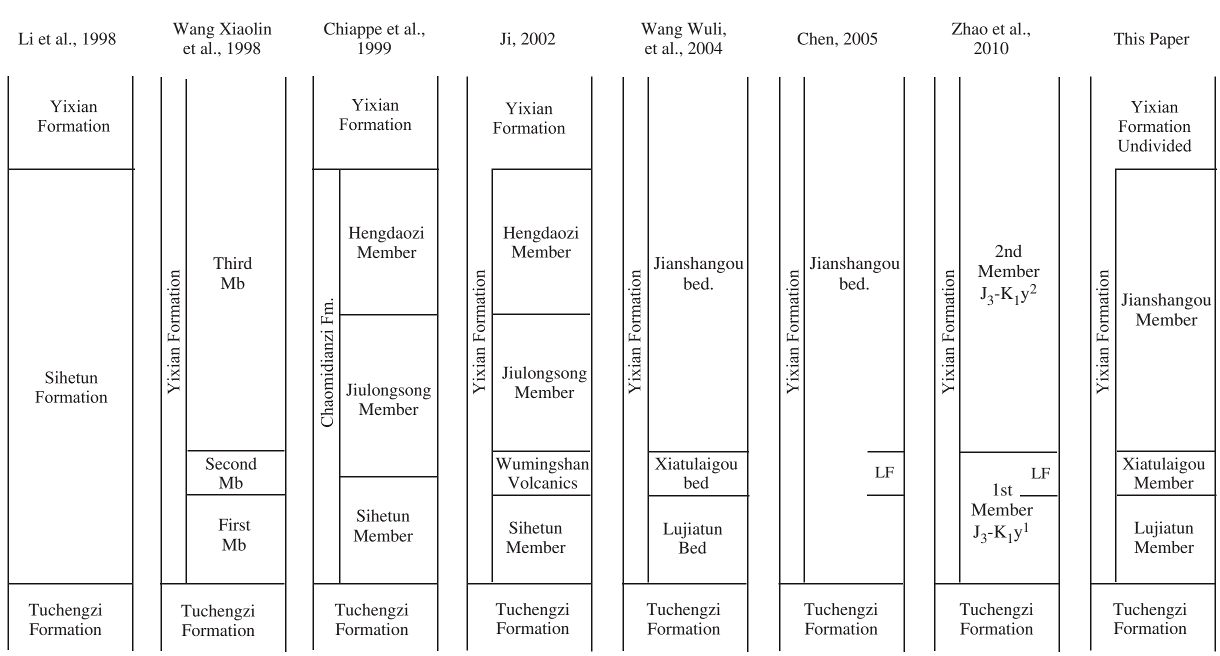

Fig. 10. Nomenclatural history of units discussed in text.

Huangbanjigou, and its upper boundary is marked by a return to microlaminated darker mudstones with graded ash beds of the Huangbanjigou Bed (see below).

3.2.1.3.4. Huangbanjigou Bed (new). We propose the name Huangbanjigou Bed for the cyclical microlaminated, laminated, and faintly bedded mudstones and coarser volcaniclastic rocks above the Hengdaozi Bed and below the coarse undivided Yixian Formation (Fig. 4). The type section is comprised of the exposure on the southeast side of the Beipiao Bird Fossils National Nature Reserve at 41.610837°, 120.833183° (Fig. 7). Its base is marked by microlaminated darker mudstones similar to the mudstones of the Anjiagou Bed, and its top is marked by the highest laminated mudstone, contiguous with the rest of the bed.

Sand and gravel-sized volcaniclastics of the Huangbanjigou Bed consist largely of blobs of translucent, yellowish-green compact clay that we interpret as ash aggregates (accretionary lapilli) (Gilbert and Lane, 1994; Rose and Durant, 2011) in a sand matrix (Fig. 11). Most of these apparent ash aggregates are 1–5 mm in diameter with some exceeding 1 cm. Biotite crystals and other volcanic minerals, sometimes mm-scale, occur floating within the clay. The semitransparent material is very soft when wet and may be montmorillonite, most simply interpreted as altered volcanic glass. These clay blobs commonly occur on bedding planes in mudstones and are significant components of the sandstones in the Huangbanjigou Bed. Similar beds rich in these translucent clay blobs or peloids occur in the overlying undivided Yixian Formation at Huangbanjigou and are in fact an important volcaniclastic rock type in the formation in general.

3.2.1.4. Yixian Formation, undivided. Irregularly-bedded volcaniclastic siltstone, sandstone, and fine conglomerate overlie the Jianshangou Member in the larger Sihetun area (Figs. 4, 10). Beds of similar lithology are also interbedded with the upper parts of the Jianshangou Member. At least one laminated mudstone bed, resembling the Jianshangou Member, with large conchostracans occurs on the hill at Dajianshanzi (41.600374°, 120.839757°) high in the local section, roughly 35 m above the Jianshangou Member, which we also included in Yixian Formation, undivided.

4. Results from coring and correlation to outcrop

Information from these three cores, supplemented with data from nearby outcrops, yields a synoptic view of the stratigraphic relationships of the Yixian Formation in the Sihetun area of the Yixian Basin. In turn, this facilitates comparison of the Sihetun Sub-basin with other parts of the Yixian Basin and other areas of similar deposits in northeast China.

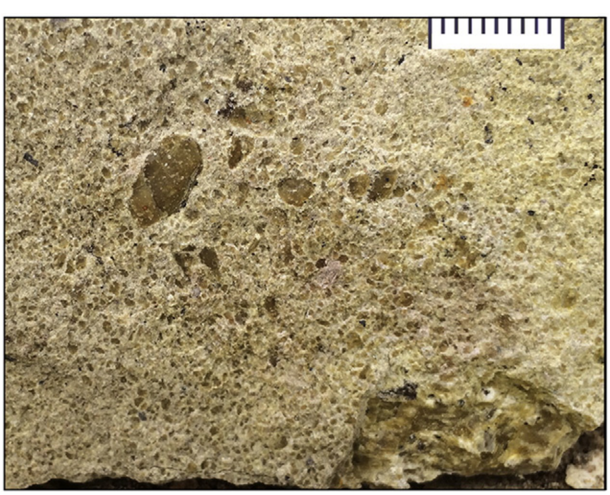

Fig. 11. Example of sandstone with volcanic glass (ash aggregates) altered to translucent amber clay from the upper Huangbanjigou Bed. Much of the sandstone in the Yixian is comprised of this lithology. Scale is 1 cm.

4.1. Sihetun no. 1 core

The hill behind the main museum building at Sihetun was the drilling site for the Sihetun no. 1 core. This is the location of huge and famous excavations that produced many iconic avian and non-avian feathered dinosaurs which were the subject of several PhD theses and numerous papers. (Fig. 1). From the top down, the core recovers the base of an unnamed intrusion, the lower three-quarters of the Jianshangou Member, including all but the upper part of the Hengdaozi Bed, all the Anjiagou and Dajianshanzi beds, and probably most of the extrusive Xiatulaigou Member.

The igneous rocks of the Xiatulaigou Member are dark gray to red, aphanitic to slightly phaneritic, massive to vesicular, olivine basalts, basaltic andesites, and vesicular trachyandesites (lower lava unit, Jiang et al., 2011, 2012). In the Sihetun no. 1 core, the bulk of the flow sequence is massive aphanitic to slightly phaneritic, dark gray rock (Figs. 4, 12). There are three reddish to purplish gray zones, at 62.8–68.3 m, 78.9–81.1 m, and 97.0–102.7 m SD (54.9–60.9 m, 70.6–72.3 m, and 83.9–88.8 m ACD, respectively). Vesicular intervals are at the top of the flow sequence at 37.5–48.7 m SD (30.0–39.9 m ACD) and 77.1–81.1 m SD (69.1–72.3 ACD). A poorly defined apparent welded breccia zone is at 64.5 m SD (56.9 m ACD). Thin, enigmatic intervals of light-colored rock occur at about 86.0 m, 88.5 m, and 96.0 m SD (76.0 m, 77.0 m, and 83.0 m ACD, respectively). These may be fault products or sedimentary fracture fill modified by slip. Although it may be tempting to interpret the lower vesicular zone, the reddish or purple zones, or the thin bands of light colored rock as marking flow boundaries, no definitive chill boundaries are present, and therefore we interpret the entire Xiatulaigou Member sequence in Sihetun no. 1 as a single flow. That said, it is not impossible that a younger sill of similar appearance intruded the flow sequence, and that accounts for the great apparent thickness of the member at this locality. However, that possibility will require detailed petrology to corroborate or reject.

This core provided the first look at unweathered Anjiagou and Dajianshanzi Bed strata (Figs. 4, 12, 13). The Dajianshanzi Bed is only about 2 m thick in the Sihetun no. 1 core (35.4–37.5 m SD; 28.3–30.0 m ACD). It consists of dark, olive-gray, volcaniclastic sandstone and gravel with come cobbles of vesicular igneous rock, plant fragments, and possible roots. Very few bedding features can be seen, plausibly because of cryptic bioturbation.

The Anjiagou Bed in Sihetun no. 1 (as in the other cores) consists of medium to dark gray laminated to microlaminated mudstone with abundant thin (sub mm to ~10 cm) light to dark gray ash layers (often weathering to yellow or orange) and thin (1–13 cm) lighter colored siltstone and sandstone beds (Fig. 14). This is the main fossil-producing unit at Sihetun and it occurs from 27.1 to 35.4 m SD (21.6 to 28.3 m ACD). In the core, bivalves are abundant in the lower 60 cm of the bed, and spinocaudatans (clam shrimp) are abundant in the rest of the core. Fish occur at 32.9 m, 33.0 m, and 33.1 m SD (26.3 m, 26.4 m, 26.5 m ACD). Although doubtlessly present elsewhere, finding them would require additional breakage of the core.

In Sihetun no. 1, the Hengdaozi Bed is represented by all but perhaps the uppermost part of the bed, present from about 6.8 to 27.1 m SD (5.2 to 21.6 m ACD); the uncertainty in the upper boundary being because of apparent core loss at the contact. It consists predominately of rare microlaminated beds, rhythmically laminated light gray and tan mudstone, and thin beds of tan to white sandstone and rare gravel (Fig. 15). Although thin ash beds are still present in the Hengdaozi Bed in the Sihetun no. 1 core, there are far fewer of them than in the underlying Anjiagou Bed. The uppermost few cm recovered in the Hengdaozi Bed is distinctly darker in color and harder than underlying parts of the bed, which we interpret as being due to contact metamorphism.

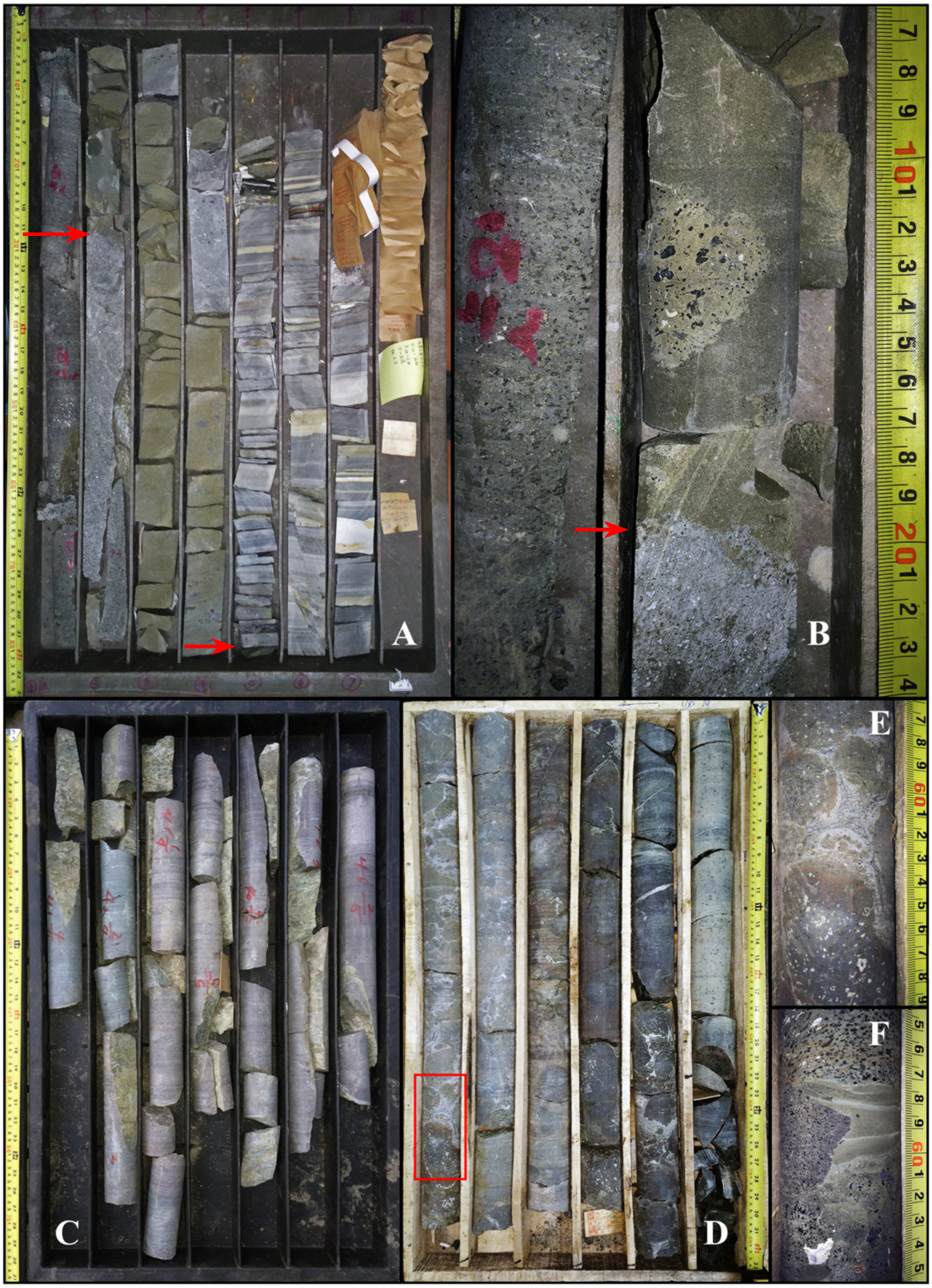

Fig. 12. Examples of Xiatulaigou Member facies: A, contact between upper Xiatulaigou Member and basal Dajianshanzi Bed of the Jianshangou Member (upper arrow) and upper Dajianshanzi Bed and basal Anjiagou Bed of the Jianshangou Member (lower arrow in the Sihetun no. 1 core (Box 15, down is right to left) - note large and small clasts of vesicular Xiatulaigou Member in the Dajianshanzi Bed; B, close up of contact between upper Xiatulaigou Member and basal Dajianshanzi Bed of A - note invasion of olive colored Dajianshanzi Bed into vesicular uppermost Xiatulaigou Member and the vesicular Xiatulaigou clast well within the Dajianshanzi Bed – these are clear indication of the extrusive nature of the Xiatulaigou Member; C, massive to very slightly vesicular purple and massive igneous rock of lower Xiatulaigou Member at bottom of Sihetun no. 1 core (Box 1: 84.7–88.8 m ACD; 98.0–102.7 m SD); D, gray, greenish, and reddish vesicular igneous rock and welded breccia in lower Xiatulaigou Member in Huangbanjigou no. 1 core (box 14: 63.5–68.3 m; ACD 66.8–71.5 m SD) – red box shows position of detail in E; E, welded igneous breccia of lower Xiatulaigou Member with vesicular clasts, some with apparent chill margins surrounded by igneous matrix with flow-banding – location shown in red box in D (box 14, line 6: 67.9 m ACD; 70.8 m SD); F, clast-supported breccia of upper Xiatulaigou Member with angular vesicular clasts surrounded by a matrix of graded beds of Dajianshanzi sandstone that infiltrated after the breccia was in place, a characteristic of an upper surface of an extrusive unit - Huangbanjigou no. 1 core (box 11, line 4: 52.1 m ACD; 55.6 m SD), position shown in Fig. 12A.

The uppermost rock recovered in the Sihetun no. 1 core, from about 1.5 to 5.5 m SD (1.1 to 4.1 ACD) is a dark, aphanitic to slightly phaneritic, massive igneous rock that we interpret to be a dioritic sill (i.e., intrusive of andesitic composition) (Fig. 16A). Similar intrusive units are exposed adjacent to the Sihetun museum and throughout the region, although they have been often confused with lava flows. This unit has essentially no stratigraphic significance and is not a lava unit.

Criteria that help to distinguish an extrusive flow from an intrusive sheet are as follows. 1) Although the sedimentary rock in contact with the bottom of the igneous sheet may be visibly metamorphosed, usually for a small vertical distance, the upper contact of a flow is not (e.g., Fig. 12A, B). An intrusive sheet metamorphoses both lower and upper contacts (Fig. 16). 2) Massive igneous rock at the upper part of

Fig. 13. Examples of Dajianshanzi Bed of the Jianshangou Member facies and structures: A, contact between breccia of upper Xiatulaigou Member and basal Dajianshanzi Bed in Huangbanjigou core no. 1 (arrow: box 11, line 2: 50.1 m ACD; 53.6 m SD) and position of Fig. 12F of Dajianshanzi Bed infiltrating breccia of the Xiatulaigou Member; B, upper Dajianshanzi Bed with contact with Anjiagou Bed (arrow: box 9, line 1: 39.3 m ACD; 43.3 m SD) – note numerous clasts of vesicular Xiatulaigou lithologies in conglomerates; C, vesicular clast of Xiatulaigou lithology within Dajianshanzi Bed of Huangbanjigou Bed (box 10, line 6: 48.4 m ACD; 52.0 m SD); D, zone of clasts of Xiatulaigou Member passing up into sandstones of Dajianshanzi Bed in Jianshangou no. 1 core (box 4: 15.1–20.0 m ACD; 15.1–20.2 m SD), with red box showing position of E of this figure – note large igneous (Xiatulaigou) clast at lower left hand corner (box 4, line 6: 19.9 m ACD; 20.1 m SD); E, deformed bedding in volcaniclastic portion Dajianshanzi Bed with dark angular clasts being apparent Xiatulaigou lithologies (box 4, line 3: 17.6 m ACD; 17.7 SD); F, weathered lower Dajianshanzi Bed with white rhizoliths (0.8 m in Fig. 8) at an exposure on road to Dajianshanzi (Fig. 1).

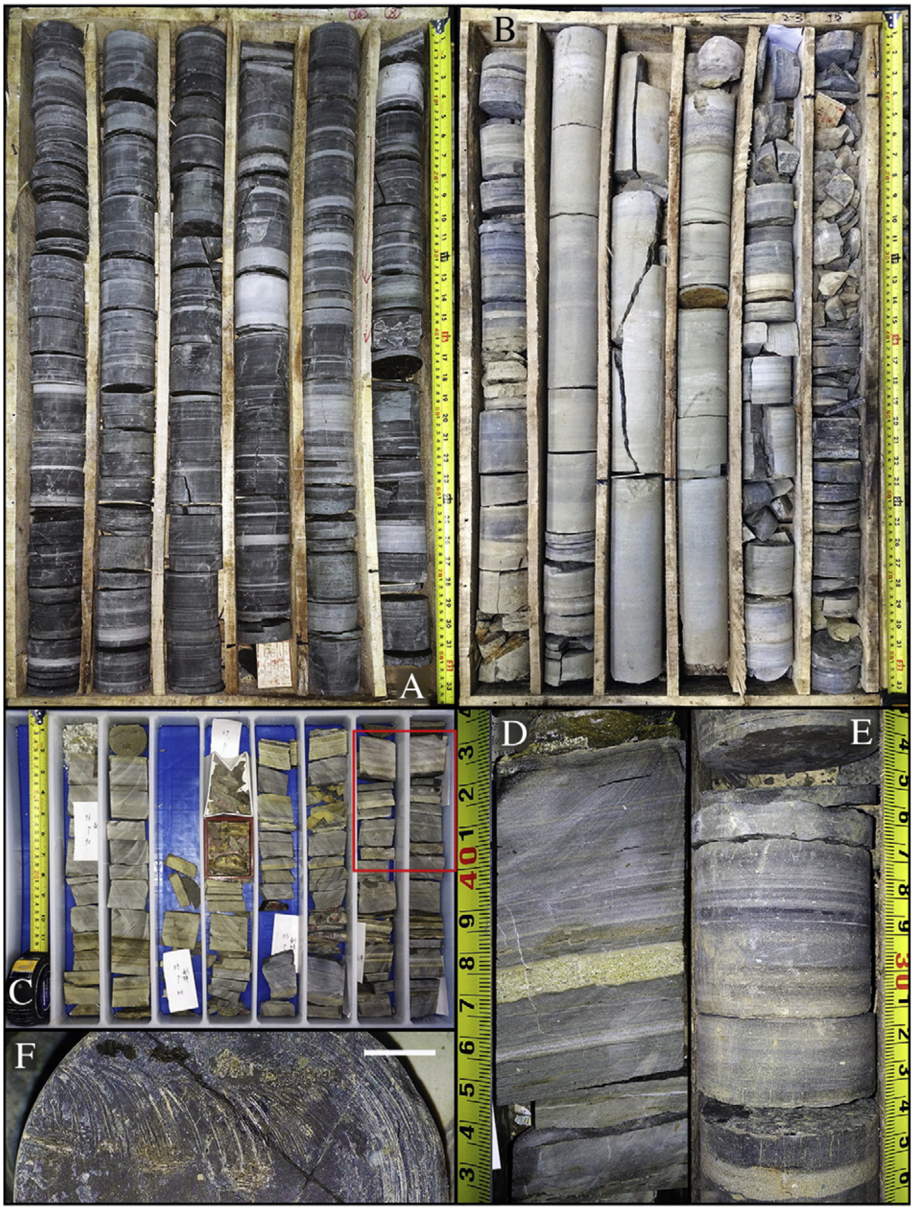

Fig. 14. Examples of Anjiagou Bed facies: A, Huangbanjigou no. 1 core (Box 8: 34.0–39.0 m ACD; 38.0–42.8 m SD); B, Jianshangou no. 1 core (box 3: 10.2–15.1 m ACD; 10.1–15.1 m SD); Sihetun no. 1 core (box 16: 25.2–26.5 m ACD; 31.5 33.1 m SD) red box demarcates split core shown in detail in Fig. 18; D, coarse ash in microlaminated mudstone near base of Anjiagou Bed, Sihetun no. 1 core (box 15, line 5: 27.7 m ACD; 34.7 m SD: piece 36); E, laminated mudstone Jianshangou no. 1 core (box 3, line 6: 14.6 m ACD and SD); F, partial articulated teleost fish, *Lycoptera* sp. in microlaminanted mudstone, Huangbanjigou no. 1 core (box 7, line 6: 33.6 m ACD; 37.5 m SD) – scale is 1 cm.

a lava flow normally exhibits a much thicker vesicular zone than at the bottom, whereas an intrusive sheet often has no vesicular zone at all (Fig. 16). 3) The upper contact of a flow is commonly overlain by sedimentary rocks containing clasts of the underlying igneous rocks that are often vesicular (Fig. 12A, B); 4) A flow often has voids as fractures, blisters, and breccia filled with sedimentary rock with features such as well-developed bedding and thin graded beds that indicate the sediments filled the voids after the flow cooled (e.g., Fig. 13F) (Olsen et al., 2012). The presence of columnar jointing is not a reliable indicator of the extrusive or intrusive nature of a sheet because the cooling fracture mechanics are similar regardless.

4.1.1. Type section of the Anjiagou Bed

Exposures directly adjacent to the Sihetun Museum constitute the type section of the Anjiagou Bed of the Jianshangou Member (Fig. 17). The section has been described by a number of authors from exposures that were available both before and after the Museum was built (Wang et al., 1998) and after (Jiang et al., 2011; Zhang and Sha, 2012; Hethke et al., 2012, 2013; Zhang et al., 2004). We use the section measured by Zhang and Sha (2012) (Fig. 17) as representative of the type sections because we are able to unequivocally correlate from that section to the Sihetun no. 1 core (Fig. 18). Generally, detailed cm-scale unit-by-unit correlation between outcrops and cores is made challenging because of small-scale core loss and occasional core inversion, bedding plane shear (Fig. 19), lateral facies and thickness changes, and weathering of the outcrop, including dramatic changes in color and swelling and disintegration of ashes. However, in this case the correlation is of high certainty. Besides the general match in relative position and thickness of beds and relative positions of the thickest ashes, the correlation is cinched by a much more detailed match between samples 135 (a distinctive light colored laminated unit) and 125–124 (a very coarse ash) in Xiaolin Zhang and Sha (2012, Fig. 3) and corresponding intervals in samples 67 and 64–2 (Box 16, line 9: 26.10–26.24 m ACD; 32.66–32.84 m SD) in Sihetun no. 1 (Fig. 18). A clear match is also

Fig. 15. Examples of facies of the Hengdaozi Bed: A, uppermost Anjiagou Bed and lower Hengdaozi Bed in the Huangbanjigou no. 1 core (box 7: 29.1–34.0 m ACD; 33.1–38.0 m SD) - contact between the two beds is in red box shown in detail in D; B, upper Hengdaozi Bed in the Huangbanjigou no. 1 core with red box showing position of E (box 4: 14.5–19.3 m ACD; 18.0–23.1 m SD); C, contact (broken) approximately at red arrow between Hengdaozi and Huangbanjigou beds in Huangbanjigou no. 1 core (at 13.4 m ACD; 16.8 SD) (box 3, lines 5 and 6; 12.9–14.5 m ACD; 16.2–18.0 SD); D, detail of contact between Anjiagou and Hengdaozi beds in Huangbanjigou no. 1 core (see inset in A) (at 8 cm in photo, 32.8 m ACD; 36.8 m SD) – note that very thin light lines traversing core is scoring caused by drilling not lamination; E, deformed bedding in Hengdaozi Bed (red box in B) at 14.8 m ACD and 18.3 m SD (box 4, line 1); F, upper Hengdaozi Bed in Sihetun no. 1 core (box 24: 6.0–8.9 m ACD; 7.9–11.4 m SD); G, fold in exposure of upper Hengdaozi Bed, west side of the hill at Huangbanjigou (41.610962°, 120.832467°), rubber part of hammer handle is 15 cm; H, fold in fold in block from exposure of upper Hengdaozi Bed, Jianshangou (41.604701°, 120.840095°), scale bar is 2 cm.

evident in the laminae between samples 135 of Xiaolin Zhang and Sha (2012) and sample 67 (32.66 m in the core (Fig. 18)). This kind of multiple-level hierarchical match is highly improbable and therefore reliable for correlation. The match between the section preserved inside the museum and the section of Xiaolin Zhang and Sha (2012) is straightforward because they are on the exposure of rock (Fig. 19).

4.2. Huangbanjigou no. 1 core

As noted by Chen et al. (2005), prior to coring, the outcrops at the Huangbanjigou section comprised perhaps the best section displaying the development of the Yixian Formation in the Sihetun Sub-basin. The Huangbanjigou no. 1 core recovered nearly the entire local thickness of the preserved Yixian Formation as well as a considerable thickness of the underlying Tuchengzi Formation.

The Tuchengzi Formation occurs from the unconformity with the Yixian Formation at 94.7 m SD (91.3 m ACD) to 200.7 m SD (192.8 m ACD), which is the total depth of the core (Fig. 4). As expressed in this core, the formation consists of complex alternating sequences of predominately tan, purplish, greenish and red planer and cross-bedded to climbing ripple cross-laminated siltstone and fine sandstone with subordinate medium sandstone with common intraformational

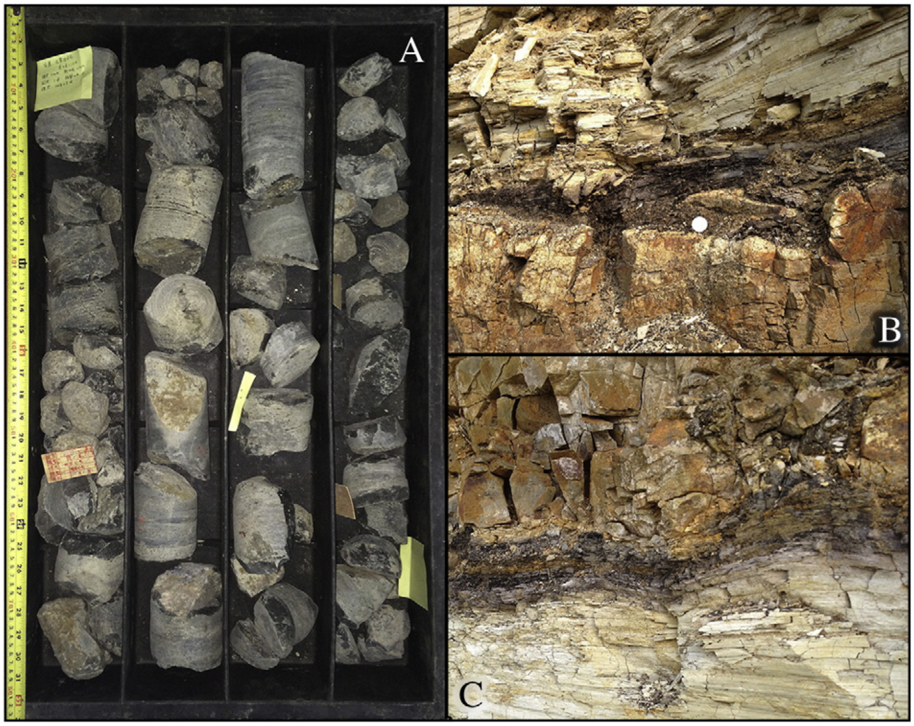

Fig. 16. Intrusive igneous rocks: A, box 27 of Sihetun no. 1 core (0.0–4.1 m ACD; 0.0–5.5 SD); B: upper contact of igneous intrusion at exposure opposite and to the south of the Sihetun Landscape Fossil Bird National Geopark museum (41.588526°, 120.792492°), note black metamorphosed zone at contact – coin is ~2.5 cm; C, lower contact of intrusion at same location, the same scale as B applies.

mudstone gravels, and subordinate beds of red, purple and gray mudstone with zones of bioturbation and possible footprints (Fig. 20). The more gray intervals tend to have mudstones with better bedding, whereas the red intervals tend to have more possible footprints. Overall, the formation shows much less variability than the overlying Yixian.

There are 4 chalky whitish siltstone intervals that may be tuffaceous and these do not seem to be associated with any particular color clastic rocks. These occur at about 156.5 m, 183.2 m, 190.8 m, and 197.1 m SD (151.6 m, 176.4 m, 183.4 m, 189.3 m ACD).

All of the divisions of the Yixian Formation discussed in detail in this paper were recovered in Huangbanjigou no. 1 core (Fig. 4), including all of the locally developed Lujiatun Member, the Xiatulaigou Member, and virtually all but the uppermost Jianshangou Member.

The unconformity between the Lujiatun Member of the Yixian Formation and the underlying Tuchengzi Formation (at 94.7 m SD: 91.3 m ACD) is marked by a greenish-gray coarse, clast-supported conglomerate with clear imbrication, consisting of angular to subrounded clasts of Tuchengzi lithologies and subordinate alien lithic clasts (Fig. 21) in a medium to fine sandstone matrix. There is no obvious angular difference between bedding in the underlying Tuchengzi Formation and the Yixian Formation. Beds of greenish to tan conglomerate and tan pebbly sandstone alternate with tan and olive tan medium sandstone. The proportion of dark gray to purple aphanitic to porphyritic volcanic clasts increases upward at the expense of Tuchengzi clasts, and clast size decreases upward with the upper Lujiatun, consisting mostly of grayish olive to brownish gray, massive, sandstone and siltstone resembling the skeleton-producing lithologies at the Lujiatun type section and elsewhere. The uppermost Lujiatun Member in the Huangbanjigou core is red brown, as it is at several of the sections described by Rogers et al. (2015). As at Lujiatun proper, these sandstone and siltstone units may be tuffaceous as well, but that has yet to be demonstrated petrographically. Faint rhizomorphs are present in the upper parts of the member (notably at 74.6 m SD; 71.4 ACD).

Large vesicular reddish igneous welded breccia at 73.9 m SD (70.6 m ACD) marks the base of the Xiatulaigou Member, the upper boundary of which is at 53.6 m SD (50.1 ACD). This lower breccia has light gray volcaniclastic intervals, and locally it has a matrix that might be entrained infiltrated ash (Fig. 12). At 67.8 m SD the reddish breccia is overlain by gray aphanitic igneous rock with few vesicles, which continues upward to about 61.6 SD (58.3 m ACD) where it grades into progressively more vesicular lighter gray then reddish vesicular igneous rock to the top of the member. Cracks in the upper Xiatulaigou Member are filled with reddish volcaniclastic sandstone at about 57.7 m SD (54.2 m ACD). Gray-green very vesicular breccia with sedimentary matrix is present from 55.5 m SD (52.0 m ACD) to 53.6 m SD (50.1 m ACD), marking the top of this member. The gray siltstsone and sandstone between the clasts exhibits thin- and parallel-bedding, especially lower down, requiring infiltration and deposition of sediment after the breccia came to rest at the rubbly top of a volcanic flow. This is why this breccia is grouped with the Xiatulaigou Member, rather than the overlying Jianshangou Member, the base of which also contains volcanic detritus.

The base of the Jianshangou Member and Dajianshanzi Bed is marked by a dark medium, olive-gray pebbly volcaniclastic sandstone. This grades upward into dark gray bioturbated fine to coarse volcaniclastic sandstone and siltstone with desiccation cracks, rhizomorphs, and bivalves (Fig. 13) to its contact with the laminated dark gray mudstones of the Anjiagou Bed at 43.3 m SD (39.4 m ACD). This interval comprises the type section of the Dajianshanzi Bed.

Dark gray microlaminated to laminated mudstones with abundant ashes of various degrees of coarseness from 36.8 m to 43.3 m SD (32.6 m to 39.4 m ACD) comprise the Anjiagou Bed in Huangbanjigou no. 1. The overall facies is indistinguishable from the same bed in Sihetun no. 1, but the bed is thinner in Huangbanjigou no. 1 (6.5 m vs. 8.3 m at Sihetun) (4). A few notable fossils seen in the core (Fig. 14) include an articulated teleost fish at 37.54 m SD (33.55 m ACD) consistent with *Lycoptera*, a clustered assemblage of bivalve fragments of multiple individuals consistent with a gastric ejection at 40.72 SD (36.80 ACD), and numerous spinocaudatans. A recumbent fold is present at 37.8 m SD (33.8 m ACD).

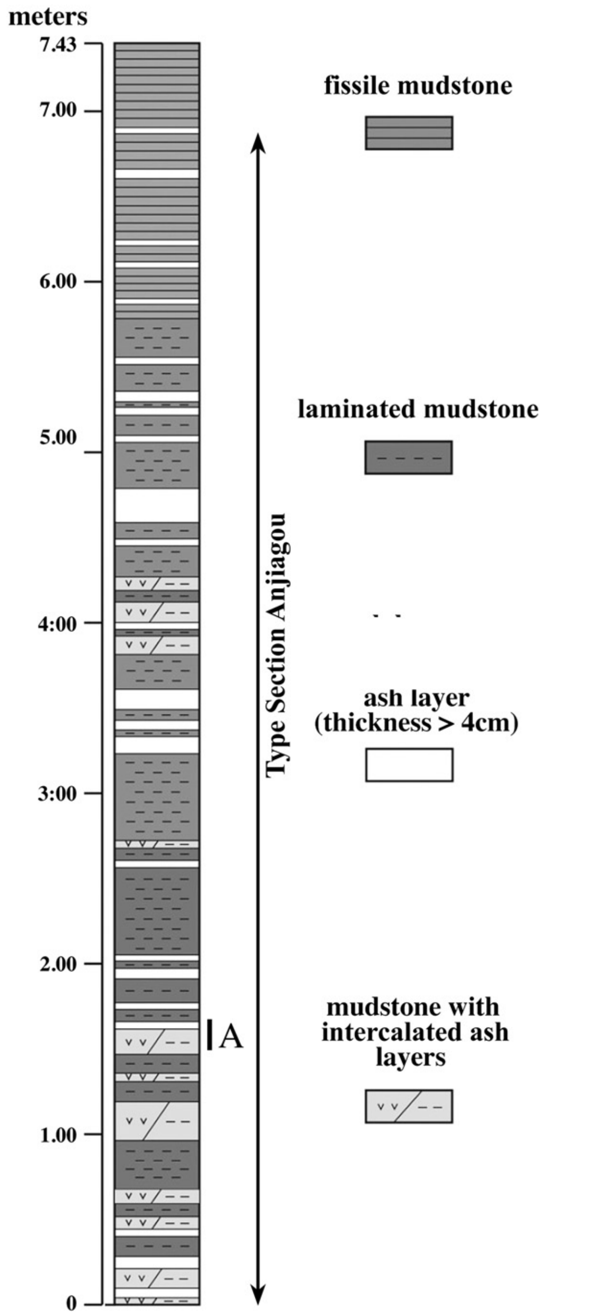

Fig. 17. Type section Anjiagou Bed, Sihetun Museum modified from Zhang and Sha (2012). A indicates position of samples shown in Fig. 18.

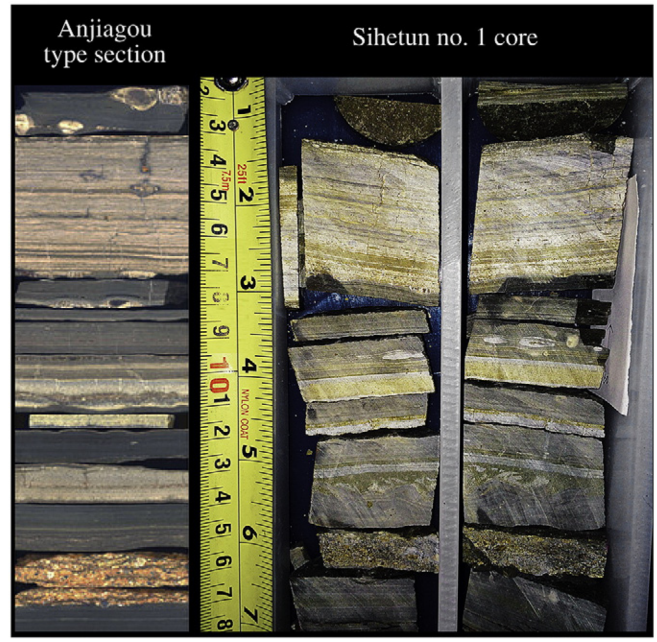

Fig. 18. Match between sample beds 124 to 136 of Zhang and Sha (2012) of the type section and the Sihetun no. 1 core (Box 16, rows 9 and 10, samples 64–1–67-3: 26.1–26.3 m ACD; 32.7–32.9 m SD), which is split, with both splits being shown. Scale is the same for both columns.

The transition from the Anjiagou Bed upward into the 19.8 m thick Hengdaozi Bed is marked by an abrupt shift at 36.8 m SD (32.8 ACD) from very dark gray microlaminated mudstone with ash beds, to thin-bedded light gray mudstone and siltstone with dark laminae at centimeter-scale intervals that lack distinct ash beds (Fig. 15). These dark bands decrease in intensity and frequency upward. Beds of fine sandstone increase in frequency and coarseness towards the middle of the bed, decrease again towards top, with the coarsest bed being a medium-grained sandstone at about 28.6 m (24.6 m ACD). The top of the Hengdaozi Bed is at 17.0 m SD (13.6 m ACD) (Fig. 4). Some of the sandstone and siltstone beds have faint oscillatory ripples, faint burrows (Fig. 15), and even some possible desiccation cracks (e.g., at 25.24 m SD; 21.30 m ACD).

The upper 3.5 m of the Hengdaozi Bed (17.0 m to 20.5 m SD; 13.6 m to 16.8 m ACD) is the famous "main insect bed" of Huangbanjigou excavations that has produced one of the richest fossil insect assemblages in the world as well as a number of remarkable early angiosperms and abundant well preserved fossil fish with soft tissue preservation (Fig. 15). The main insect bed is a light gray when unweathered and a pale cream color when slightly weathered. It has finer laminae and is partly microlaminated, resembling the basal Hengdaozi Bed, with darker laminae at centimeter-scale spacing. The upper 1.0 m of the "main insect bed" (17.0 m to 18.0 m SD; 13.6 m to 14.5 m ACD) is deformed into recumbent folds with smaller-scale deformation features such as crinkling and kink-bands. This feature is apparently characteristic of the uppermost main insect beds over all of the Huangbanjigou area at least to Jianshangou (Fig. 15). Other intervals of the Hengdaozi Bed exhibit deformation as well but to a lesser extent.

An upward transition to microlaminated mudstone with abundant ashes at 17.0 m SD (13.6 m ACD) marks the boundary between the Hengdaozi Bed and the overlying Huangbanjigou Bed (Fig. 4). Microlaminated and finely laminated mudstones in the Huangbanjigou Bed resemble the main lithologies of Anjiagou Bed, but these lithologies occur cyclically and periodically interbedded with weakly laminated mudstones and volcaniclastic sandstones. Unfortunately, recovery of the upper 12 m of Huangbanjigou no. 1 core was poor because of weathering and thus details of all but the lower part of the Huangbanjigou Bed are obscured. Therefore we rely on adjacent outcrop for details of this bed and its type section (see below).

The top of the Huangbanjigou Bed is at the locally highest laminated bed overlain by volcaniclastic sandstones of the undivided Yixian Formation. This boundary seems to be at about 4.2 m SD (3.1 m ACD), but the core is very broken up in this interval obscuring details.

4.2.1. Huangbanjigou Bed type section

During construction for the Beipiao Bird Fossils National Nature Reserve in September 2015, we measured the section equivalent to the upper 17 m (SD) of the Huangbanjigou no. 1 core, in adjacent new exposures developed for the park. The outcrop is correlated to the core using the top of the Hengdaozi Bed and overlying distinctive sets of thin ashes and interbedded microlaminated and thin-bedded units up to 16.5 m SD (13.2 m ACD). We were able to trace the correlative interval completely around the northeast, southwest, and southeast

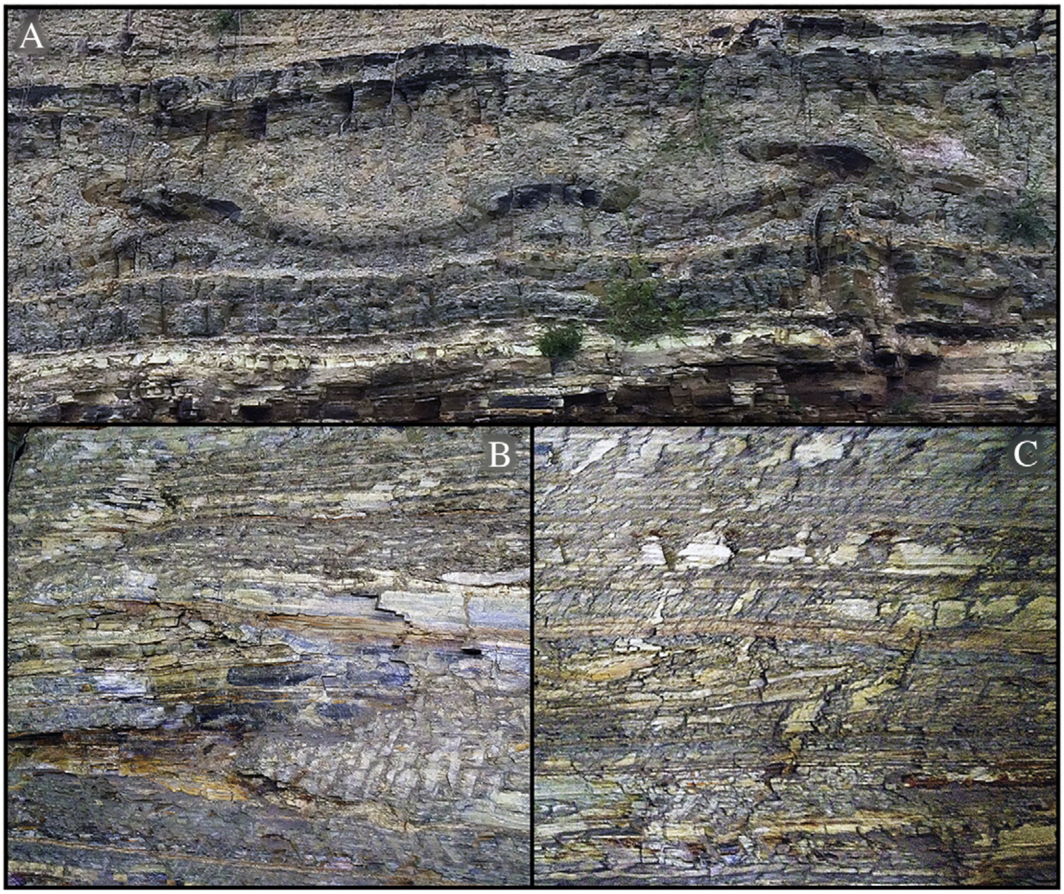

Fig. 19. Bedding-parallel-shear structures in the Yixian Formation: A, southeast exposures at hill at Huangbanjigou, in Huangbanjigou bed (1.5–3.0 m in Fig. 7 on right); B and C, examples of bedding-plane-shear duplexes in type section of the Anjiagou Bed, in the exposure inside the Sihetun Landscape Fossil Bird National Geopark museum visible at the level of the researchers heads in Fig. 6A (images span about 50 cm vertically).

sides of the hill on which the core was drilled in nearly continuous exposures. It is on the southeastern side of the hill, however, that the most extensive exposures are present, and these comprise the type section of the Huangbanjigou Bed (Fig. 4).

As exposed, the type section consists of 11.2 m of gray and tan cyclical and periodic (in thickness) alternations of microlaminated beds with characteristic Jehol Biota fossils and thin ashes, poorly laminated mudstone, and volcaniclastic sandstone. As a whole, the Huangbanjigou Bed coarsens upward with laminated and microlaminated beds with ashes becoming less common and volcaniclastic sandstone and gravel beds, some with cross bedding or tilted bed forms, becoming more common upward (Figs. 4, 6).

A very distinctive style of deformation is present in the interval from 1.7 to 2.6 m in the Huangbanjigou Bed type section (Fig. 6), consisting of thrust faults verging south with associated, flame-like, meter-scale, periodically-spaced recumbent folds (Fig. 19). These folds are present across the entire hill, but unless the exposure face is oriented transverse to the fold axes, the bedding orientation and deformation style is very difficult to interpret.

The overlying coarser volcaniclastics of the undivided Yixian Formation exhibit oblique, if obscure, bedding (Fig. 6) at Huangbanjigou. These strata produce poorly preserved (and highly weathered) plant fragments as well as turtles, and ostracodes (Chen et al., 2005).

4.3. Jianshangou no. 1 core

Drilled to explore lateral facies changes within the Jianshangou Member, Jianshangou no. 1 (Fig. 4) recovered a thinned and coarsened facies of the lower divisions of the Yixian Formation as locally expressed, except the flows of Xiatulaigou Member that appears absent. However, clasts of the Xiatulaigou Member are present at the appropriate stratigraphic position, and a thick sequence of underlying Tuchengzi Formation was recovered as well.

Overall the roughly 75 m of Tuchengzi Formation encountered in Jianshangou no. 1 (23.1 m to 100.1 m SD total depth; 22.8 m to 97.2 m ACD) resembles that seen in Huangbanjigou no. 1 with predominately tan, purplish, greenish and red planar and cross-bedded to climbing ripple cross-laminated siltstone and fine sandstone with subordinate medium sandstone with common intraformational mudstone gravels and subordinate beds of red, purple and gray mudstone with zones of bioturbation and possible footprints (Fig. 20). But in detail, the sequences are different. Red strata comprise a larger proportion of the section in Jianshangou no. 1 and no detailed correspondence between beds is present.

There are two chalky white beds, at 65.8 m SD (63.9 m ACD) and 68.4 m SD (66.2 ACD) that could be ash beds, but these do not seem to correlate with the ash-like beds in Huangbanjigou no. 1 based on their sedimentary stratigraphic context.

The unconformity with the overlying Lujiatun Member of the Yixian Formation at 23.1 m SD (22.8 m ACD) resembles that in Huangbanjigou no.1 with the overlying Lujiatun likewise consisting of a 5.5 m (23.1 m to 17.6 m SD: 17.5 m to 22.8 m ACD) conglomerate comprised of angular clasts of Tuchengzi, with polymict often porphyritic igneous clasts (that do not look like the Xiatulaigou Member) that increase in percentage upward (Fig. 21). This is followed by 3 m (17.6 m to 14.6 m SD: to 17.5 m 14.6 m ACD) of volcanic conglomerate, comprised of largely vesicular clasts that resemble the Xiatulaigou Member, which grades upward into medium to coarse, dark colored, volcaniclastic sandstone and dark siltstone, characteristic of the Dajianshanzi Bed of

Fig. 20. Photos of Tuchengzi Formation: A, tan and greenish-gray fine sandstone with gray mud chips (Huangbanjigou no. 1: box 22: 102.5–107.6 m ACD; 106.1–111.3 m SD); B, variegated fine sandstone and mudstone with white and purplish possible ash (Huangbanjigou no. 1: box 37: 176.6–181.6 m ACD; 183.5–188.9 m SD); C, red purplish and white possible ash and red brown and tan mudstone and fine sandstone (Jianshangou no. 1: box 14: 64.5–69.5 ACD; 66.5–71.7 SD); D, bioturbated and desiccation cracked red-brown and gray-green mudstone and light tan sandstone - large pellet-filled burrow at 83 cm (Jianshangou no. 1: box 12, lines 1 and 2: centered on 55.1 m ACD, 56.7 m SD and 55.9 m ACD, 57.5 m SD, respectively); E, possible footprint in red and tan siltstone and very fine sandstone (Jianshangou no. 1: box 7, line 6: centered on 34.4 m ACD, 35.1 m SD); F, reddish mudstone-filled desiccation crack in light greenish gray fine silty sandstone (Jianshangou no. 1: box 13, line 4: centered on 62.6 m ACD; 64.1 m SD). Deeper in core is right to left.

the Jianshangou Member, the upper part of which contains abundant bivalves (Fig. 13). Apparently, no *in situ* Xiatulaigou Member flow material is present, and we regard the member as absent. Correspondingly, the Dajianshanzi Bed of the Jianshangou Member rests directly on the Lujiatun bed in the Jianshangou no. 1 core (Fig. 4).

Laminated dark gray mudstone marks the base of the 6-m-thick Anjiagou Bed (8.6 m to 14.6 m SD: 8.5 m to 14.6 m ACD). The lower 3.3 m of the Anjiagou Bed (8.5 m to 11.8 m SD: 8.6 m to 11.9 ACD) consists mostly of tan sandstone and coarse volcaniclastic sandstone and possible ash, followed by more typical dark gray finely laminated to weakly microlaminated mudstone with abundant ash beds (Figs. 4, 14). Much of this and the rest of the upper part of the core is badly fragmented with poor recovery.

A total of 4.8 m of tan siltstones and sandstones, some volcaniclastic with ash aggregates, comprise the lower Hengdaozi Bed (3.7 m to 8.5 m SD: m 3.8 m to 8.6 m ACD), which overlies the Anjiagou Bed in the Jianshangou no. 1 core. This is succeeded by 3.7 m SD: (3.8 m ACD) of thin to thick bedded light tan mudstone to fine sandstone with large spinocaudatans, which is weathered and badly broken up by drilling with poor recovery. We regard these beds as part of the upper Hengdaozi Bed.

4.4. Ditch along road to Dajianshanzi

Exposures along a ditch on the north side of the road to Dajianshanzi reveal a section starting in the Xiatulaigou Member, extending through

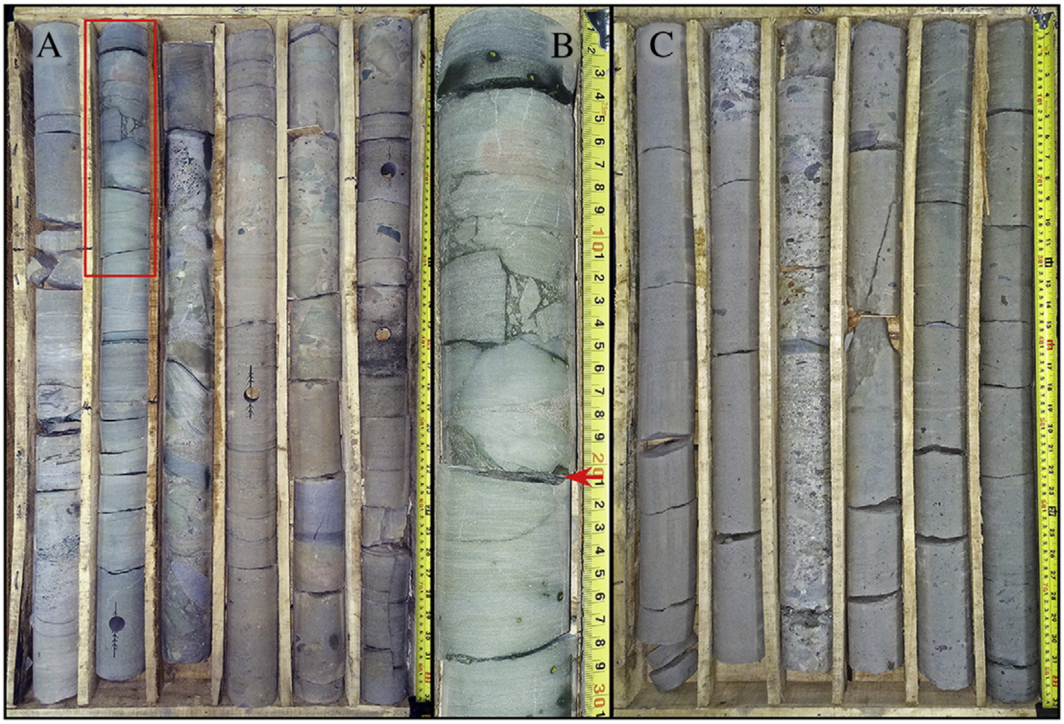

Fig. 21. Lujiatun Member in Huangbanjigou no. 1 core: A, basal Lujiatun Member and contact with underlying Tuchengzi Formation (box 19: 87.7–92.7 m ACD; 91.1–96.2 SD)–Lujiatun is here comprised of breccia of Tuchengzi clasts with sandstone matrix and overlying conglomerates and olive-tan sandstones with increasing abundances of non-Yixian (?) igneous clasts upward –red box show position of B; B, contact between Tuchengzi Formation and overlying Lujiatun Member of the Yixian Formation (red arrow) made up of breccia of Tuchengzi with sandstone matrix (box 19, line 5: 91.2 m ACD; 94.7 m SD); C, olive-tan sandstones and conglomerate (box 16: 73.1–77.9 m ACD; 76.3–81.2 m SD).

the lower Jianshanzigou Member, including the Dajianshanzi Bed and most if not all of the Anjiagou Bed (Fig. 8).

The Xiatulaigou Member outcrops in gullies on either side of the road, with the best being on the northwest side in September 2015. Although the outcrops were not good enough to measure a section, it is clear that there are minimally 20 or more meters of lavas, based on the difference in elevation between the upper contact and the rough position of the lower contact.

The contact of the Xiatulaigou Member with the Dajianshanzi Bed is rubbly, reddish, and very vesicular. The Dajianshanzi Bed is about 1.6 m thick and is comprised of largely volcaniclastic sandstone with abundant large white rhizoliths and overlying sandstones and siltstones with abundant bivalves. The Anjiagou Bed is thin (~3.8 m) and decidedly coarser than other locations with fewer intervals of fine laminations as well interbedded lithologies resembling the Hengdaozi Bed and sandstones. The overlying beds are presumably equivalent to the Hengdaozi Bed but are not objectively differentiable from undivided Yixian Formation tuffaceous sandstones.

4.5. Dajianshanzi

A small excavation on the southeast side of the access road to the top of Dajianshanzi (41.600374°, 120.839757°) reveals white, weathered, microlaminated mudstone with abundant large spinocaudatans that underlies the igneous intrusion capping the hill. The microlaminated mudstone overlies light tan and white weathered volcaniclastic sandstones of undivided Yixian Formation that makes up most of the rest of the hill. Based on height of the mudstone above the Hengdaozi Bed at Jianshangou and at the ditch along the road to Dajianshanzi (above), the laminated unit should be between roughly 25 to 35 m above the Hengdaozi Bed as seen at Jianshangou and is thus stratigraphically higher than any unit exposed at Sihetun or Huangbanjigou.

5. Correlation of cores and outcrops

Lithostratigraphic correlation at multiple scales between the cores and outcrops and cores is important to establish because it forms the basis for testing hypotheses of the scale of the depositional environments, particularly the sizes and depths of lakes. At the finest scale, event beds that are arguably isochronous have the most power to distinguish between competing hypotheses. Amongst the event beds, the most distinctive are the ashes, especially those we interpret as air fall, and combinations of sequences of ashes and other distinctive beds.

The overall homotaxiality of the lithologically defined members, particularly the lava of the Xiatulaigou Member, suggests an obvious general correlation between cores and cores and outcrops. Unsurprisingly, correlations of smaller scale units, such as parts of each member are most easily supportable for outcrops that are close to the cores, particularly the type section of the Anjiagou Bed to the Sihetun no. 1 core and the exposures at Huangbanjigou to Huangbanjigou no. 1. Fine scale correlation is less certain between Huangbanjigou no. 1 and Sihetun no. 1 cores and yet more uncertain between Jianshangou no. 1 and the other cores and outcrops, both because of clear lateral changes in facies and the disappearance of distinctive ashes.

Weathering-induced changes in color and fissility and the tendency for the ashes to swell to several times their thickness makes fine-scale correlation challenging between the cores and outcrops. However, as is the case with the cores themselves, the overall pattern is obvious. It is worth stressing that the Xiatulaigou Member is the only one true lava sequence (extrusive) we have identified in the Yixian Formation region around Sihetun. Thus, the Xiatulaigou Member provides a clear stratigraphic marker. This is especially important for the Lujiatun Member because while there is a clear lithological similarity between the type section at Lujiatun and the core sections of the member as well as the overlying lavas. The latter outcrops are further from cores than others discussed here, and erosion has removed the strata overlying the Xiatulaigou Member.

Fine-scale correlation of beds within the sections of the Tuchengzi in the Sihetun and Huangbanjigou cores is not apparent. Although there is a strong overall similarity in facies between the two cores, there is not smaller-scale homotaxiality between the sequences, nor are there similar trends of clear key marker beds. This is consistent with the unconformity at the Tuchengzi-Yixian contact, which is otherwise based only at the erosive conglomerate at the base of the latter within the cores.

6. Summary of stratigraphy, facies relationships, and fossil levels

Placing the cores and outcrops in a transect from Sihetun no. 1 to Jianshangou no. 1 suggests significant basin deepening and towards the west (Fig. 4) within the Sihetun Sub-basin. This is most dramatically seen in the Xiatulaigou Member that thickens from 0 at Jianshangou no. 1 to 20 m at Huangbanjigou no. 1 and >65 m at Sihetun no. 1. Similarly, the Anjiagou Bed fines, becomes much finer laminated, and thickens from Jianshangou no. 1 to Huangbanjigou no. 1 and Sihetun no. 1. The Xiatulaigou Member also thickens from southeast to northwest as documented by the sections in Jiang et al. (2011). The resultant direction suggests general thickening and deepening towards the northwest. Data are presently insufficient to tell if this thickening and deepening trend occurs within a complex of fault blocks, in one fault block comprising the Sihetun Sub-basin, or if there was pre-Yixian preserved topography. It is also unclear how the trends in the Sihetun Sub-basin relate to the type area of the Yixian Formation. However, the existing data do permit the conclusion that there was a sediment source and shallower water on the southeastern side of the Sihetun Sub-basin for the deposition of the Jianshangou Member, suggesting that the lake system depositing that member had shorelines relatively close to the southeastern margin of the Sihetun Sub-basin but not necessarily within it. We think that this precludes the Anjiagou Bed of the Jianshangou Member from being deposited by a lake of simple shape that extended over the whole of the outcrop area of the Yixian Formation in western Liaoning. However, the present data do not preclude a large lake of more complex shape with islands and inselbergs developed on a faulted Tuchengzi basement that extended far beyond the present erosional limits of the Sihetun Sub-basin.

Although our observations are limited to two cores (Huangbanjigou no. 1 and Jianshangou no.1), it is clear that the direction of facies change in the Tuchengzi Formation cannot be like that seen in the overlying Jehol Group. We recognize we are not looking at correlative intervals of Tuchengzi Formation in the two cores because there is no hint of coarsening from Huangbanjigou no. 1 towards Jianshangou no.1 or other coherent facies gradients. We suspect that the structural control of what we see in the Yixian Formation postdates the Tuchengzi Formation.

Results for the Yixian Formation from the cores largely support the basic correlation and facies relationships diagramed by Chen et al. (2005), the only major difference being the their hypothesized correlation of our Jianshangou Member with our Lujiatun Member. We argue that the hypothesis is falsified by the homotaxiality of the lithologies of the Lujiatun type section and superimposed lavas compared to the section in the Huangbanjigou no. 1 core that are more simply interpreted as Xiatulaigou Member, which agrees with recent work (c.f., Hethke et al., 2013). This assumes that at least some of the stratigraphic divisions seen in the Sihetun Sub-basin extend into at least the western edge of the main area of Yixian outcrops in the Yixian Basin.

Additional thickness, fossil level, and facies data from Jiang et al. (2011), correlated to the nearby cores described here, also allows important fossil localities and levels to be placed in a unified stratigraphic framework (Fig. 3).

7. Environmental interpretations

The complete lack of marine invertebrates and abundance of invertebrates known to be restricted to fresh water (most aquatic insects, the spinocaudatans (clam shrimp), and specific groups of ostracodes has long been interpreted as showing that the Yixian and Tuchengzi formations were deposited in continental environments, largely lakes. Within that overall context, however, there has been little agreement. The correlations described here between the three cores and outcrops inform and constrain the interpretations of the depositional environments, most importantly for the Yixian Formation to which we will restrict our comments.

The deepest water lacustrine deposits are clearly the dark gray to black microlaminated mudstones with abundant thin ashes, typical of the Anjiagou Bed. This facies has been described in detail by Hethke et al. (2012) and Zhang and Sha (2012) for the Yixian Formation, and it consists of sub-millimeter to millimeter-scale couplets interpreted as varves. This is the facies that produces the largest number of articulated vertebrates within the Yixian Formation of the Sihetun Sub-basin and is the characteristic facies of the Anjiagou Bed. This facies does however occur sparingly in the Hengdaozi Bed, cyclically in the Huangbanjigou Bed, where it produces characteristic Jehol Biota fishes, and higher in undivided Yixian as at Dajianshanzi.

Similar facies in deposits of various ages produce broadly similar taphofacies, qualifying as konservat Lagerstätten (Seilacher, 1970) as well, such as the Triassic Cow Branch Formation (Olsen et al., 1978, 2015; Fraser et al., 1996), the latest Triassic-Early Jurassic fish-bearing strata of the Hartford and Newark basins (Olsen, 1985, 1988; Whiteside et al., 2011; LeTourneau et al., 2015); and the Eocene Green River Formation (Bradley, 1930; Grande, 2013).

This type of facies has long been interpreted as deposited in the profundal zone of perennially, chemically stratified bodies of water (e.g., Bradley, 1930) – i.e., meromictic – and has been one of the interpretations applied to the Anjiagou Bed (Hethke et al., 2012). Such water bodies, must be deep compared to their fetch (the distance across which wind can blow) so that the work of the wind does not tend to homogenize the water column, and productive enough so that bacterial respiration can deplete the lower parts of the water column of oxygen and exclude macrobenthos. Thus, the lakes must be deeper than the dynamically maintained oxicline would be otherwise. This relationship is a relative one so that lakes with appropriate proportions can be small in size (e.g., Fayettville Green Lake, New York, USA, 1 km, 52 m deep; Lake Bosumtwi, Ghana, 8.5 km, 81 m deep), medium sized (e.g., Lake Van, Turkey; 119 km, 451 m deep), large (e.g., Lake Malawi, East Africa, 570 km, 706 m deep), or extremely large in size (e.g., the Black Sea, Europe, 1175 km, 2212 m deep). Lakes that are relatively shallow relative to their size do not produce microlaminated sediments regardless of their absolute dimensions or productivity (e.g., Lake Victoria, Equatorial East Africa, 337 km, 83 m deep) (see Hutchinson, 1937, Hutchinson, 1957; Olsen, 1990; Cohen, 2003). If the water depth decreases, the same lake can switch from meromictic, producing microlaminated sediments in the profundal zone, to holomictic, producing coarsely laminated or massive bedding (e.g., Lake Malawi, Scholz et al., 2007; Cohen et al., 2007).

We interpret the very abundant and well-defined ash beds that occur in the microlaminated to very well laminated mudstones of the Anjiagou Bed as airfalls (Fig. 14). They tend to be, but are not always, graded. The grading could occur in deposition from the air, but also from settling though the water column. It is also possible that some of the beds are reworked and deposited as turbidites (e.g., hypopycnal plumes from rivers).

Less well-laminated bedding, especially mudstones, are deposited when micro- to macrobioturbation and wave mixing occurs in lakes that are relatively large in area compared to their depth and in the same lake basin. This generally occurs during drops in lake depth and culminates with subaereal exposure, soil formation, and fluvial deposition. Abundant thin ashes typical of the Anjiagou Bed in Sihetun no. 1 and Huangbanjigou no. 2 cores are nearly absent in non-microlaminated facies, which we attribute to mixing of the ash with the sediment by the same process that prevents the preservation of microlaminae, i.e., microbioturbation and wave action. This is a striking relationship that can be seen in vertical as well as lateral facies transitions, and it is a pattern seen globally in lacustrine deposits of various ages.

Lighter colored (even when unweathered), laminated but not microlaminated, mudstones, virtually lacking thin, discrete ashes were thus deposited in shallower water. Transitions between microlaminated and non-microlaminated strata vertically show episodic return of fine dark microlaminae (Fig. 15). Although hypopycnal plumes (e.g., Hethke et al., 2012) may have contributed to the non-microlaminated bands, they are more simply explained as a consequence of a breakdown in meromixis because of decreasing water depths. The Hengdaozi Bed is dominated by this facies (including mf-6 of Hethke et al., 2012), including the "main insect bed". The presence of complete insects and whole fish in the latter is most simply explained by short term to returns to meromixis. In that context, the "main" insect bed is transitional into the overlying Huangbanjigou Bed, which marks a return to the microlaminated facies with thin ashes, albeit cyclically and not as consistently as the Anjiagou Bed. The interpretation of the Hengdaozi Bed as a shallower water deposit than the underlying Anjiagou Bed or overlying Huangbanjigou Bed (basal part) would seem to be opposite in interpretation of that of Hethke et al. (2012), in which the Anjiagou Bed is interpreted as being deposited during a more arid phase than the Hengdaozi Bed. The simplest explanation of lowering water depth to break down stratification during Hengdaozi Bed deposition is by evaporation, which presumably would occur during more arid times. That said, existing data do not permit excluding a lowering of the outlet by erosion or tectonics as an explanation of a change in water depth, although that could be tested once a high-resolution age model based on CA-ID-TIMS.

U-Pb zircon geochronology is in place (e.g., Kinney et al., in press) (see below). As evidenced by the lateral changes at homotaxial levels in the cores and outcrops, some microlaminated strata of the Anjiagou Bed do change laterally into less well-laminated strata resembling the Hengdaozi Bed as at the ditch along road to Dajianshanzi. This facies transition occurs in the same direction as the whole Anjiagou Bed thins and coarsens and the underlying Xiatulaigou Member thins to zero. Therefore, it is simplest to argue that the overall water depth for the Anjiagou Bed was shallowing in that direction, and some beds were deposited above the chemocline closer to a shoreline at the ditch exposure while contemporaneous strata in deeper water were deposited in anoxic water. This line of argument requires that the paleoelevation of the lake floor during Anjiagou Bed-time was significantly higher towards the east and southeast edges of the Sihetun Sub-basin towards a shoreline edge of the lake and not on an isolated high in the middle of a much larger lake. The latter scenario would predict truncation of the Anjiagou Bed lake level drop without the observed facies transition to coarser grain size within the bed.

The less-well laminated mudstone facies likewise pass laterally into sandstones, often with abundant ash-aggregates. The Hengdaozi and Huangbanjigou beds pass laterally into ash-aggregate-rich sandstone towards Jianshangou no. 1, and into gravelly beds.

Analysis of the depositional environment of the Lujiatun Member volcaniclastic sandstones and conglomerates has focused on the mechanism of preservation of the extraordinary articulated tetrapods, including mammals and dinosaurs (Meng et al., 2004; Hu et al., 2005; Qi et al., 2007; Zhao et al., 2013; Rogers et al., 2015). Although opinions have varied dramatically on the depositional environments of the striking articulated tetrapod-bearing portions of the member, from lahars (Wang and Zhou, 2003; Qi et al., 2007) to ignimbrites (Benton et al., 2008; Rogers et al., 2015), and ashes or a combination of primary and reworked volcaniclastic material (Rogers et al., 2015). It appears that the Lujiatun Member was deposited in multiple episodes and is not equivalent to a lake sequence deeper in the Sihetun Sub-basin. Although Rogers et al. (2015) dismiss the idea that many of the tetrapods found in the Lujiatun Member were preserved in burrows (e.g., Meng et al., 2004) because traces of the burrow walls have not been described or not visible, that is not a good criterion at this stage in research. Even in cases where part of a burrow can be spectacularly visible where intersecting a mud bed, other parts of the burrow in coarser clastic may be completely obscure, especially if collapsed. Given the fact that few if any specimens have been collected in a manner that would preserve burrows if they were present, preservation in burrows is not only possible, it is also the most parsimonious hypothesis explaining the lack of disturbance of tight clusters of juveniles or very small theropods in sleeping, resting, or quiet expiring positions. This is because it uncouples the preservational attitude of the tetrapods from the depositional environment of the strata they are preserved in. The environmental implication of the burrows, however, is that the strata were well drained during the time they were occupied.

Tuchengzi strata are very strongly dominated by traction current deposition with a dominance of silt- and sandstone with ripple cross lamination, planar and cross bedding, and mud-chip conglomerates (Fig. 20). Some ripple cross laminated beds fine upward and suggest deceleration-of-flow sequences. Mudstones comprise a small fraction of the strata and when present are interbedded with traction current deposits. Evidence of subaerial exposure is not abundant, although desiccation cracks and rhizomorphs are sometimes present, along with small-scale curved slickensides and rare nodules suggestive of pedogenesis. Deformed bedding consistent with footprints is common (Fig. 20). Presumed invertebrate bioturbation is common but rarely obliterates bedding. The lack of bed-scale geometry beyond the cores and the lack of repetitive simple upward-fining or upward coarsening sequences makes it difficult to assign the strata to a particular depositional environment. Overall, the relatively infrequent evidence of exposure and pedogenesis, coupled with pervasive evidence of traction currents, suggests shallow water, low angle delta, lake margin, or fluvial environments. In outcrop, suspension-dominated, laminated muds with spinocaudatans occur sparingly in the Yixian Basin (e.g., ~1 km east of Xiagujiazi at 41.506667°, 120.807000°), but we have seen no evidence of microlaminated strata indicative of deep stratified lakes.

8. Cyclicity

Of all the units encountered in the core, the only one with visually apparent cyclicity in outcrop is the Jianshangou Member of the Yixian Formation, notably the Huangbanjigou Bed, (Figs. 4, 7) with cycles averaging between 1 m and 2 m thick. The cyclicity consists of beds of well laminated to microlaminated mudstones with typical Jehol Biota arthropods, alternating with more massive mudstones and siltstones. These sequences of facies are most simply interpreted as lake depth fluctuations. We used a color index (1 = white; 3 = black) and a lamination index (1 = massive; 5 = microlaminated) for the spliced outcrop section of the Huangbanjigou Bed and the core section of the Anjiagou Bed (joined at their mutual boundary) to provide a semi-quantitative depth-series that could be examined using Fourier analysis similar to the methods employed by Olsen (1986), Olsen and Kent (1996, 1999), and Sha et al. (2015) for Triassic-Jurassic sequences. Multitaper Method Fourier Analysis of the spliced section reveals significant and high amplitude periods around 1 m and 2 m (Fig. 22), consistent with what is visually observed in the field (Fig. 7). How these periods relate to possible forcing of environmental variations is unclear, but the cyclical and periodic lake-level fluctuations are plausibly caused by climatic changes that in turn may be Milankovitch orbitally forced cycles.

The periods identified in the Huangbanjigou core and outcrop sections are consistent with our preliminary results from the Sihetun no. 1 core, and most notably, the strongest thickness periods (at ~2, and ~1 m) in the analysis by Wu et al. (2013) of the type section of the Sihetun, based on anhysteretic remanent magnetization and magnetic susceptibility. We hypothesize that the ~1 m cycles reflect the climatic precession cycle (~20 ky) and the ~2 m cycles reflect

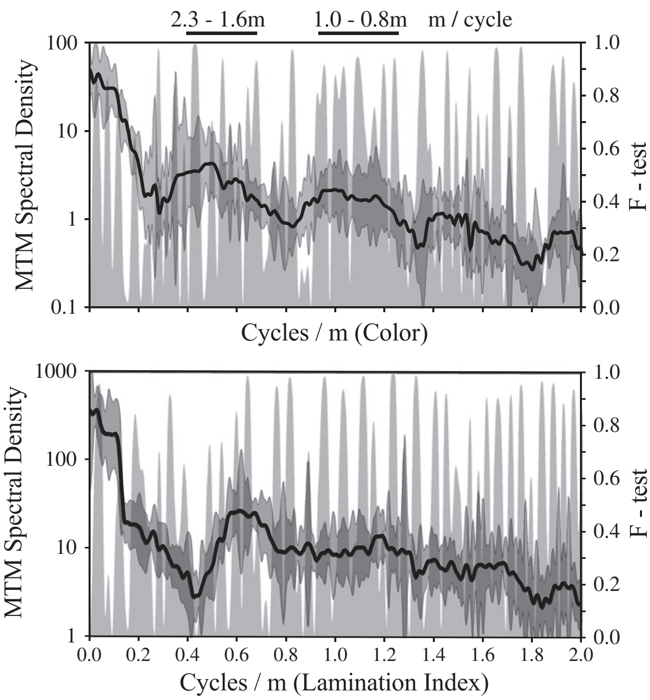

Fig. 22. Multitaper Method (MTM) spectral estimates of color and lamination index of the upper 43 m (SD) of the Huangbanjigou no. 1 core (Anjiagou, Hengdaozi) and outcrop section of Huangbanjigou beds and overlying undivided Yixian Fm. At Huangbanjigou. Section interpolated at 1 cm intervals (Analyseries options, detrended, width.ndata product = 4 and 4 windows).

obliquity forcing (~37 ky), although it is also possible that the ~2 m cycle is climatic precession and the ~1 m cycle, hemiprecession. We recognize that without a clear hierarchy of cycles, it is impossible to distinguish between the two. Either of our interpretations, however, differs from that of Wu et al. (2013) in being larger by a factor of 5 to 10, who argue that the ~2 and ~1 m cycles reflect the ~100 ky cycles of short eccentricity and the obliquity cycles and climatic precession cycles averaging 48 cm and ~20 cm respectively. This large difference of interpretation is not resolvable by analysis of the noisy spectra themselves, but could be resolved by high-resolution CA ID-TIMS U–Pb zircon geochronology of ashes from the section now underway (Kinney et al., in press). Using the accumulation rate derived from the Huangbanjigou core and outcrop and Sihetun core and outcrop, assuming the ~1 m cycle reflects the 20 ky cycle of climatic precession or the ~2 m cycle represents climatic precession, and assuming no major hiatuses, the entire Anjiagou through Huangbanjigou bed sequence (~41 m) should have a duration of ~820 or ~410 ky, whereas the accumulation rate derived from Wu et al. (2013) predicts a duration of the same interval of 4.1 Myr, well within the precession limits of U-Pb zircon geochronology. The difference between our and Wu et al.'s assessments of accumulation rates amounts to the difference between the Yixian Formation spanning more than one Early Cretaceous stage such as the Barremian vs. it spanning only a small fraction of a stage.

9. Conclusions

For the first time, the remarkable feathered dinosaur deposits of the Sihetun Sub-basin of the Yixian Basin are described in detail, based on continuous core, correlated to outcrops, and with unquestionable superposition of units. This detail and certainty of stratigraphy allow us to refine the stratigraphic nomenclature of the Yixian Formation and to better understand the sequence of facies and environments in which the fossils accumulated. It is apparent from cores and outcrops that the three members of the Yixian Formation represent historical phases in the basin, not lateral facies equivalents. The basal Lujiatun Member is fluvial and volcaniclastic in origin, housing 3-d terrestrial tetrapods, likely preserved in collapsed burrows. The Xiatulaigou Member lavas and breccias are the only lava flow units in the area. The Jianshangou Member laminites, air-falls, and tuffaceous rocks (housing the Jehol Biota) are the products of relatively deep, perennial lakes that fluctuated in depth modestly, plausibly forced by orbitally-paced climate change, preserving the spectacular Jehol Lagerstätte during the deepest lake intervals.

Although there is evidence of only one lava flow sequence in the Sihetun Sub-basin, other reported lava flows being intrusions, there are multiple flow sequences with interbedded lacustrine strata in the main Yixian Basin, especially in the formation's type area, closer to Yixian, comprising an aggregate thickness more than an order of magnitude greater than Yixian strata in the Sihetun Sub-basin. How exactly the Sihetun Sub-basin strata relate to the type area, or for that matter the Jiufotang Formation, remains a frontier of study, one that can be at least partially addressed through further high-resolution geochronology and physical stratigraphy in intervening areas.

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