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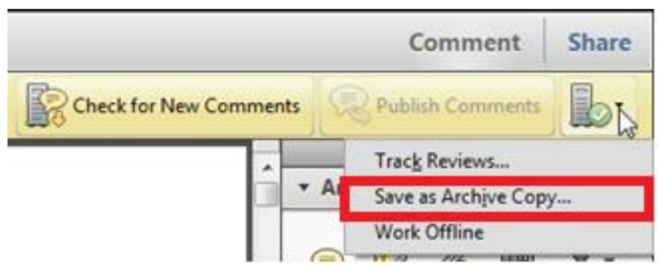

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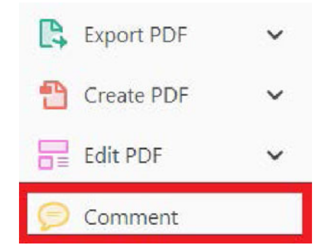

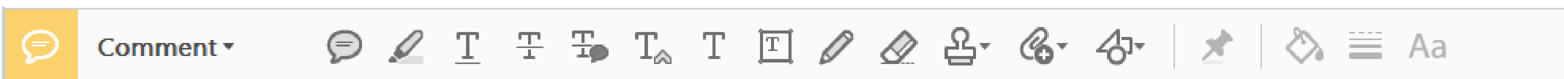

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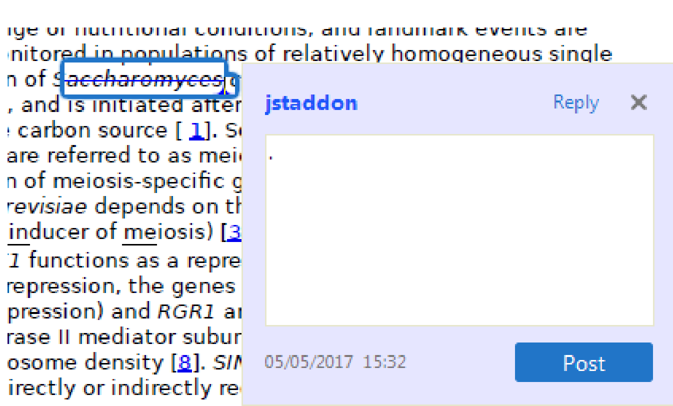

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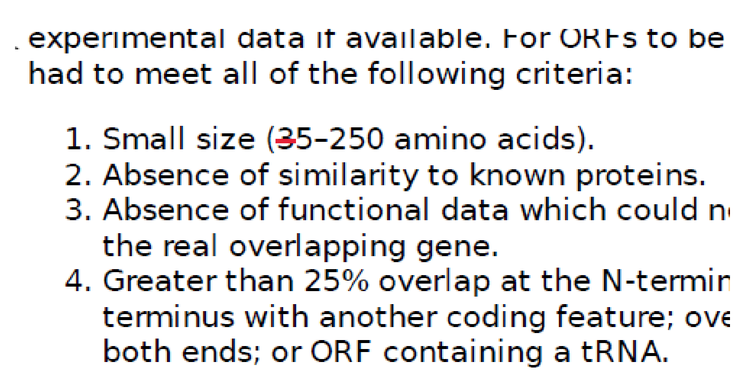

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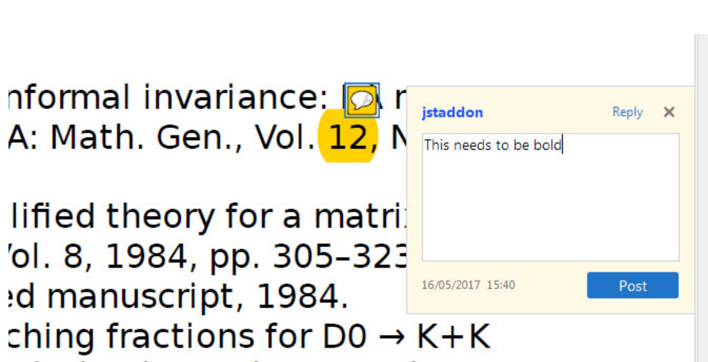

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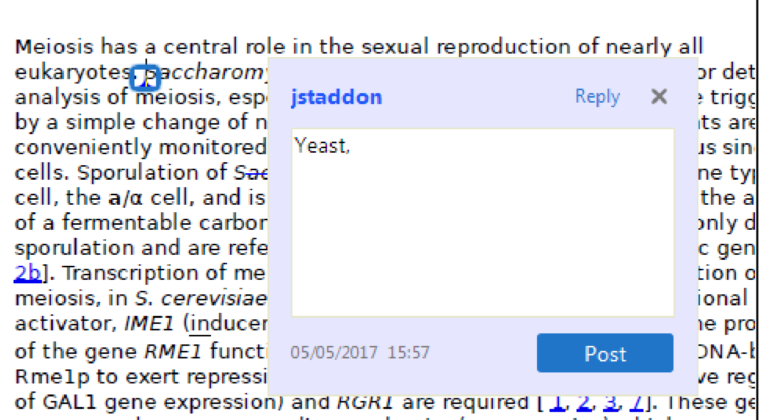

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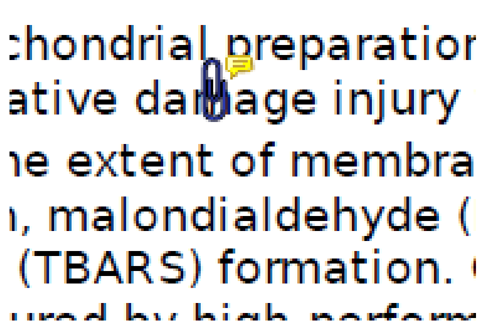

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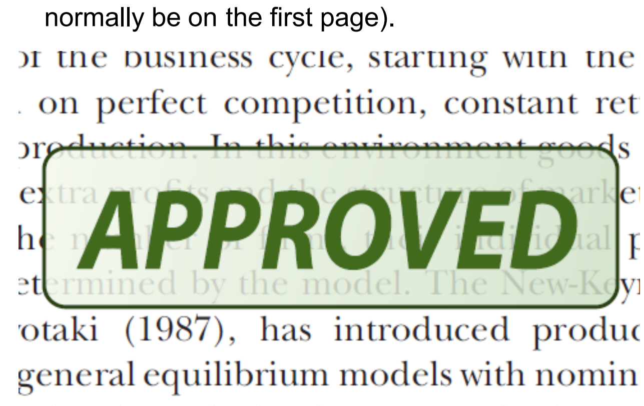

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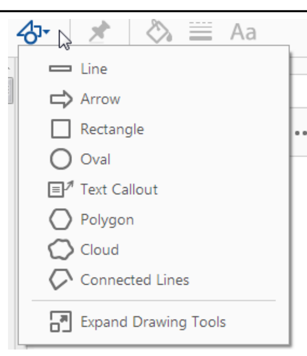

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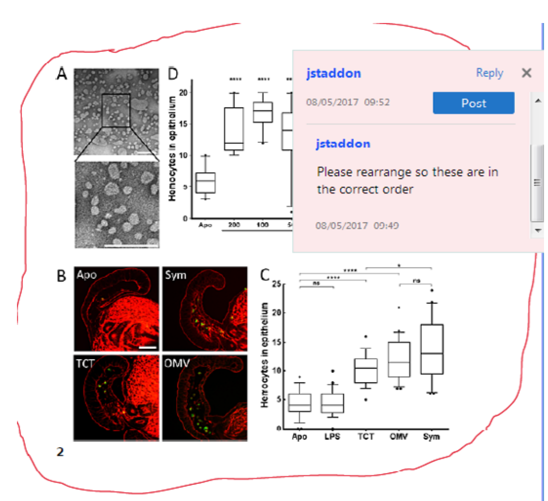

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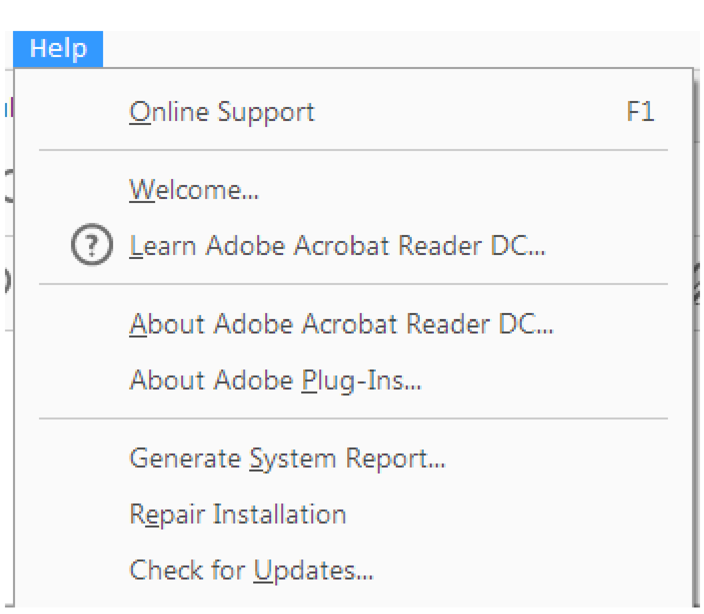

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RESEARCH ARTICLE

Upper Ordovician continuous lithological succession in outer-shelf facies, Yangtze Platform, South China: Facies changes and oceanographic reconstruction up to the Late Ordovician Hirnantian glaciation

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Ordovician sequences at Huanghuachang, northern Yichang City of Hubei Province, Central China, are representative of an outer-shelf setting of the Yangtze epicontinental sea, South China Block. Continuous drill cores of the Well Yihuang 1 penetrated the Upper Ordovician units of the Miaopo, Pagoda, Linhsiang, Wufeng, and Kuanyinchiao Formations in ascending order. Such a continuous succession gives valuable insights into environmental changes and an extinction event through Late Ordovician time. Results suggest that sluggish circulation and oligotrophic conditions were characteristic of the region from Sandbian to early Hirnantian Epochs of the Late Ordovician. Thin-bedded limestones within the Miaopo Formation shales and nodular limestones of the Pagoda and Linhsiang Formations are mainly wackestones and mudstones with sparse and fine-grained trilobite, cephalopod, gastropod, ostracod, and crinoid bioclasts with rare brachiopod and bivalve bioclasts, further showing gradual decreasing in abundance and grain size upwards through the succession. Such biological and lithological changes are interpreted as a trend towards a deeper and calmer seafloor below storm wave-base. The Kwangsian Orogeny of the late Katian Epoch altered the geography of the region, creating a large embayment in the area of the Well Yihuang 1 core. Thus the sequence developed upwards to the Wufeng Formation graptolitic black shales consistent with formation in a dysoxic and stagnant embayment that excluded carbonate production and benthic biota, but ideal for preservation of planktic graptolite fossils. Bioclastic packstone and quartz grain lenses interlayered with the black shales are occasionally sourced from southeastward shallow submarine highs closed to the Cathaysian Land. Change from this interpreted sluggish ocean circulation affecting the ocean floor was delayed to the early Hirnantian Epoch, when active circulation is related to the onset of the latest Ordovician glaciation which resulted in an oxygenated ocean floor during regression, favorable for the thriving shelly *Hirnantia* Fauna.

KEYWORDS

environmental parameters, microfacies, outer-shelf of the Yangtze epicontinental sea, South China block, Upper Ordovician

1 | INTRODUCTION

The Yangtze epicontinental sea covered most of the isolated South China Block, which was located in the subtropical to tropical belt, within 30° south latitude to 30° north latitude of peri-Gondwana during the Late Ordovician to Early Silurian periods (e.g. Boucot, Chen, & Scotese, 1995; X. Chen & Rong, 1992; X. Chen, Zhou, & Fan, 2010; Copper, 2002; Melchin, Mitchell, Holmden, & Štorch, 2013; Scotese & McKerrow, 1990, 1995; Torsvik & Cocks, 2013). Tectonic uplift beginning in the Sandbian Epoch and developing through the

Katian Epoch of the Late Ordovician Period reduced the size of the sedimentary basin (Figure 1). The Kwangsian Orogeny, northwestward expansion of Cathaysian Land from the southeast together with uplift from Chengdu Land in the west and Dian-Qian-Gui Land in the southwest of the Yangtze epicontinental sea exposed some marine areas above sea level (X. Chen et al., 2014; X. Chen & Mitchell, 1996; X. Chen, Zhang, Fan, Tang, & Sun, 2012; Rong et al., 2003). Global cooling and extinction events took place in the Hirnantian Stage of the latest Ordovician Period (Harper, Hammarlund, & Rasmussen, 2013) and eliminated many taxa of marine invertebrate animals (Jablonski, 1991; Sheehan, 2001). Biotic and geochemical evidence based on high-resolution stratigraphic schemes from the South China Block shows that sea-level fluctuation, climatic shifts and tectonic movement were key factors in controlling litho- and biofacies (e.g. X. Chen et al., 2000; X. Chen, Rong, Li, & Boucot, 2004; Cheng & Wang, 1991; Feng, Yu, Fang, & Bian, 1993; Y. Li & Kershaw, 2003; Y. Liu, Li, Algeo, Fan, & Peng, 2016; Munnecke, Zhang, Liu, & Cheng, 2011; Rong, 1984; Rong & Chen, 1987; Rong, Chen, & Harper, 2002; Yan, Chen, Wang, & Wang, 2010; Yang et al., 2016; T. S. Zhang, Kershaw, Wan, & Lan, 2000; L. Zhou et al., 2011).

Ordovician sequences dominated by carbonates widely distributed in the northern Yichang District of western Hubei Province are representatives of nearly continuous deposition in outer-shelf environments on the Yangtze epicontinental sea favorable for classic paleontological, stratigraphic and palaeoenvironmental investigations (e.g. X. Chen & Qiu, 1986; Lee & Chao, 1924; Mu, Zhu, Lin, & Wu, 1984; W. T. Zhang, 1962; Zeng et al., 1987). The Huanghuachang and Wangjiawan North sections in this region are well-known as Global Stratotype Section and Points (GSSPs) for the Dapingian of the lower Middle Ordovician and Hirnantian of the uppermost Ordovician respectively (X. Chen et al., 2006; X. F. Wang et al., 2005). Both lithological and paleontological data suggest an outer-shelf setting less in terrigenous supplement and idealized for insight evolutionary pattern of Ordovician biota in aspects of biodiversity and abundance. Earlier literature focused mainly on paleontological, biostratigraphic and geochemical analyses (e.g. X. Chen et al., 1999; Fan et al., 2011; Fan, Peng, & Melchin, 2009; J. Li, Thomas, & Yan, 2014; Yan, Chen, Wang, Wang, & Wang, 2009). Nevertheless, lithological microfacies and their environmental parameters have been given less attention.

Organic-matter rich black shales that occur throughout the Ordovician–Silurian transition from the outer-shelf area and are considered hot spots for economic geology in China because of their shale gas significance (S. B. Chen et al., 2011; C. Liang et al., 2016; S. G. Liu, 2013). The drilling project of the Well Yihuang 1 at Huanghuachang Town was carried out in 2014. Yi means Yichang District; huang means Huanghuachang, a small town situated in the northern suburb of Yichang City (30°52′50.05″N, 111°24′0.94″E, Figure 1). This new drill core material aids assessment both for petrologic data and palaeoenvironmental parameters of shale gas. The aim of this study is to characterize the bio- and lithofacies changes throughout the Upper Ordovician in a single, almost continuous section of a well core located in the centre of the Yangtze epicontinental sea, allowing more complete understanding of the synergetic evolution between biota and oceanographic background than has been previously achieved. The extent to which these tectonic and biotic events affected the regional environments in outer-shelf settings of the

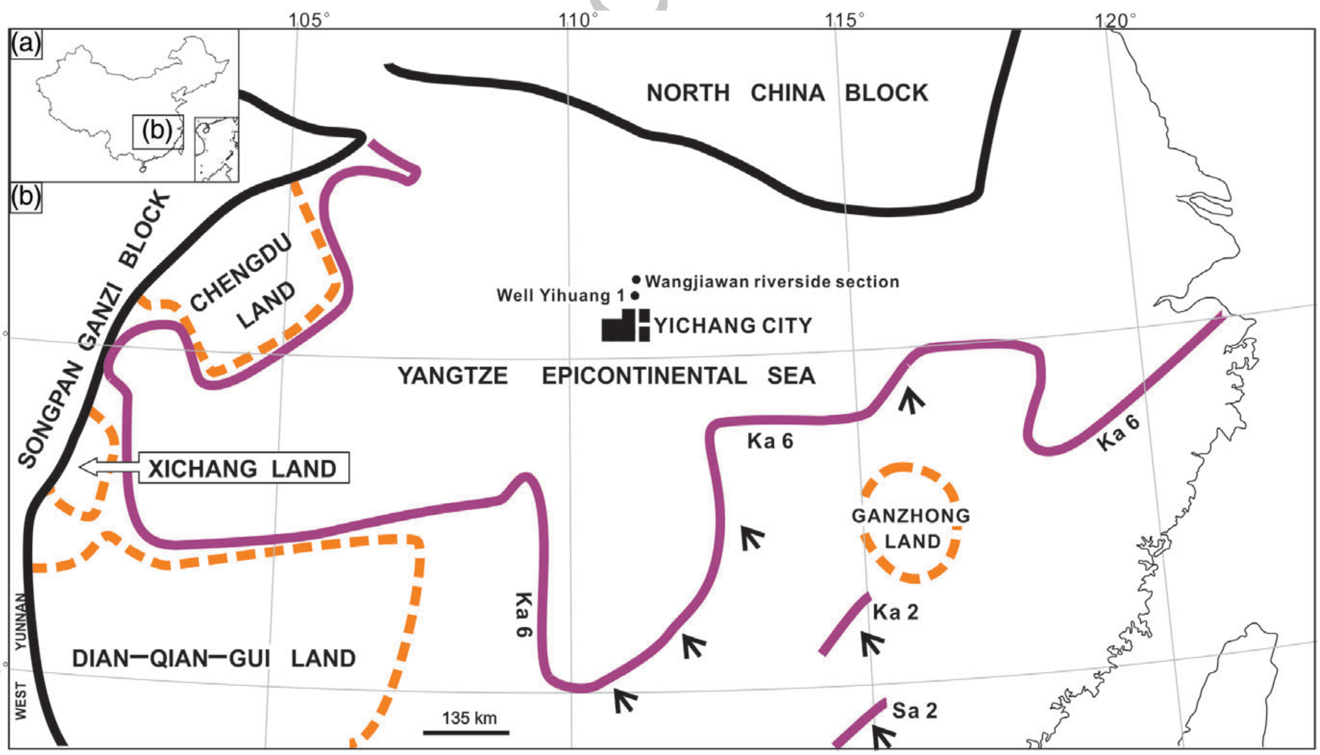

FIGURE 1 Palaeogeographic pattern of the South China Block in Late Ordovician time, with outer-shelf locations of the Well Yihuang 1 and Wangjiawan riverside section. Migrations of shorelines surrounding Yangtze epicontinental sea (marked by arrows) are after X. Chen, Fan, Chen, Tang, and Hou (2014), their biostratigraphic dating by graptolitic zonations respectively marked:Sa2, *Climacograptus bicornis* Biozone, middle Sandbian; Ka2, *Diplacanthograptus spiniferus* Biozone, early Katian; Ka6, *Dicellograptus complexus* Biozone, late Katian

Yangtze epicontinental sea during the Late Ordovician is the topic of this paper. Our results suggest that a low latitude but transgressional marine floor below storm wave-base was essentially unfavorable for concentrations of benthic fauna in advance of latest Ordovician glaciation; and further recognize truncation of oceanographic parameters from vertical gradients, sluggish circulation and oligotrophic conditions of pre-Hirnantian to ocean circulation of the Hirnantian in the study region.

2 | MATERIALS

Upper Ordovician deposits at Huanghuachang Town contain neither sedimentary lacunae nor shallow intertidal indicators (Zeng et al., 1987). Their bio- and lithofacies of the sequences are implications for evolutionary pattern in aspects of paleontology and palaeogeography in a deep outer-shelf setting. The Well Yihuang 1 at this town penetrates 72 m of drilling depth from the upper Kuniutan Formation (upper Darriwilian of Middle Ordovician, the deepest drilling level) to the lower Lungmachi Formation (Llandovery, Silurian). Strata at Well Yihuang 1 dip gently, thus, the depth of the drilling cores is approximately equal to their measured thicknesses. Upper Ordovician Miaopo, Pagoda, Linhsiang, Wufeng and Kuanyinchiao Formations in ascending order of the well are condensed with total thicknesses less than 40 m (Figure 2). Drill cores can be biostratigraphically and lithostratigraphically correlated with the nearby outcrops described by Zeng et al., (1987, shown on the left side of the Figure 2). Age-dating of the lithological units through the Upper Ordovician formations described below correspond to the current international standard of the Upper Ordovician (Cohen, Finney, Gibbard, & Fan, 2013). Zeng et al. (1987) listed macrofossils, which were easily collected from outcrop but difficult from cores. Therefore, bioclastic components of the Upper Ordovician from the well in the Figure 2 are based on our microfacies identification. Altogether 53 samples, mainly of bioclastic limestones, were collected from the core for thin section study; their sampling horizons and summarized bioclastic components are marked in Figure 2. Terminology for limestone classification follows Dunham (1962) and Flügel (2004); lithologic features concerning palaeoenvironmental parameters are described as follows.

3 | LITHOLOGICAL SUCCESSIONS OF THE UPPER ORDOVICIAN IN WELL YIHUANG 1

3.1 | Miaopo Formation

The Miaopo Formation dominated by dark shelly-rich shales interlaminated by limestone lenses could be assigned to the *Pycodus serra*, *Pycodus anserinus* and *Baltoniodus alobatus* conodont biozones or upper '*Hestedograptus teretiusculus*' and *Nemagraptus gracilis* graptolitic biozones in ascending order, nevertheless, its main parts are of early Sandbian age (An, 1987; X. Chen, Bergstrom, Zhang, Goldman, & Chen, 2011; Ding, Chen, Zhang, Cao, & Bao, 1993; Z. H. Wang, Bergstrom, & Lane, 1996; Z. H. Wang, Bergstrom, Ma, Song, & Zhang, 2015; X. F. Wang, Ni, & Zhou, 1980; Zeng et al., 1983). This formation is 1.98 m thick (depth: 74.00–75.98 m) in Well Yihuang 1. Well-preserved trilobites, brachiopods, and cephalopods are generally abundant in shales, but graptolites are sparse. Limestone lenses within the shales are bioclastic wackestones with fragments of trilobites, gastropods, crinoids, ostracods, and brachiopods (Figure 3). Shelly fragments of the lower formation is poorly-sorted, some trilobite and brachiopod shells are more than 0.8 mm in length (Figure 3a,b). Bioclastic material from the middle and upper part of the formation are moderately-sorted and finer in grain-sizes (Figure 3c–e); some gastropod shells are very thin and therefore easily broken (Figure 3a,c), probably indicating some transportation. Organic burrows (Figure 3d) indicate an oxygenated floor. X. Chen and Qiu (1986) suggested that shales of the Miaopo Formation have limited spatial distributions within intra-platform depressions of the Yangtze Platform surrounded by equivalent limestone of the Datianba Formation; Song et al. (2017) further outline a short-term and gentle transitional slope between the formations. *Foliomena* Fauna (brachiopod) from the Miaopo Formation in Yichang was considered as the indicator of marine-floor depth to be Benthic Assemblage 4, below storm wave-base (Rong, Zhan, & Harper, 1999).

3.2 | Pagoda Formation

The Pagoda Formation limestones with its characteristic shrinkage cracks of uncertain origin occupied almost the whole Yangtze epicontinental sea in a calm subtidal environment. Benthic macrofossils are not abundant, but nektonic nautiloids (some very large up to 1 m) are distinctive (Zeng et al., 1987). The formation could be subdivided stratigraphically using conodont biozones of the *Hamarodus europaeus* and *Protopanderodus insculptus* zones in ascending order correlated to middle Sandbian to early Katian age (An, 1982, 1987; X. Chen et al., 1995; X. Chen, Bergstrom, et al., 2011; Zeng et al., 1983; Zhan et al., 2016). The Pagoda Formation is 10.47 m thick (63.53 m to 74.00 m) at Well Yihuang 1, dominated by grey to greyish brown medium-thick-bedded limestones intercalated with thin-bedded nodular limestones, which are partly shown in the Figure 4.

Bioclastic content is variable, and most of the unit is composed of bioclastic wackestone (Figure 5a–d) interbedded with mudstones containing less bioclastic material (Figure 5e–f) yielding poorly-sorted and fine-medium sized fragments of trilobites, cephalopods, gastropod, brachiopods, ostracod, and crinoids; some shelly taxa in the micritic limestones are mostly broken and not identifiable. Burrows are sparse (Figure 5f).

Biotic evidence of nautiloids (J. Y. Chen, 1988), *Foliomena* fauna (Rong et al., 1999; Zhan & Jin, 2005) and trilobites (Z. Q. Zhou, Zhou, & Xiang, 2016; Z. Zhou et al., 2016) together with lithological features of micritic-dominated facies without sedimentary structures formed in a turbulent shallow belt (Zhan et al., 2016), suggests the depth of the sedimentary basin was likely more than 100 m.

3.3 | Linhsiang Formation

The *Protopanderodus insculptus* conodont Biozone and presence of *Nankinolithus* (trilobite) indicates Linhsiang Formation to be the late Katian (X. Chen et al., 1995; Chen, Bergstrom, et al., 2011; Zeng et al.,

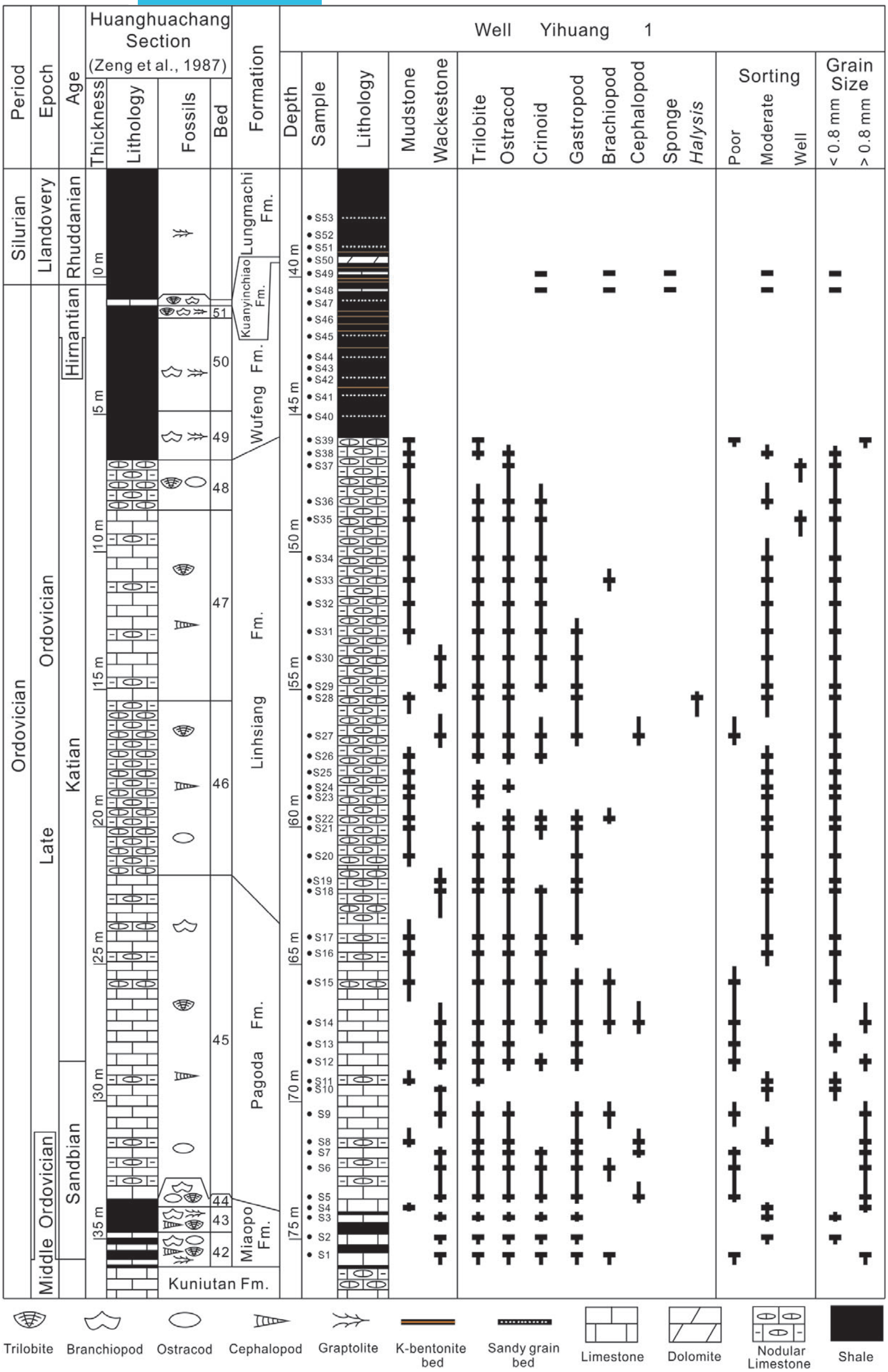

FIGURE 2 Litho- and biofacies logs of the Well Yihuang 1 and nearby Huanghuachang section. Bioclast data are presence/absence records of these fossils. Types of limestones are shown in Figures 3 and 5–8, respectively. The small hyphens mean horizontal occurrences of the lithological contains; and the vertical lines mean contine occurrences of same lithological, biotical, and taphonomic features. Fm., formation

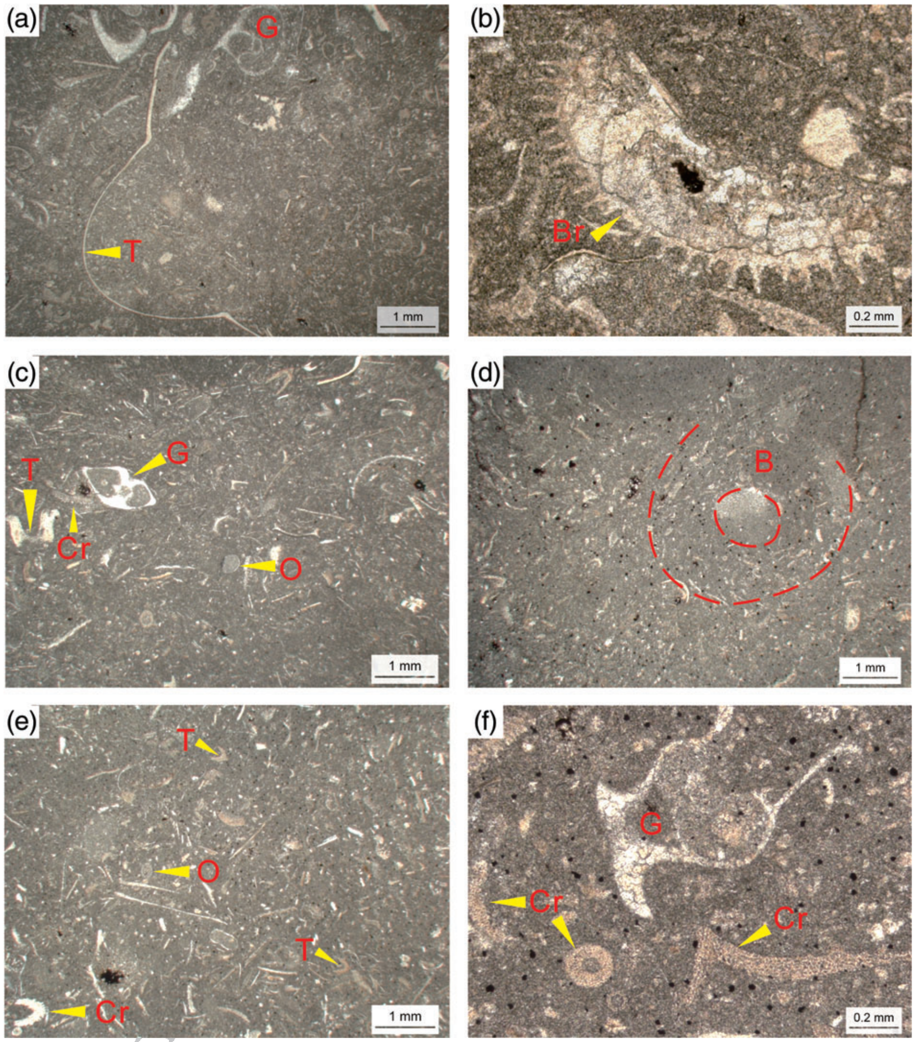

FIGURE 3 Bioclastic wackestones of the Miaopo Formation at Well Yihuang 1 (sampling horizons shown in the Figure 2). (a,b) Sample No. S1. (c,d) Sample No. S2. (e,f) Sample No. S3. Letters inside photos: B, burrow; Br, brachiopod; Cr, crinoid; G, gastropod; O; ostracod; T, trilobite

1983; Z. Q. Zhou et al., 2016; Z. Q. Zhou, Zhou, & Yuan, 2005). The Linhsiang Formation is 17.75 m thick in the well (depth: 39.42–63.53 m). Its lower part is mainly of greyish brown nodular limestones intercalated with thin-bedded limestones, and the middle and upper part are grey in color and rich in nodular limestones (Figure 4). Trilobites, cephalopods, and crinoid bioclasts are in the drill cores. Bioclastic wackestones occur from the lower formation, mudstones become dominant upward (Figure 2). Taphonomically, fine and moderately-sorted fragments of trilobites, gastropods, ostracods, crinoids, cephalopods, brachiopods, *Halysis* (calcareous algae), and small burrows are quite rare (Figure 6). Compared to the Pagoda Formation below, more frequent occurrence of mudstones with little bioclastic debris are typical in the Linhsiang Formation; gastropods essentially decline from the upper Linhsiang Formation indicating an initial episode excluding inhabitation of benthic fauna.

3.4 | Wufeng Formation

Condensed, stagnant and dysoxic sedimentation of the graptolitic black shales of the Wufeng Formation was common in the outer-shelf belt of the Yangtze epicontinental sea unfavorable for carbonate deposition (X. Chen et al., 1999, 2004; X. Chen, Xiao, & Chen, 1987). Wilde and Berry (1984) suggested that a stagnant ocean implies strong density stratification and dysoxic marine floor; such a hypothesis was further available for the oceanographic pattern of the Yangtze epicontinental sea where dysoxic and increasing salinity of the deeper water largely excluded inhabitations of benthic fauna during this time-interval (Cheng & Wang, 1991). The formation is subdivided into the *Dicellograptus complanatus*, *Dicellograptus complexus*, *Tangyagraptus typicus-Paraorthograptus pacificus*, *Diceratograptus mirus*, and *Normalograptus extraordinarius* graptolitic biozones in ascending order with time-interval from late Katian to early Hirnantian in age (X. Chen et al., 1995, 2000, 2006; X. Chen, Rong, & Zhou, 2003; Mu, 1954; Mu et al., 1993; X. F. Wang et al., 1983). The Wufeng Formation is 6.36 m thick (depth: 39.42–45.78 m) in the Well Yihuang 1 core and almost completely dominated by graptolitic black shales intercalated with two limestone lenses and several sandy grains and K-bentonite beds. Sparse trilobites and brachiopods are found in the upper part. Sandy-grained quartz lenses are recognized in graptolitic black shales of the Wufeng Formation (Figure 7a). Ran et al. (2015) suggested that ball-like grains in the Wufeng Formation are radiolarians. However, no basic radiolarian morphology is recognized from these grains, instead they are poorly-sorted but well-rounded quartz grains. A packstone lens comprising fine-grained and highly broken bioclastic debris of crinoids, sponge spicules and brachiopods, with fine sand-size quartz, occurs interbedded with the graptolitic black shales from the middle of the formation (Figure 7b). The black shale of

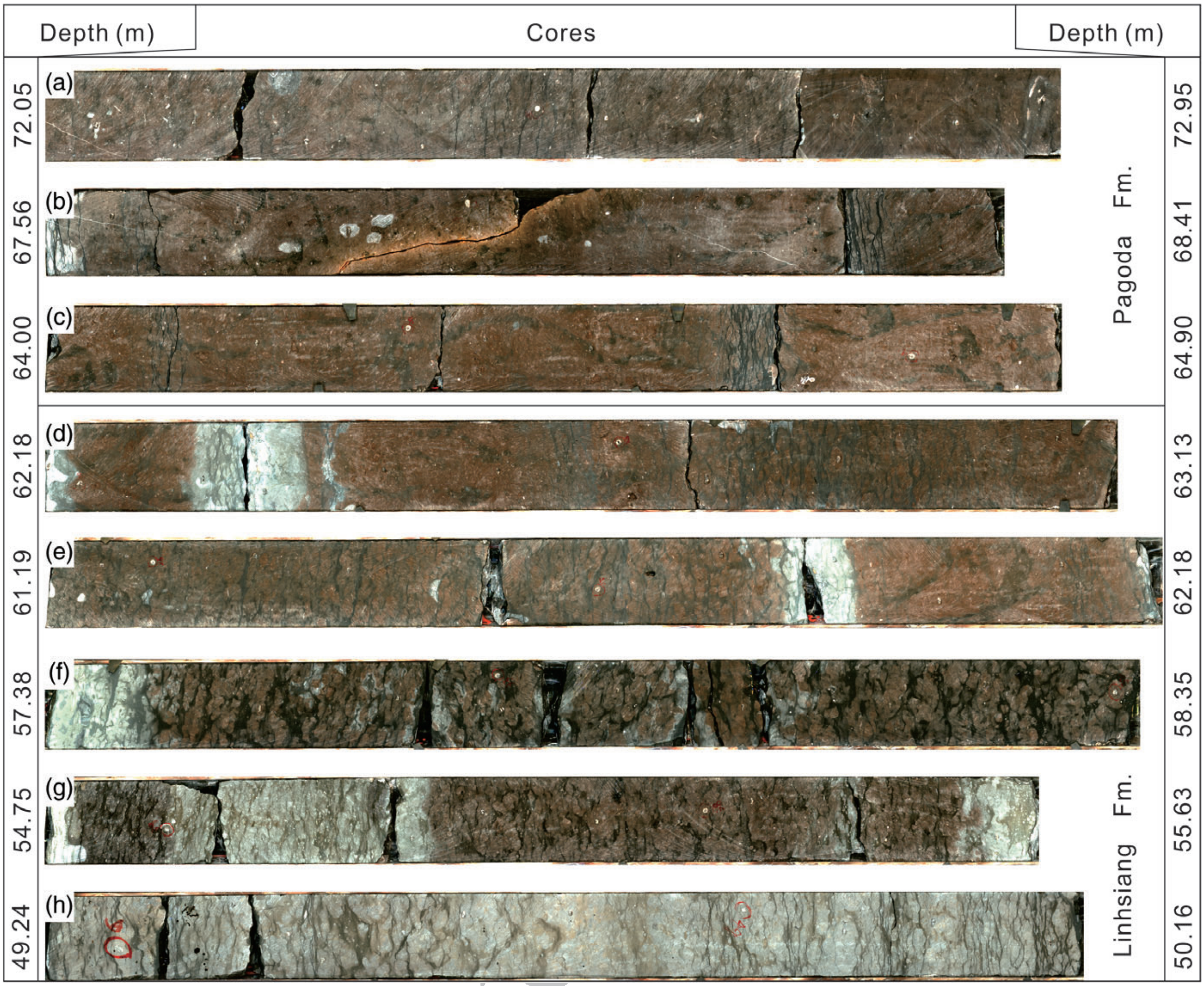

FIGURE 4 Nodular limestones of the Pagoda and Linhsiang Formations partly shown from cores of the Well Yihuang 1. Fm., formation

the Wufeng Formation was deposited in a dysoxic, stagnant and semi-closed environment (X. Chen, 1984; X. Chen et al., 1987; X. Chen & Qiu, 1986; Y. Liu et al., 2016; Mu et al., 1981; Rong & Chen, 1987; Yan, Chen, Wang, & Wang, 2012), and occurs in most parts of the Yangtze epicontinental sea (X. Chen et al., 2004). Coarse quartz and bioclastic debris within the lenses shown in the Figure 7 are likely of distal origin, derived by gravity flows and finally deposited in deep stagnant and dysoxic marine floor occasionally.

3.5 | Kuanyinchiao Formation

The Kuanyinchiao Formation, Hirnantian of the uppermost Ordovician in age, yields typical *Hirnantia* Fauna consisting of brachiopods and trilobites, matching the glacial peak of the Gondwana Continent (X. Chen, 1984; Rong, 1984; Rong & Harper, 1988; T. G. Zhang, Shen, Zhan, Shen, & Chen, 2009). Some outcrops of this unit in the Yichang District were described as yellow claystones since the carbonate rocks are intensively weathered (X. Chen et al., 2000; Mu & Rong, 1983; Zeng et al., 1987). The Kuanyinchiao Formation sections in Yichang area are generally rich in shelly *Hirnantia* Fauna fossils accumulated under a shallow but cool water environment (X. Chen et al., 2004, 2006; Fan et al., 2013; Gorjan, Kaiho, Fike, & Chen, 2012; J. B. Liu, Rong, & Chen, 2001; Rong, 1984; Rong & Chen, 1987; Rong et al., 2002; L. N. Zhang, Fan, & Chen, 2016)). The Kuanyinchiao Formation is 0.16 m thick (depth: 39.26–39.42 m) in the Well Yihuang 1 core dominantly composed of secondary recrystallized dolomites inserted by three calcareous marlstones with thin lamina but few in coarse bioclastics and not ideal for investigation of biotic structure (Figure 8).

The outcrop of the Kuanyinchiao Formation near the well is covered by modern construction nowadays. Wangjiawan, about 24 km north of the Well Yihuang 1, is a small village and well-known for the GSSP of the Hirnantian. We sampled fresh limestone of the Kuanyinchiao Formation from the Wangjiawan riverside section nearby the GSSP (location marked in Figure 1) for additional lithological description in the present paper. Development of the Hirnantia Fauna of the Kuanyinchiao Formation from the section does not exactly coincide with the biostratigraphic boundary of the Hirnantian, where the latter is defined by the FAD of the *N. extraordinarius* Biozone from the black shales of the Wufeng Formation.

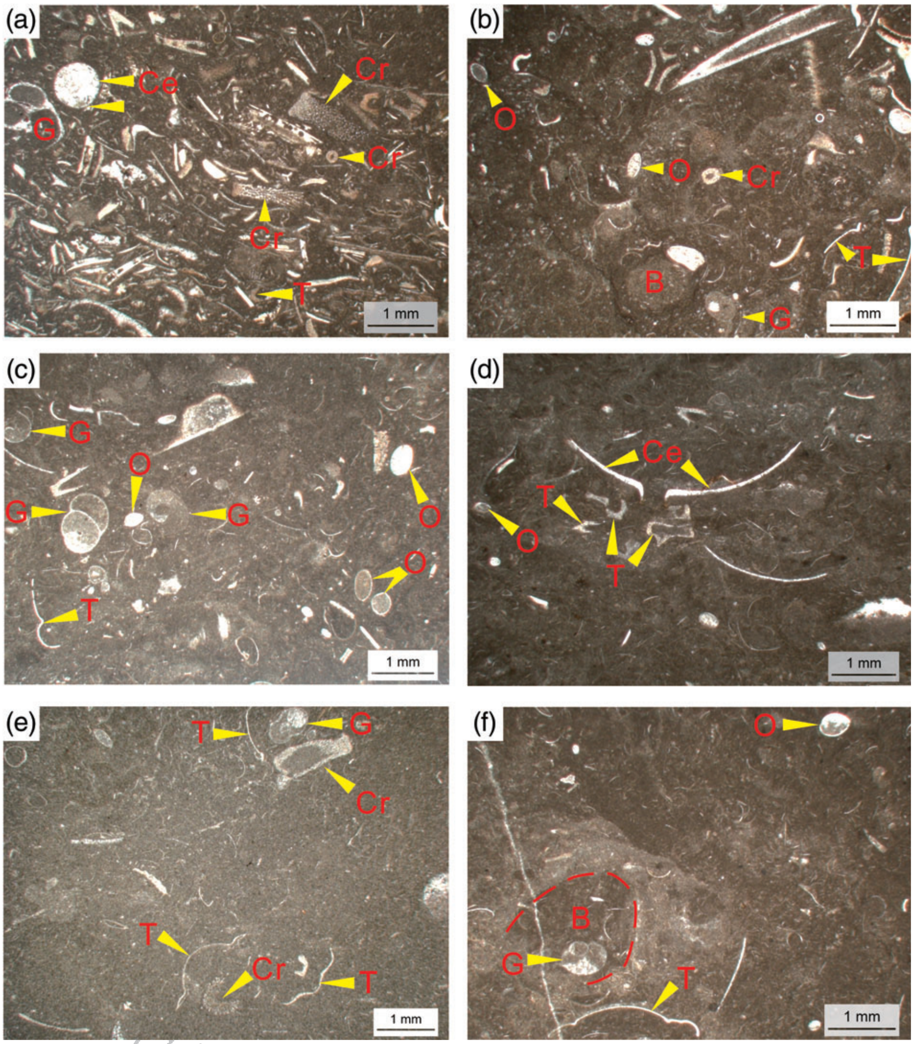

FIGURE 5 Microfacies of the Pagoda Formation at Well Yihuang 1 (sampling horizons shown in the Figure 2). (a) Bioclastic wackestone, Sample No. S5. (b) Bioclastic wackestone, Sample No. S7. (c) bioclastic wackestone, Sample No. S10. (d) Bioclastic wackestone, Sample No. S14. (e) Bioclastic mudstone, Sample No. S15. (f) Bioclastic mudstone, Sample No. S17. Letters inside photos: B, burrow; Ce, cephalopod; Cr, crinoid; G, gastropod; O; ostracod; T, trilobite

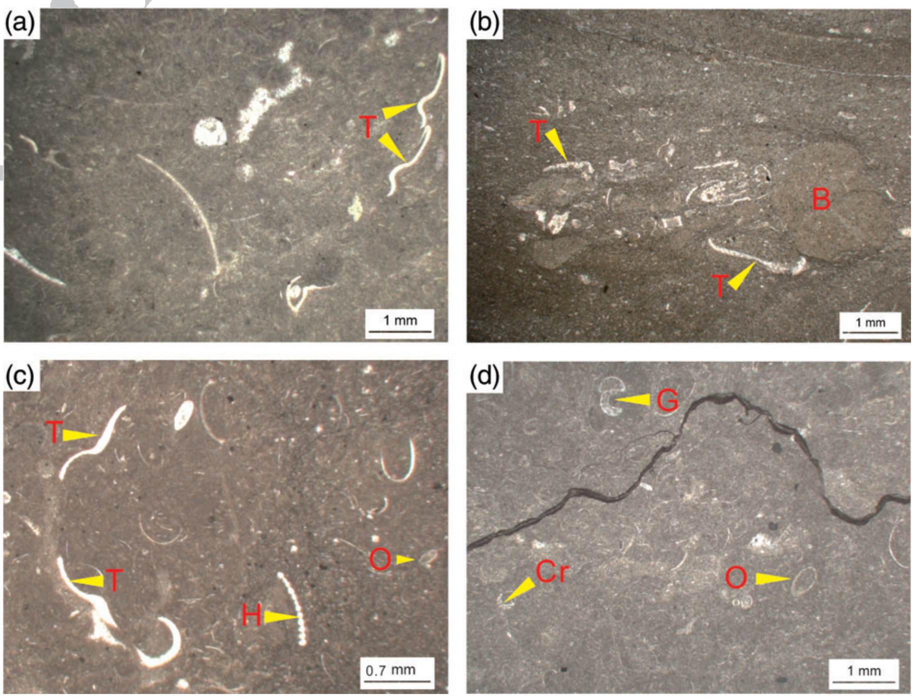

FIGURE 6 Microfacies of the Linhsiang Formation at Well Yihuang 1 (sampling horizons shown in the Figure 2). (a) Bioclastic wackestone, Sample No. S18. (b) Mudstone with sparse bioclasts and burrow, Sample No. S23. (c) Bioclastic mudstone, Sample No. S28. (d) Mudstone with sparse bioclasts, S31. Letters inside photos: B, burrow; Cr, crinoid; H, *Halysis*; G, gastropod; O; ostracod; T, trilobite

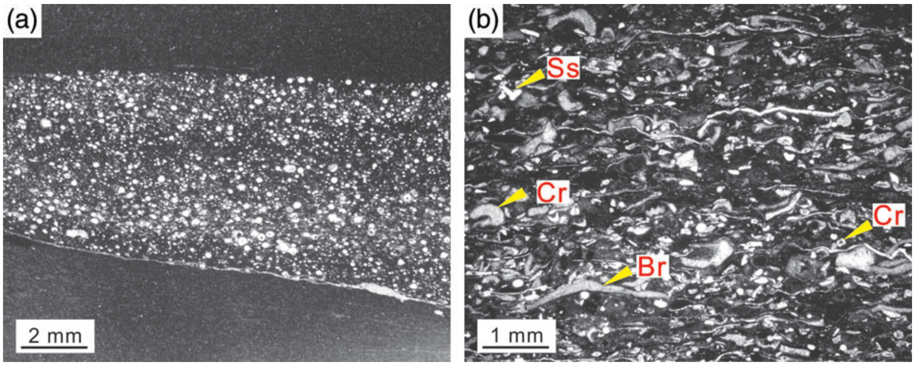

FIGURE 7 Microfacies of the Wufeng Formation at Well Yihuang 1. (a) Quartz grain lens in black shale, Wufeng Formation, S42. (b) Bioclastic packstone, Wufeng Formation, S49. Letters inside photos: Br, brachiopod; Cr, crinoid; Ss, sponge spicule

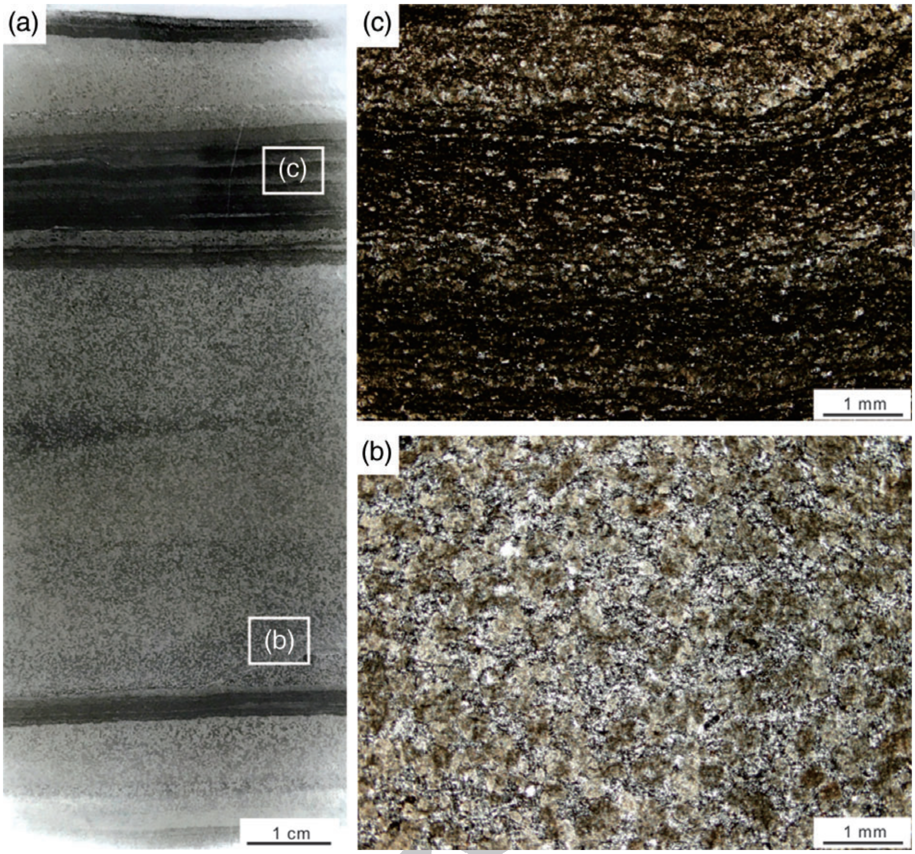

FIGURE 8 Microfacies of the Kuanyinchiao Formation at Well Yihuang 1. (a) Polished slab of the core with sampling horizon of the photo (b) and (c). (b) dolomite. (c) Calcareous marlstone

The Kuanyinchiao Formation at the Wangjiawan riverside section is 0.27 m thick. Biotic elements in packstones are rich in brachiopod fragments, typical benthic *Hirnantia* Fauna. Some burrows are indicators of benthic fauna actives (Figure 9a). Shelly components also include rich crinoid fragments, which are not reported in the literature (Figure 9b). Microfacies herein show that the oxygenated marine floor was suitable for a well-developed metazoan fauna.

4 | DISCUSSION

Microfacies profiles of the bioclastic components in the present paper show higher biodiversity of fossils in the units. Some small-sized benthic biota of crinoids, gastropods, burrowing organisms, and rare *Halysis* (calcareous algae) of the Late Ordovician were present on the marine floor, though their taxonomic details are poorly known. Biodiversity change in the Upper Ordovician, concerning biotic events especially Hirnantian mass extinction episodes in the study area, was mostly documented from macro- and microfossils which are important for systematic paleontology. Nautiloid depth zonation (J. Chen, 1988), trilobite assemblages (Z. Q. Zhou et al., 2005; Z. Q. Zhou et al., 2016; Z. Y. Zhou, Zhou, Yuan, & Zhou, 2000) and brachiopod fauna (*Foliomena*) (Y. Liang, Zhan, & Jin, 2014; Rong et al., 1999; Rong & Zhan, 1995, 1996; Zhan & Jin, 2005; Zhan, Wang, & Wu, 2010) recognized from limestones of the Miaopo, Pagoda, and Linhsiang Formations are paleoecological evidence of marine depth below storm wave-base.

Ordovician seas were mainly of gentle latitudinal and vertical gradients, sluggish oligotrophic conditions thus weak in ocean circulation (Martin, 1995, 1996). The gentle vertical gradients and sluggish marine-floor circulation in Martin's oceanographic model are consistent with the present lithofacies from the Sandbian to lower Hirnantian (from the Miaopo Formation to the top of the Wufeng Formation) from a calm and less biotic production of the marine floor in the outer-shelf of the Yangtze epicontinental sea. Small-sized and

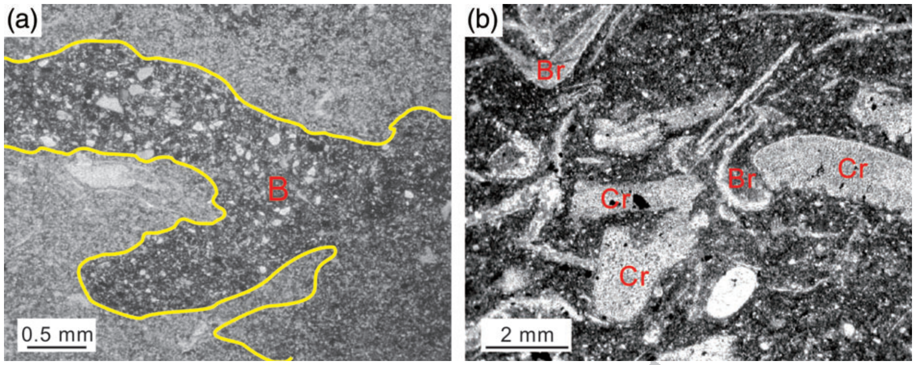

FIGURE 9 Microfacies of the Kuanyinchiao Formation at Wangjiawan riverside section. (a) Branch-shaped burrow filled by quartz grains within bioclastic mudstone. (b) Wackestone with coarse crinoid (Cr) and brachiopod (Br) fragments

strongly broken fragments of benthic elements of trilobites, cephalopods, gastropods, ostracods, crinoids, and rare brachiopods and bivalve indicate the oxygenation of sea bottom; nevertheless they are altogether low in abundance in wackestones and mudstones. Lack of intraclasts indicates that there was no early lithification or no submarine erosion. Thus, both matrix-supported lithoficies and grain component represent a low rate of carbonate production. In the Late Ordovician time, typical warm-water taxa with potential for reef-building such as calcareous algae, bryozoa, corals and stromatoporoids occurred only in the near shoal belt of the South China Block (Y. Li, Kershaw, & Mu, 2004), matching the green house episode of the Boda Event (Boucot, Rong, Chen, & Scotese, 2003) but few recognized from the Yihuang 1 well further indicating a deeper outer-shelf belt unfavorable for reef-building. Oligotrophic conditions (Martin, 1995, 1996) possibly existed in the outer-shelf setting where there was less input of terrigenous debris. A dysoxic marine floor can be the reason for well-preserved graptolites in black shales of the Wufeng Formation. Thus poor ocean circulation was likely maintained until the early Hirnantian on the Yangzte epicontinental sea. Berry and Wilde (1978) and Wilde (1991) suggested that a cooling event promoting ocean circulation of the Late Ordovician had already happened before the latest Ordovician glaciation. However, no dramatic change is shown in lithological sequences of Well Yihuang 1, so if there was active ocean circulation elsewhere, this did not interrupt poor deep water circulation during the depositional interval of the Wufeng Formation.

The total thickness of the Upper Ordovician in the Well Yihuang 1 is less than 40 m suggesting that the depositional rate of both shales and limestones was quite low and thus did not cause shallowing of the sea floor during this time. The global sea-level change pattern (Haq & Schutter, 2008) shows an overall transgression and then regression during the Late Ordovician from Sandbian to Katian. However, subsidence of the basement in the outer-shelf belt of the Yangtze epicontinental sea played a more significant role in creating deeper and low energy marine sediments dominated by lime mud. The oxygenated character of limestones of the upper Kuniutan Formation (uppermost Middle Ordovician) of Well Yihuang 1 implies an oxygenated and cool marine-floor depth below major wave-base (Yu, Li, & Mao, 2016). Compared to the Kuniutan Formation, Upper Ordovician limestones show a tendency of increasing lime mud and decreasing of bioclastic content. Less bioclastic components from the upper Linhsiang Formation possibly suggest a gradual transition towards a weaker hydrodynamic even stagnated and anoxic marine basin towards the dysoxic Wufeng Formation.

Shelly bioclastics wackestones and sandy grain beds interbedded with the black graptolitic shales of the Wufeng Formation suggest the existence of narrow shallow submarine highs for inhabitation of shelly fauna and intermittent water flow while most parts of the sea floor are dominated by a dysoxic environment (X. Chen et al., 1987, 1999, 2004). The Kwangsian Orogeny and expansion of the other landmasses played key roles in controlling distribution of land and sea. Former deep marine regions of the Jiangnan Slope and Zhujiang Basin from the Cambrian to early Late Ordovician were gradually shallowing upwards, with rapid deposition of coarser terrigenous clasts due to the active tectonic setting (X. Chen et al., 2012, 2014; Rong et al., 2003). However, coarser terrigenous clastics weathered from expanding lands did not immediately notably effect the condensed nature of sediment deposition in outer-shelf settings; marine-water maintained high clarity in the Late Ordovician, the evidence for which is in the abundant faunas. Lands surrounding the Yangtze epicontinental sea were important information of a semi-enclosed anoxic basin low in carbonate deposition, which excluded benthic biota during the graptolitic black shale episode of the Wufeng Formation in advance the peak of the Hirnantian glaciation. Regional narrow shallow submarine highs for inhabitation of shelly fauna existed closed to the Cathaysian Land (L. N. Zhang, Fan, Chen, & Wu, 2014), leading to input of bioclastics and quartz grains into the area where black shales had previously formed. Depositional rates increased later, in the late Aeronian (Llandovery of Silurian) Yangtze Uplift (X. Chen et al., 1996; Rong et al., 2003). Q11

5 | CONCLUSIONS

1. Lithological data through the Late Ordovician, from the Well Yihuang 1 and additional information from the Kuanyinchiao Formation at the Wangjiawan riverside section, are used to reconstruct the Late Ordovician seafloor scenario in the outer-shelf belt of the Yangtze epicontinental sea, and prominent close relationship between biotic profiles and environments.
2. A low-latitude, deep basin is consistent with sparse benthic biota and calcareous mud-dominated sediments, where low energy, cool conditions did not favor reef community development. Condensed sequences of the Miaopo, Pagoda, and Linhsiang Formations in core from Well Yihuang 1 are dominated by wackestones and mudstones, and bioclastic material became less common from the upper Linhsiang Formation upwards.

3. Formation of the dysoxic and stagnant environment of the Wufeng Formation was related to the gradual expansion of the Kwangsian Orogeny in aspects of the land-sea configuration. Ocean circulation was not as active during this time.
4. Subsidence of the basement herein is interpreted as a component in the upward deepening and development of the dysoxic sea-floor. Ocean circulation increased into the middle Hirnantian episode when glaciation peaked. Sea-level fall promoted development of the Hirnantia Fauna of the Kuanyinchiao Formation even in the Hirnantian cool episode.

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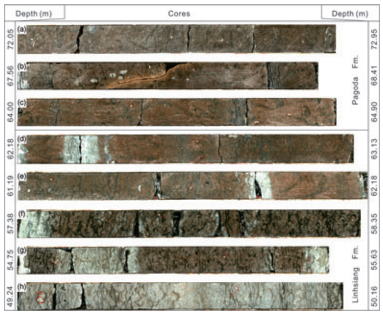
Graphical abstract

Upper Ordovician continuous lithological succession in outer-shelf facies, Yangtze Platform, South China: Facies changes and oceanographic reconstruction up to the Late Ordovician Hirnantian glaciation

Shenyang Yu, Qing Chen, Stephen Kershaw, Yue Li, and Chao Li



Late Ordovician sequences from the outer-shelf setting are available for reconstruction of the seafloor scenario in the Yangtze epicontinental sea of the South China Block. Microfacies of the limestones from Sandbian to middle Katian are dominated by wackestones and mudstones illustrating a deeper and calmer seafloor depth below major wave-base. Late Katian graptolitic black shales in the dysoxic basin excluded benthic biota. Such a bio- and lithofacies is related to the embayment pattern configured by tectonic uplifting, ocean circulation was not as active in advance of the Hirnantian glacial event