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Review

Stratigraphic refinement unveils high-resolution shallow marine biotic dynamics immediately preceding the Late Ordovician Mass Extinction in South China

Guang-Xu Wang and Ren-Bin Zhan **E-mails:** gxwang@nigpas.ac.cn; rbzhan@nigpas.ac.cn

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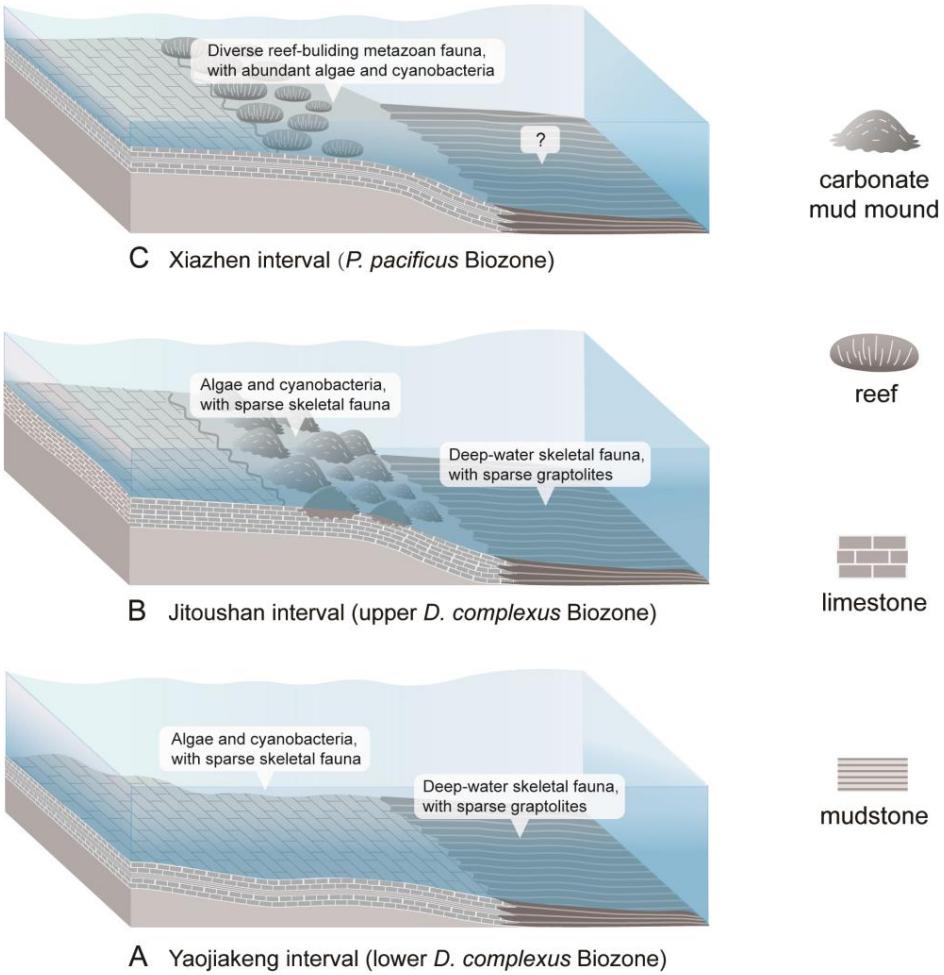
Graphical Abstract



Highlights:

- Refined Sanqushan Group clarifies Katian Zhe-Gan platform stratigraphy in South China.
- Xiazhen Formation redefined as upper Sanqushan, not a nearshore equivalent.
- Biozone correlation reveals shallow-marine biotic shifts before Ordovician extinction.

Stratigraphic refinement unveils high-resolution shallow marine biotic dynamics immediately preceding the Late Ordovician Mass Extinction in South China

Guang-Xu Wang[1] and Ren-Bin Zhan[1,2]

[1] State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing 210008, China

[2] University of Chinese Academy of Sciences, Beijing 100049, China

E-mails: gxwang@nigpas.ac.cn; rbzhan@nigpas.ac.cn.

Abstract: Exceptionally preserved Late Ordovician successions in South China offer a globally significant archive for investigating both the Great Ordovician Biodiversification Event (GOBE) and the Late Ordovician Mass Extinction (LOME). In contrast to the graptolitic facies that dominate much of the region, the late Katian carbonate deposits in the Jiangshan–Changshan–Yushan (JCY) area of East China (South China paleoplate), formerly referred to as the Sanqushan Formation (or its equivalents), are virtually the only strata in South China preserving diverse shallow marine biotas, providing rare ecological snapshots of the final biodiversity peak of the GOBE immediately preceding the LOME. Despite their importance, the lithostratigraphic framework and age constraints of these fossiliferous rocks remain debated. The prevailing view interprets the Xiazhen Formation as a nearshore equivalent of the Sanqushan Formation, with both units broadly assigned to a generalized late Katian age. Based on a critical review of integrated sedimentologic and paleontologic data, supplemented by new field observations, we support the interpretation that the Xiazhen Formation represents the upper portion of the 'Sanqushan Formation', and propose to elevate the latter to group rank to represent platform facies of this entire interval. The revised Sanqushan Group comprises, in ascending order, the Yaojiakeng, the Jitoushan, and the Xiazhen formations. The Yaojiakeng and the Jitoushan formations correlate more precisely with the *Dicellograptus complexus* Biozone, while the Xiazhen Formation aligns with the *Paraorthograptus pacificus* Biozone. This refined stratigraphic framework enables high-resolution reconstruction of biotic evolution prior to the LOME, offering new insights into regional ecological dynamics and their broader global significance.

Keywords: Katian stratigraphy; shallow-marine biotas; South China; Late Ordovician Mass Extinction

1. Introduction

The exceptionally preserved Late Ordovician successions in South China have established it as a globally significant region for investigating both the final episode of the Great Ordovician Biodiversification Event (Zhan *et al.* 2013; Harper *et al.* 2015; Deng *et al.* 2021) and the Late Ordovician Mass Extinction (Zhou *et al.* 2004; Wang *et al.* 2019; Rong *et al.* 2020), two major biotic events of the Early Paleozoic.

While the interior Yangtze Platform is characterized by the late Katian graptolitic black shales of the Wufeng Formation, carbonate-rich deposits bearing diverse shallow-water fossils are exclusively developed in the Jiangshan–Changshan–Yushan area of the Zhejiang-Jiangxi border region, East China (Figure 1) (Zhang *et al.* 2007, 2021; Chen *et al.* 2018; Rong *et al.* 2025). These rocks yield abundant and diverse fossil assemblages, such as brachiopods (Zhan and Cocks 1998; Xu and Li 2002; Zhan *et al.* 2002; Jin *et al.* 2006), corals (Lin and Chow 1977, 1986), sponges (Jeon *et al.* 2018, 2022*a*, *b*, *c*; Li *et al.* 2021), cephalopods (Lu *et al.* 1976; Lai 1980), bryozoans (Hu 1986; Zhang *et al.* 2018), trilobites (Zhou *et al.* 2004; Lee 2013), graptolites (Chen *et al.* 2016), calcareous algae (Bian and Zhou 1990; Chen *et al.* 1995), and calcified cyanobacteria (Bian and Zhou 1990; Wu *et al.* 2020), alongside reefs and carbonate mud mounds (Yu *et al.* 1992; Fang *et al.* 1993; Bian *et al.* 1996; Li 2004). This exceptional fossil record constitutes virtually the only evidence of shallow-marine ecosystems in South China, therefore offering crucial insights into the process and dynamics of both the GOBE and LOME within South China and across the globe.

Despite their significance, the lithostratigraphic framework and precise age assignments of these fossiliferous deposits remain highly debated. A central point of contention is whether the typical Xiazhen Formation represents a lateral equivalent of the entire Sanqushan Formation (Liang 1977; Chen *et al.* 1987; Zhan and Fu 1994; Zhang *et al.* 2021; Rong *et al.* 2025), or merely its upper portion (Bian and Zhou 1990; Yu *et al.* 1992; Lai and Lin 1993; Bian *et al.* 1996; Wang *et al.* 1996).

Besides, although these strata are now widely considered to be of late Katian age (Zhan and Fu 1994; Zhang *et al.* 2007, 2021; Rong *et al.* 2025), some authors proposed a significantly earlier age (*i.e.*, early–middle Katian) (An 1987; Zhen and Percival 2017; Li *et al.* 2020).

This study aims to investigate these long-standing uncertainties through the integration of refined lithostratigraphic and biostratigraphic data. By establishing a more precise temporal and spatial framework, we seek to reconstruct the evolutionary trajectory of shallow-water biotas leading up to the LOME, thereby enhancing our understanding of extinction dynamics in South China and their broader global implications. The term 'late Katian' is applied in the sense of Ka4 as defined by Bergström *et al.* (2009), spanning the *Dicellograptus complanatus* to the *Paraorthograptus pacificus* biozones.

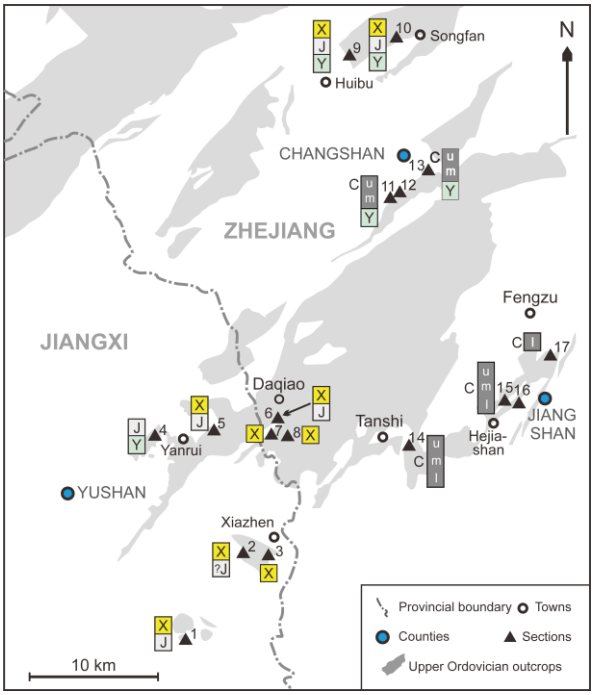


Figure 1. Map illustrating the distribution of the upper Katian Sanqushan Group and its more offshore equivalent, the Changwu Formation, in the JCY area, Zhejiang–Jiangxi border region, East China. 1, Zhuzhai; 2, Tashan; 3, Shiyanshan; 4, Jitoushan; 5, Wangjiaba (Dashanjiao); 6, Daqiao Cement Plant (Shiyang); 7, Shiyangwei; 8, Dianbian; 9, Huishandi; 10, Sanqushan; 11, Zhoutang (Highway 205); 12, Shikeng; 13, Putangkou; 14, Mulinlong; 15, Wujialong; 16, Pengli; 17, Shangwu. Abbreviations: C, Changwu Formation; J, Jitoushan Formation; l, lower; m, middle; u, upper; X, Xiazhen Formation; Y, Yaojiakeng Formation.

2. Previous studies on the Sanqushan Group

The traditional Sanqushan Formation is herein promoted to group rank (*i.e.*, the Sanqushan Group) to represent the late Katian carbonate succession in the JCY area. It is conformably underlain and overlain by the Huangnekang (basal upper Katian) and the Hongjiawu (uppermost Katian) formations, respectively (Wang *et al.* 2004; Zhang *et al.* 2007, 2021; Rong *et al.* 2025). These carbonates exhibit typical platform facies that laterally grade into the more offshore, siliciclastic-dominated deposits of the Changwu Formation on the Zhexi Slope (Lu *et al.* 1955; Zhang *et al.* 2007, 2021).

2.1. Previous lithostratigraphic classification

The lithostratigraphic classification of these carbonate rocks has undergone substantial modifications over time, with various nomenclatures applied to parts or the entirety of this stratigraphic interval (Figure 2). Historic designations include the Sanqushan Limestone (Sheng 1951), the Xiazhen Limestone and the Daqiao Limestone (Lu *et al.* 1976), the Jitoushan Limestone (Liang 1977; Rong and Chen 1987), and the Yaojiakeng Member (Lai and Lin 1993). Among these, the term "Daqiao Limestone" is now largely obsolete, as it is now considered synonymous with the more widely accepted Xiazhen and/or Sanqushan formations (Liang 1977; Lai and Lin 1993; Zhan and Fu 1994).

Two principal approaches have been employed to subdivide these strata. The first treats the typical Xiazhen Formation as a discrete lithostratigraphic unit, characterized by interbedded siliciclastic and carbonate deposits (Liang 1977; Chen *et al.* 1987; Rong and Chen 1987; Zhan and Fu 1994). This unit is interpreted as a more proximal, nearshore equivalent of the Sanqushan Formation, characterized by the development of carbonate mud mounds. Such a correlation scheme has gained widespread acceptance in subsequent regional studies (Zhang *et al.* 2007; Chen *et al.* 2018; Li *et al.* 2019; Park *et al.* 2021; Rong *et al.* 2025).

The second approach regards the Xiazhen Formation as the upper part of the Sanqushan Formation in the JCY area. Within this framework, two slightly different schemes were proposed during the 1990s, though neither of them was widely accepted. Bian and his colleagues (Bian and Zhou 1990; Yu *et al.* 1992; Bian *et al.* 1996) proposed a five-member subdivision (Members 1–5) for the Sanqushan Formation. Meanwhile, Lai and Lin (1993) introduced a formal three-member scheme, comprising the newly defined Yaojiakeng Member at the base, followed by the Jitoushan and the Xiazhen members as the middle and upper units, respectively. These three members broadly correspond to Member 1, Members 2–3, and Members 4–5 of Bian's framework (see Figure 2).

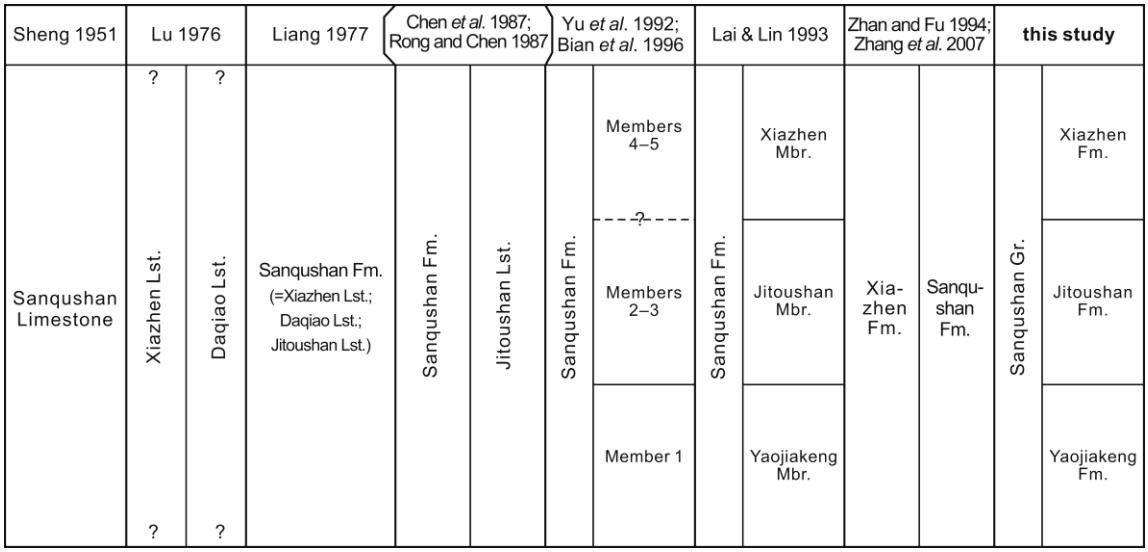


Figure 2. Historic overview of the lithostratigraphic classification of the late Katian carbonate succession assigned here to the Sanqushan Group in the JCY area, East China.

2.2. Previous age constraints

The Sanqushan Group, as revised herein, has traditionally been interpreted as late Katian in age. This assignment is primarily supported by the presence of the *Altaethyrella* brachiopod fauna (Zhan and Cocks 1998; Zhan *et al.* 2002), the corals *Agetolites* and *Sarcinula* (Lin 1960; Lin and Chow 1977, 1986), and rare graptolites (Chen *et al.* 2016), along with the notable absence of key elements of the terminal Ordovician *Hirnantia* Fauna (Chen *et al.* 1987; Zhan and Fu 1994; Zhan *et al.* 2002), as well as evidence from its underlying and overlain rocks (Chen *et al.* 1995; Zhang *et al.* 2021). This age interpretation is further corroborated by data from the presumed lateral equivalent, the Changwu Formation, where graptolites corresponding to the *Dicellograptus complexus* Biozone have been documented (Zhan and Fu 1994; Zhan and Cocks 1998; Zhan *et al.* 2002; Zhang *et al.* 2021).

However, conodonts recovered from the Sanqushan Group have been controversially interpreted as indicative of a significantly older, early–middle Katian age (An 1987; Zhen and Percival 2017; Li *et al.* 2020). A critical reevaluation of this line of evidence is presented below.

3. Revised lithostratigraphy

3.1. Definition of the Sanqushan Group

In this study, the distinctiveness of the tripartite subdivision of the Sanqushan Formation across the JCY area, as recognized by Lai and Lin (1993), is reaffirmed through a critical reassessment of both published and newly acquired data, as summarized below. Based on this reassessment, we propose to promote the Sanqushan Formation to group rank. The newly defined Sanqushan Group comprises, in ascending order, the Yaojiakeng, the Jitoushan, and the Xiazhen formations. These formations correspond respectively to the Yaojiakeng, the Jitoushan, and the Xiazhen members of the Sanqushan Formation defined by Lai and Lin (1993), with their definitions outlined below and in Table 1.

The Yaojiakeng Formation was originally proposed by Lai and Lin (1993) as the basal member of the Sanqushan Formation, with Huishandi, approximately 10 km north of Changshan County town, designated as the type section. At Huishandi, this formation comprises approximately 690 m of grey to dark grey banded argillaceous limestone, featuring large-scale slump structures particularly prominent near the base (Lai and Lin 1993; Lin 1993). It conformably overlies the greyish-green calcareous mudstone with limestone nodules of the Huangnekang Formation and is itself conformably overlain by thick-bedded to massive grey limestone of the Jitoushan Formation. Fossil content includes calcareous algae and calcified cyanobacteria, with rare occurrences of metazoan skeletal fossils (Bian and Zhou 1990; Lin 1993).

The Jitoushan Formation was originally derived from the "Jitoushan Limestone" exposed at Jitoushan, approximately 8 km northeast of Yushan County town (Liang 1977; Rong and Chen 1987). It was subsequently defined by Lai and Lin (1993) as the middle member of the Sanqushan Formation. This unit is characterized by grey thick-bedded to massive limestone with the development of carbonate mud mounds, and it occurs conformably between both the underlying Yaojiakeng and the overlying Xiazhen formations. Similar to the Yaojiakeng Formation, metazoan skeletal fossils are rare in this formation, but calcareous algae and calcified cyanobacteria are relatively abundant (Bian and Zhou 1990; Lin 1993). The formation is generally partially exposed in the area, except at Huishandi where it is fully exposed with a total thickness of 544 m (Lai and Lin 1993).

The Xiazhen Formation was originally termed the "Xiazhen Limestone" by Lu *et al.* (1976), with its type locality near Tashan, 1.5 km southwest of the Xiazhen

township, Yushan County. This is a mixed carbonate-siliciclastic interval characterized by the diverse skeletal fossils and reef structures (Lai and Lin 1993). In the JCY area, only two localities, namely Wangjiaba (Yushan) and Huishandi (Changshan), exhibit conformable contacts with both the underlying Jitoushan Formation and the overlying poorly fossiliferous mudstone and sandstone of the Hongjiawu Formation. The total thicknesses at these sites are 110 m and 290 m, respectively (see discussion below).

Table 1. Summary of the revised lithostratigraphy of the Sanqushan Group.

Formation	Type Locality	Typical Lithology and Fossils	Stratigraphic Contacts (JCY area)
Xiazhen Fm.	Tashan, Yushan	marls and mudstones containing diverse skeletal fauna	conformably bounded by the Jitoushan Fm. below and the Hongjiawu Fm. above
Jitoushan Fm.	Jitoushan, Yushan	thick-bedded to massive limestone with sparse skeletal fauna	conformably underlain by the Yaojiakeng Fm.
Yaojiakeng Fm.	Huishandi, Changshan	banded argillaceous limestone with sparse skeletal fauna	conformably underlain by the Huangnekang Fm.

3.2. Regional stratigraphy and correlation

Below, we critically reassess the published and newly acquired data on the Sanqushan Group and its coeval Changwu Formation across key stratigraphic sections in the JCY area, aiming to elucidate the spatial distribution, lithologic variation, and regional correlation of the group's three constituent formations (Figures 1 and 3).

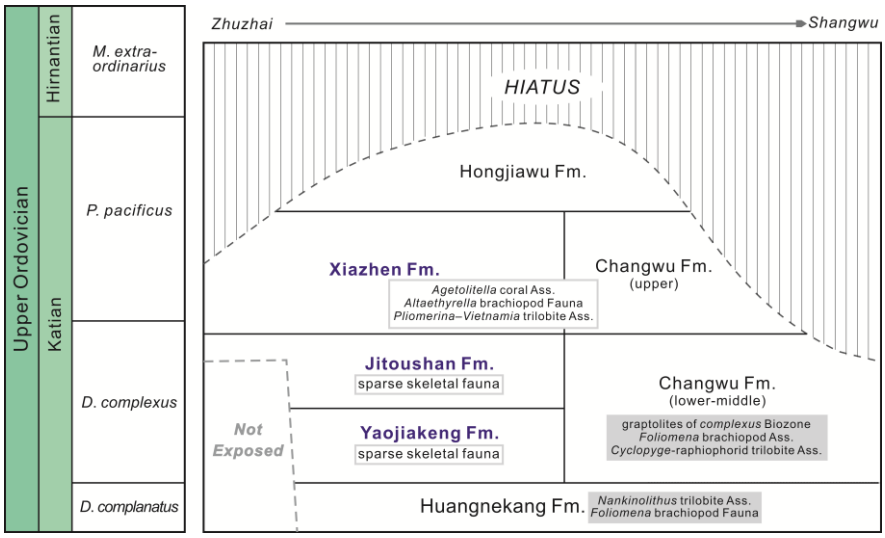


Figure 3. Refined stratigraphic framework of the upper Katian in the JCY area, East China. Chronostratigraphy and graptolite biozones are based on Goldman *et al.* (2020).

3.2.1. Zhuzhai, Yushan (Figure 1, Locality 1)

First described by Chen *et al.* (1987), the Zhuzhai section is located at Qianzhou Village, approximately 15 km southeast of Yushan County town. At this locality, the Sanqushan Group has an exposed thickness of about 185 m, with its base faulted against Jurassic strata and its top is disconformably overlain by Carboniferous rocks (Chen *et al.* 1987; Zhang *et al.* 2007).

Lee *et al.* (2012) identified four informal lithologic units within the group at this section: a lower limestone member, a lower shale member, a middle mixed-lithology member, and an upper shale member. The lower limestone member comprises approximately 75 m of fenestral structure-bearing limestone yielding rare metazoan skeletal fossils (Lee *et al.* 2012). A similar succession is also exposed at nearby Dongkengwu, about 5 km northeast of Zhuzhai (Park *et al.* 2015, 2017). It is therefore plausible that the lower limestone member represents the upper part of the Jitoushan Formation. Fossils and reefal structures from this interval have been documented in the literature (Kwon *et al.* 2012; Park *et al.* 2015, 2017). In contrast, the overlying three members exhibit lithologic features typical of the Xiazhen Formation and are more appropriately assigned to it, although Lee *et al.* (2012) noted that fossils from the lower shale member differ from those of the overlying middle mixed-lithology and upper shale members. Fossils documented from this formation include brachiopods (Zhan and Cocks 1998; Zhan and Li 1998; Xu and Li 2002; Zhan *et al.* 2002), corals (Deng 1986; Lin 1993; Sun *et al.* 2014, 2016, 2019; Liang *et al.* 2016), bryozoans (Hu 1986; Zhang *et al.* 2018), trilobites (Zhou *et al.* 2004; Lee 2013), calcareous algae (Bian and Zhou 1990), and sponges (Lin and Webby 1988; Lin 1993; Jeon *et al.* 2018, 2022*a*, *b*). Biostromes have also been reported from this interval (Li *et al.* 2004, 2015). In addition, Munnecke

et al. (2011) conducted chemostratigraphic analyses for the Sanqushan Group at this locality.

3.2.2. Tashan and Shiyanshan, Yushan (Figure 1, Localities 2, 3)

The Tashan section, designated as the type locality of the Xiazhen Limestone by Lu *et al*. (1976), is approximately 1.5 km southwest of Xiazhen township and about 16 km southeast of Yushan County town. The succession has a faulted contact with underlying yellow-brown sandstone of uncertain age, and a disconformable contact with overlying Carboniferous strata (Lin and Chow 1977; Lai and Lin 1993). The basal part comprises 16.45 m of grey, thick-bedded limestone (corresponding to the Bed 1 in Lin and Chow (1977), interpreted by Lai and Lin (1993) as the uppermost portion of the Jitoushan Formation, a reassignment that appears highly plausible. The overlying rocks belong to the typical Xiazhen Formation, consisting of about 227 m of marls and calcareous mudstones rich in skeletal fossils. At Shiyanshan, about 1 km southeast of Tashan, the stratigraphic succession is less complete, exposing solely the Xiazhen Formation, whose lower and upper contacts are covered (Lin and Chow 1977; Zhan and Fu 1994).

Fossils previously documented from these sites are exclusively derived from the Xiazhen Formation and include mainly brachiopods (Zhan and Cocks 1998; Zhan *et al.* 2002), corals (Lin and Chow 1977, 1986; Li and Gong 1996) and cephalopods (Lai 1980).

3.2.3. Jitoushan and Wangjiaba, Yushan (Figure 1, Localities 4, 5)

Located approximately 8 km northeast of Yushan County town, the Jitoushan section serves as the type locality of the Jitoushan Limestone (Liang 1977; Rong and Chen 1987). At this site, both the Yaojiakeng and the Jitoushan formations are exposed, although the base of the former and the top of the latter are covered by Quaternary deposits. The Yaojiakeng Formation is about 140 m thick, consisting mainly of grey limestone intercalated with argillaceous layers, while the Jitoushan Formation exceeds 150 m in thickness, and is dominated by grey thick-bedded to massive limestones (Lai and Lin 1993). Metazoan skeletal fossils from these formations are relatively rare. The Yaojiakeng Formation has produced a few brachiopods, including *Triplesia zhejiangensis*, *Altaethyrella zhejiangensis*, *Eospirigerina yulangensis*, and *Antizygospira liquanensis* (Zhan and Cocks 1998); the Jitoushan Formation has yielded limited corals and sponges (Lin 1993). In contrast, calcareous algae and calcified cyanobacteria are relatively abundant in both formations (Bian and Zhou 1990).

Approximately 4 km east of the Jitoushan section is Wangjiaba, also known as Dashanjiao. Here, around 60 m of thick-bedded to massive limestone belonging to the uppermost Jitoushan Formation is exposed. This unit is overlain by about 110 m of interbedded mudstone and calcareous limestone (corresponding to Beds 3–6 of Lai and Lin (1993)) interpreted herein as belonging to the Xiazhen Formation. Overlying the Xiazhen Formation is approximately 100 m of greyish-green sandstone and mudstone (corresponding to Bed 7 of Lai and Lin (1993)), which we attribute to the Member 1 of the Hongjiawu Formation defined by Wang *et al.* (2004). Fossils previously described from this locality are all from the Xiazhen Formation, including brachiopods (Zhan and Cocks 1998), stromatoporoid sponges (Lin and Webby 1988), and rugose and tabulate corals (Lin and Chow 1977; Li and Gong 1996). Patch reefs have also been studied from this interval at this site (Yu *et al.* 1992; Fang *et al.* 1993; Bian *et al.* 1996; Li 2004; Li *et al.* 2004).

3.2.4. Daqiao Cement plant, Shiyangwei and Dianbian, Jiangshan (Figure 1, Localities 6–8)

Located approximately 2 km south of Daqiao township and about 35 km northwest of Jiangshan County town, the Daqiao Cement Plant (or Shiyang) section serves as the type locality for the "Daqiao Limestone" as defined by Lu *et al*. (1976). At this site, the Jitoushan Formation exceeds 120 m in thickness and is predominantly composed of grey, thick-bedded to massive limestone. This unit is overlain by the Xiazhen Formation, which comprises roughly 80 m of marls and mudstones (Lai and Lin 1993). Both the base of the Jitoushan Formation and the top of the Xiazhen Formation are not exposed.

Situated approximately 1.4 km southwest and 1.0 km southeast of the Daqiao Cement Plant are Shiyangwei and Dianbian, respectively. At both sites, only the upper portion of the Xiazhen Formation is exposed, consisting of marls and mudstones. This unit is conformably overlain by the purplish-red and greyish-green sandstone and mudstone of the Hongjiawu Formation (Wang *et al.* 2004). Although Lai and Lin (1993) reported the presence of the Jitoushan Formation at Dianbian, our field investigations did not confirm this observation.

Fossils from the Jitoushan Formation at these sites are exclusively derived from the Daqiao Cement Plant section, where an agetolitid tabulate coral, *Agetolites grandiformis*, was described (Lai and Lin 1993). Additionally, cephalopods reported by Lu *et al*. (1976) were noted to originate from the "grey massive limestone interval" of the "Daqiao Limestone," confirming their stratigraphic assignment to the same unit. Fossils from the overlying Xiazhen Formation are derived from Dianbian and/or nearby Shiyangwei and include brachiopods (Zhan and Cocks 1998; Zhan *et al.* 2002), corals (Lin and Chow 1977), cephalopods (Lai 1980), and stromatoporoids (Lin and Webby 1988).

3.2.5. Sanqushan and Huishandi, Changshan (Figure 1, Localities 9, 10)

As noted by Zhan and Fu (1994) and Zhang *et al*. (2007), the type locality of the former Sanqushan Formation is Sanqushan, located in Songfan, approximately 10 km north

of Changshan County town. Prior to this clarification, Huishandi, just a few kilometers west of Sanqushan, had long been mistakenly regarded as the type locality of the Sanqushan Formation and was extensively studied (Qian 1987; Bian *et al.* 1996; Lai and Lin 1993; Yu 1996; Zhang *et al.* 2007).

At Huishandi, the Sanqushan Group is conformably underlain by the Huangnekang Formation and overlain by the Hongjiawu Formation (Wang *et al.* 2004; Zhang *et al.* 2007). The Yaojiakeng Formation is about 690 m thick, consisting of dark grey to grey limestone interbedded with argillaceous bands. The overlying Jitoushan Formation is 544 m thick, composed of thick-bedded to massive bioclastic limestone. The Xiazhen Formation is about 290 m thick, comprising nodular limestone interbedded with shale rich in skeletal fossils, including corals, bryozoans, brachiopods, and stromatoporoids. Notably, the Xiazhen Formation at these localities includes nearly 300 m of reefal limestone, exhibiting a more carbonate-rich succession than that observed at its type area in Xiazhen.

Fossils documented from the Yaojiakeng and the Jitoushan formations at these localities include calcareous algae (Bian and Zhou 1990), while the Xiazhen Formation has yielded corals (Lin and Chow 1977; Li and Gong 1996) and calcareous algae (Bian and Zhou 1990; Chen *et al.* 1995). Although the exact horizon of trilobites reported by Zhou *et al.* (2004) was not specified, they were likely found from the Xiazhen Formation, given their close resemblance to the specimens from Zhuzhai. Stromatoporoids described from Huishandi (Jeon *et al.* 2022c) are also probably from this formation. In addition, chemostratigraphic analyses have been conducted at Sanqushan of Songfan, Changshan (Munnecke *et al.* 2011).

3.2.6. Zhoutang, Shikeng and Putangkou, Changshan (Figure 1, Localities 11–13)

The Zhoutang section, also known as the Highway 205 section (Zhang *et al.* 2007), is approximately 4 km south of Changshan County town and about 2 km east of the Huangnitang section, which is the GSSP for the base of the Darriwilian (upper Middle Ordovician). Detailed descriptions of this section are available in the literature (Zhang *et al.* 2007; Li *et al.* 2018, 2019).

At this locality, the lower part of the Sanqushan Group (*i.e.*, the Yaojiakeng Formation) conformably overlies the purple-red Huangnekang Formation. The Yaojiakeng Formation is approximately 73 m thick and consists mainly of thin-bedded limestone intercalated with argillaceous layers, accompanied by large-scale slump structures. Overlying the Yaojiakeng Formation are siliciclastic-dominated deposits, interpreted here as representing the middle part of the Changwu Formation, which is likely correlated with the Jitoushan Formation. These deposits consist of a lower interval of purple-red limestone nodules and greyish-green shales, and an upper interval of approximately 100 m of greenish-yellow silty mudstone, mudstone, and sandstone. This succession is unconformably overlain by the Jurassic strata. Sparse calcareous nodules within these deposits yield a limited assemblage of shelly skeletal fossils and graptolites, including brachiopods characteristic of the *Foliomena* Fauna (Zhan and Cocks 1998; Rong *et al.* 1999).

Approximately 2 km and 4 km northeast of the Zhoutang section are the Shikeng and Putangkou sections, respectively. Both expose stratigraphic successions similar to that of Zhoutang (Munnecke *et al.* 2011; Li *et al.* 2018, 2019) and are therefore not discussed further here.

Fossils from the upper Katian succession at these sites have been mentioned in the literature (Zhang *et al.* 2007; Li *et al.* 2018, 2019), though without formal descriptions.

3.2.7. Mulinlong, Wujialong, Pengli and Shangwu, Jiangshan (Figure 1, Localities 14–17)

The upper Katian strata at these localities are represented by the Changwu Formation, which rests conformably on the Huangnekang Formation and is disconformably overlain by Carboniferous strata at all sites (Zhan and Cocks 1998; Rong *et al.* 2010, 2025).

At Mulinlong (also known as Mulinnong), located 2.5 km east of Tanshi township and 10.6 km west of Jiangshan County town, the formation is exposed discontinuously, with an estimated thickness exceeding 400 m. The lower part comprises approximately 89 m of yellowish-green mudstone and shale (Lin and Chow 1977), yielding the deep-water *Foliomena* brachiopod fauna (Rong *et al.* 1999; Zhan *et al.* 2002). The remainder of the succession consists of siltstone and mudstone with minor limestone interbeds, yielding corals and brachiopods indicative of a shallower depositional environment (Zhan *et al.* 2002; Rong *et al.* 2010, 2025). A similar shallowing-upward trend is observed at Wujialong (alternatively referred to as Wujianong), approximately 3km west of Jiangshan County town, and at nearby Pengli, about 700 m east of Wujialong (Zhan *et al.* 2002; Rong *et al.* 2010). This pattern is further corroborated at several localities beyond the JCY area in western and northwestern Zhejiang, where the Changwu Formation is conformably overlain by the Hongjiawu/Wenchang Formation (uppermost Katian) (Rong *et al.* 2025).

At the type locality Shangwu, however, the Changwu Formation comprises 280 m of yellowish-green mudstone and siltstone, yielding the *Foliomena* brachiopod fauna, the *Cyclopyge*–raphiophorid trilobite association, and graptolites (Chen *et al.* 1995; Zhan *et al.* 2002; Zhou *et al.* 2004; Rong *et al.* 2010, 2025). The absence of shallower-water fauna at this site suggests that the upper part of the Changwu Formation is likely missing, probably removed by subsequent erosion.

4. Refined chronostratigraphy

As noted above, the Sanqushan Group has been assigned a late Katian age based on macrofossils (e.g., corals, brachiopods, and sparse graptolites), while conodont data have alternatively suggested an early–middle

Katian age. By integrating refined lithostratigraphic and biostratigraphic data, we present a more precise chronological framework for the constituent formations of this group. Additionally, previously applied conodont-based age interpretations are critically reassessed.

4.1. Age refinement of the Yaojiakeng and Jitoushan formations

Metazoan skeletal fossil records from the Yaojiakeng and the Jitoushan formations are relatively sparse, with the majority of identified taxa being long-ranging and thus offering limited biostratigraphic resolution. In the Yaojiakeng Formation, reported fossils include the brachiopods *Triplesia zhejiangensis*, *Altaethyrella zhejiangensis*, *Eospirigerina yulangensis*, *Antizygospira liquanensis*, *Ovalospira dichotoma* (Zhan and Cocks 1998), the corals *Plasmoporella* and *Palaeophyllum* (Lin 1993), and the stromatoporoid *Cystostroma* (Lin 1993). Similarly, the Jitoushan Formation yields a limited assemblage of metazoan skeletal fossils, including corals and sponges (Lin and Chow 1977; Lin 1993). Calcareous algae (Bian and Zhou 1990; Chen *et al.* 1995) and calcified cyanobacteria (Bian and Zhou 1990; Wu *et al.* 2020) are also present in both formations, although they likewise lack biostratigraphic significance.

The refined age assignment of these formations to the *Dicellograptus complexus* Biozone is primarily based on their stratigraphic position between the underlying Huangnekang Formation (the *Dicellograptus complanatus* Biozone) and the overlying Xiazhen Formation (probably the *Paraorthograptus pacificus* Biozone). The Huangnekang Formation is dated by the presence of the trilobite *Nankinolithus* (Chen *et al.* 1995; Zhang *et al.* 2007) and further supported by conodont data from the underlying Yenwashan Formation, which preserves a succession of biozones from the Sandbian to middle Katian (*Pygodus anserinus* to *Hamarodus brevirameus*) (Wang *et al.* 2015). The age of the Xiazhen Formation is discussed in the following section.

4.2. Age of the Xiazhen Formation

The Xiazhen Formation is probably assigned to the *Paraorthograptus pacificus* Biozone of latest Katian age, based on reassessment of its coral and brachiopod assemblages, as well as graptolite data from the underlying strata (Figure 3).

The coral fauna is notably diverse, including genera such as *Palaeofavosites*, *Agetolitella*, and *Agetolitoides* (Yoh 1933; Yu 1960; Lin and Chow 1977, 1986; Wang and Cui 2025). *Agetolitella* is now recognized as temporally restricted to the *Paraorthograptus pacificus* Biozone (Wang and Cui 2025). This assemblage shows strong affinities with coral faunas from coeval strata in the Malachis Hill Formation (eastern Australia), the Ulkuntas Limestone (southern Kazakhstan), the Chashmankalon and the Archalyk members (South Tien Shan), and the unit O (northeastern Russia) (Koren and Sobolevskaya 2008; Popov and Cocks 2017; Wang *et al.* 2020; Ghobadi Pour *et al.* 2023; Kim *et al.* 2025).

Brachiopod assemblages from the Xiazhen Formation have been recognized as belonging to the famous *Altaethyrella* Fauna of late Katian age, with several distinct communities further distinguished (Zhan and Cocks 1998; Zhan *et al.* 2002). Notably, the genus *Deloprosopus* (Jin *et al.* 2006), previously identified as *Eoconchidium* or *Tcherskidium*, was first described from this formation and has since been reported from strata of *Paraorthograptus pacificus* Biozone in southern Kazakhstan and likely equivalent rocks in North Greenland (Jin *et al.* 2022, 2024). Closely related virgianid genera such as *Tcherskidium*, *Proconchidium*, and *Holorhynchus* also appear restricted to the latest Katian (Jin *et al.* 2022, 2024).

Additional support comes from graptolites found beneath skeletal faunas identical to those of the Xiazhen Formation in the JCY area, including *Normalograptus* species and *Rectograptus socialis* (Lapworth), indicative of the *Dicellograptus complexus* Biozone (Zhan and Fu 1994; Zhan and Cocks 1998).

Further biostratigraphic evidence includes the occurrence of the graptolite *Anticostia uniformis* in the upper part of the formation at Zhuzhai, spanning from the *Dicellograptus complanatus* to *Metabolograptus persculptus* biozones (Chen *et al.* 2016). Chitinozoans identified by Tang *et al.* (2023) from the top of the Xiazhen Formation include *Tanuchitina laurentiana*, previously known from an interval spanning the *Dicellograptus complexus* to *Metabolograptus extraordinarius* biozones in Laurentia (Soufiane and Achab 2000; Achab *et al.* 2013). This species has also been recorded from the lower Terekawat Formation in the Bachu area of Kalpin. Tang *et al.* (2023) suggested this level corresponds to the upper *Paraorthograptus pacificus* Biozone, although no associated graptolites have been found to confirm this interpretation.

4.3. Critical reassessment of conodont evidence

As previously noted, conodonts recovered from the Sanqushan Group were interpreted to indicate an early–middle Katian age (An 1987; Zhen and Percival 2017; Li *et al.* 2020). This interpretation is based primarily on specimens identified by An (1987) from Beds 1–5 in Lin and Chow (1977) at Tashan, which are now considered to correspond to the uppermost Jitoushan and the lower Xiazhen formations. Key taxa include *Yaoxianognathus yaoxianensis*, *Taoqupognathus blandus*, and *Belodina shiyangensis*, with the Pb element of *Y. yaoxianensis* later revised to *Y. neimengguensis* (Zhen and Percival 2017). Li *et al.* (2020) also reported elements of the conodont *Yaoxianognathus yaoxianensis* Zone in the upper Xiazhen Formation at Zhuzhai, although species-level information was not provided. Conodonts have additionally been listed from the Yaojiakeng Formation at Putangkou (Li *et al.* 2018), but detailed taxonomic descriptions remain unavailable.

However, these age assignments rely on conodont biozones established in North China and Australia, where upper Katian conodonts are largely missing (Wang *et al.* 2016; Zhen and Percival 2017), rather than on frameworks developed for South China. Importantly, several conodont taxa from the Sanqushan Group are now known to extend well into the upper Katian strata across South China. For instance, *Yaoxianognathus yaoxianensis*, previously regarded as a middle Katian index fossil, has been documented in the Tangtou Formation (*Dicellograptus complanatus* Biozone) of northern Jiangsu (Duan 1990; Chen *et al.* 1995), the Daduhe Formation (*Paraorthograptus pacificus* Biozone) of southwestern Sichuan and northeastern Yunnan (Chen *et al.* 2022), and the Shiyanhe Formation (upper Katian) of southwestern Henan (Jing *et al.* 2017), a region likely part of South China during the Ordovician (Rong *et al.* 2015).

In summary, these findings suggest that the previously inferred early–middle Katian age based on conodonts may no longer be valid. Further research is needed to reconcile these biostratigraphic inconsistencies and refine the conodont-based chronostratigraphy of the Sanqushan Group.

5. Revisiting the evolution of late Katian shallow-water biotas in the JCY area

The revised stratigraphic framework necessitates a re-evaluation of the evolutionary trajectory of shallow-water biotas on the Zhe-Gan Platform, which capture the final stage of GOBE-related diversification immediately preceding the LOME in South China (Zhan *et al.* 2013). This reassessment is detailed below and illustrated in Figure 4.

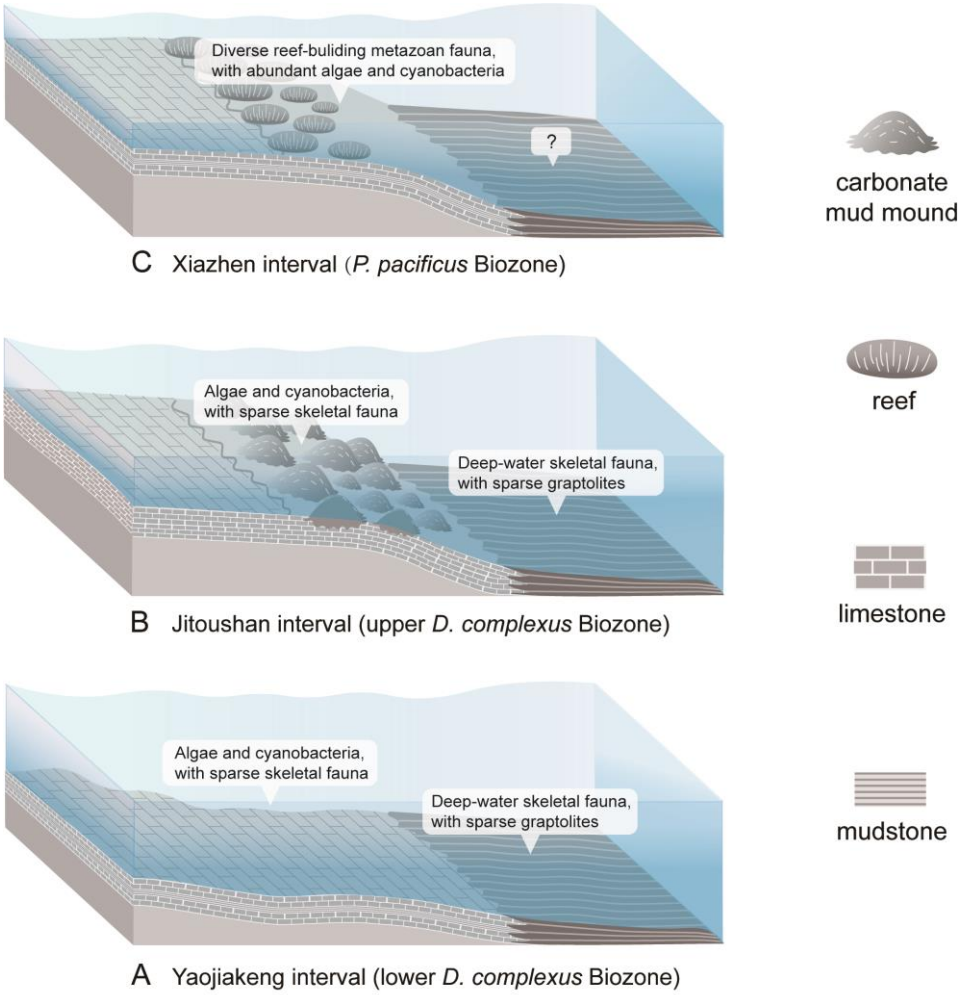


Figure 4. Diagrams depicting the evolutionary history of the late Katian biotas in the JCY area, East China.

5.1. Yaojiakeng interval (lower Dicellograptus complexus Biozone) (Figure 4A)

During this interval, the skeletal fauna was notably sparse, with only a few corals and brachiopods documented (Lin 1993; Zhan and Cocks 1998). Calcareous algae of this interval are represented by the *Coelosphaeridium cyclocrinophilum* community (Bian and Zhou 1990). In deeper slope settings, notably along the Zhexi Slope, however, typical deep-water skeletal fossils were present, including the *Foliomena* brachiopod fauna (Rong *et al.* 1999; Zhan *et al.* 2002) and the *Cyclopyge*–raphiophorid trilobite association (Zhou *et al.* 2004).

5.2. Jitoushan interval (upper Dicellograptus complexus Biozone) (Figure 4B)

The early phase of the Jitoushan interval was marked by the development of carbonate mud mounds. Within these environments, metazoan skeletal fossils (e.g., brachiopods, corals, and sponges) were extremely rare. In contrast, calcareous algae and calcified cyanobacteria were abundant, with the former represented by the *Phacelophyton yushanensis-Renalcis devonicus* community (Bian and Zhou 1990). During the later phase of this interval, skeletal fauna, calcareous algae and calcified cyanobacteria persisted but remained scarce (Bian and Zhou 1990), with only a few sponges recorded (Lin 1993).

On the Zhexi Slope, deep-water brachiopods and trilobites similar to those of the preceding interval continued to occur, though they were less abundant and diverse than before (Rong *et al.* 1999; Zhan *et al.* 2002; Zhou *et al.* 2004).

5.3. Xiazhen interval (Paraorthograptus pacificus Biozone) (Figure 4C)

This interval witnessed the development of widespread biostromes and patch reefs, indicating the flourishing of abundant and diverse reef-building skeletal organisms (Yu *et al.* 1992; Fang *et al.* 1993; Bian *et al.* 1996; Webby 2002; Li 2004; Li *et al.* 2004, 2015). These assemblages represent the final diversity acme of GOBE in South China immediately preceding the regional onset of the LOME.

Seven distinct brachiopod-dominated communities (*i.e.*, the *Kassinella*, the *Deloprosopus*, the *Altaethyrella*, the *Antizygospira–Sowerbyella*, the *Ovalospira*, the *Eospirifer*, and the *Ectenoglossa* communities) have been recognized, reflecting the flourishing of the shallow marine ecosystem and the dynamic sea-level fluctuations during this interval (Zhan and Cocks 1998; Zhan *et al.* 2002; Jin *et al.* 2006). Corals are attributed to the *Agetolitella* Association (Lin 1960; Lin and Chow 1977; Sun *et al.* 2014, 2016, 2019; Wang and Cui 2025). Trilobites belong to the shallow-water *Pliomerina-Vietnamia* Association (Zhou *et al.* 2004; Lee 2013). Calcareous algae are represented by the *Ajakmalajsoria rotunda* Community (Bian and Zhou 1990; Chen *et al.* 1995) and calcified cyanobacteria (Bian and Zhou 1990; Wu *et al.* 2020) thrived in these reefal environments. Also present are sponges (Lin and Webby 1988; Jeon *et al.* 2018, 2022*a*, *b*; Li *et al.* 2021), cephalopods (Lai 1980), and bryozoans (Hu 1986; Zhang *et al.* 2018), as well as rare graptolites (Chen *et al.* 2016).

6. Conclusion

This study, grounded in a rigorous integration of refined lithostratigraphic and biostratigraphic data, establishes a revised stratigraphic framework through formally elevating the Sanqushan Formation to group rank. The new framework comprises, in stratigraphic ascending order, the Yaojiakeng, the Jitoushan, and the Xiazhen formations. Moreover, the Yaojiakeng and the Jitoushan formations are precisely correlated with the *Dicellograptus complexus* Biozone, while the Xiazhen Formation roughly aligns with the *Paraorthograptus pacificus* Biozone. This high-resolution stratigraphy offers critical insights into the structure and dynamics of the final diversity acme of the GOBE in South China in marine ecosystems immediately preceding the LOME. It also provides a foundation for reinterpreting the processes and consequences of these major biotic events in the region.

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Authors' contribution

Conceptualization, investigation, writing—original draft preparation, writing—review and editing, funding acquisition, Guang-Xu Wang and Ren-Bin Zhan. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

Ren-Bin Zhan holds the position of Associate Editor for *Continent and Life Evolution* and has not peer reviewed or made any editorial decisions for this paper.

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