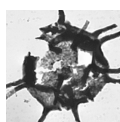


A Katian microphytoplankton assemblage from Wanhe, Yongshan County, northeastern Yunnan Province, South China: stratigraphy, paleogeography and paleoenvironment

KUI YAN, JUN LI & THOMAS SERVAIS



This study describes a Katian acritarch assemblage from the Wanhe section, northeastern Yunnan, South China, and discusses its biostratigraphic, paleogeographic, and paleoenvironmental implications. Thirty-eight samples were collected from the Zhenxiong, Lianfeng, Daduhe, and Lungmachi formations, with 11 yielding acritarchs from the upper Lianfeng and lower Daduhe formations. A total of 26 species assigned to 20 genera were identified, including 12 species in open nomenclature. Biostratigraphically, the assemblage is constrained to the late Katian (Ka4) based on co-occurring graptolite biozones (*Dicellograptus complanatus*, *D. complexus*) and zircon U-Pb dates (444.65–442.99 Ma) from K-bentonites. Key taxa such as *Baltisphaeridium aspersilumiferum*, and *Cheuletochroa homoia* confirm a Late Ordovician age, with some taxa (e.g., *Oppilata* sp.) suggesting Silurian affinities. Paleogeographically, the assemblage exhibits mixed affinities with Laurentian/Baltican (e.g., *Baltisphaeridium*, *Hoegkintia*) and Gondwanan/peri-Gondwanan (low diversity, limited *Navifusa*) assemblages, supporting close links between South China, North China, and Tarim during the Katian. In terms of paleoenvironment, the assemblage reflects a deep-water setting (BA4–BA5) with a shallowing trend from the Daduhe Formation to the Kuanyinchiao Bed. A late Katian transgression followed by a latest Katian–Hirnantian sea-level drop may have influenced acritarch distribution. The dominance of *Evittia remota*, a cosmopolitan taxon, aligns with the “equatorial cold-water tongue” model, linking its occurrence to Late Ordovician climate fluctuations. • Key words: acritarchs, Katian, Yunnan, South China, paleogeography, biostratigraphy.

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As the first of the “big five” mass extinction events in the Phanerozoic, the Late Ordovician mass extinction event (LOME) was linked to oceanic anoxia following volcanic or glacial events (Liu *et al.* 2022, Zhang *et al.* 2022). Although the duration of the LOME remains controversial, the beginning of this event may occur in the early Katian (e.g., Harper 2024). The evolution of the marine phytoplankton, represented by the acritarchs, remains relatively poorly known, compared to the earlier parts of the Ordovician.

Most Ordovician acritarch assemblages from China have also been documented from the Early–Middle Ordovician, in particular from South China, whereas Late Ordovician assemblages remain sparsely reported, with few reported acritarch assemblages from western

Zhejiang (He & Yin 1993, Yin & He 2000, Yan *et al.* 2011), southern Shaanxi (Fu 1986), and the Yichang area (Yan & Li 2007). Recently, Yin *et al.* (2023) described a Late Katian to Hirnantian acritarch assemblage from the Wufeng and Kuanyinchiao formations, related to the LOME in the Sichuan, Guizhou, and Yunnan provinces.

Here, we investigate the Wanhe section, from the northeastern part of the Yunnan province, that includes Upper Ordovician to lower Silurian strata. After the report by Tang *et al.* (2017), several fossil groups have been studied from the section, such as brachiopods (Rong & Huang 2019, Chen, D. *et al.* 2022), conodonts (Chen, Z.Y. *et al.* 2022), and sponges (Li *et al.* 2025). Other research was conducted in the frame of chronostratigraphy (Ling *et al.* 2019), geochemistry (Yang *et al.* 2020a, Liao *et al.*

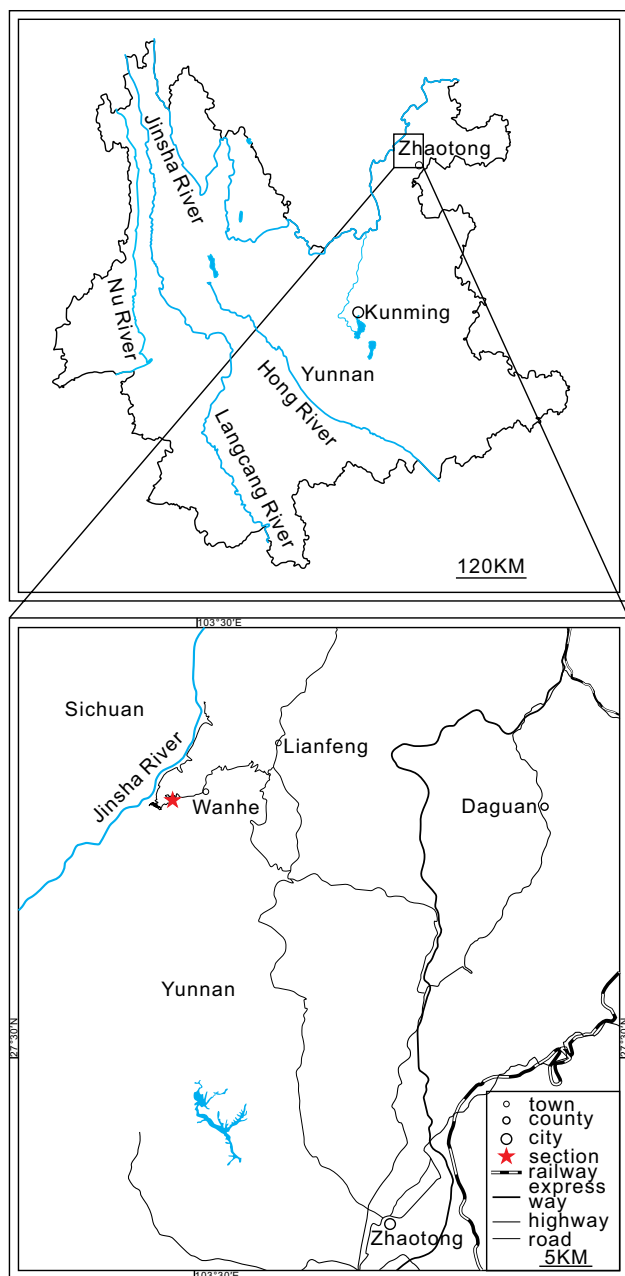


Figure 1. The location of the Wanhe section, Wanhe Village, Yongshan, Zhaotong, northeast Yunnan, China.

2025, Zhang *et al.* 2025a), the reconstruction of volcanic activity (Kong *et al.* 2025, Zhang *et al.* 2025b), environmental changes (Liao *et al.* 2025), as well as sedimentology, event stratigraphy, and carbon isotope chemostratigraphy (Yang *et al.* 2020b, Li 2021) and cyclostratigraphy (Zhong *et al.* 2020, Wang *et al.* 2025).

In this paper, we will describe the acritarch assemblage recovered from the Wanhe section, and discuss its biostratigraphic, environmental and paleogeographic implications.

Geological setting and lithostratigraphy

Northeastern Yunnan and southwestern Sichuan are considered to belong to the western margin of the Yangtze Platform in the Weiyuan-Hanyuan-Butuo-Zhenxiong region, and its Ordovician sediments represent a more offshore water environment (Wang *et al.* 2023). Kuo & Yeh (1942) first explored the Yongshan-Ludian-Qiaojia area and recognized the “Hungshihyen bed”, the “Chiaochia bed” and the “Taching limestone bed”. During the 1960s–1970s, the early Paleozoic stratigraphic frameworks in northeastern Yunnan and southern Sichuan were improved through geological exploration and mapping programs. In recent years, studies have focused on this area with a series of publications (*e.g.*, Tang *et al.* 2017; Ling *et al.* 2019; Liang *et al.* 2020, 2023; Wang *et al.* 2022a, b, 2023).

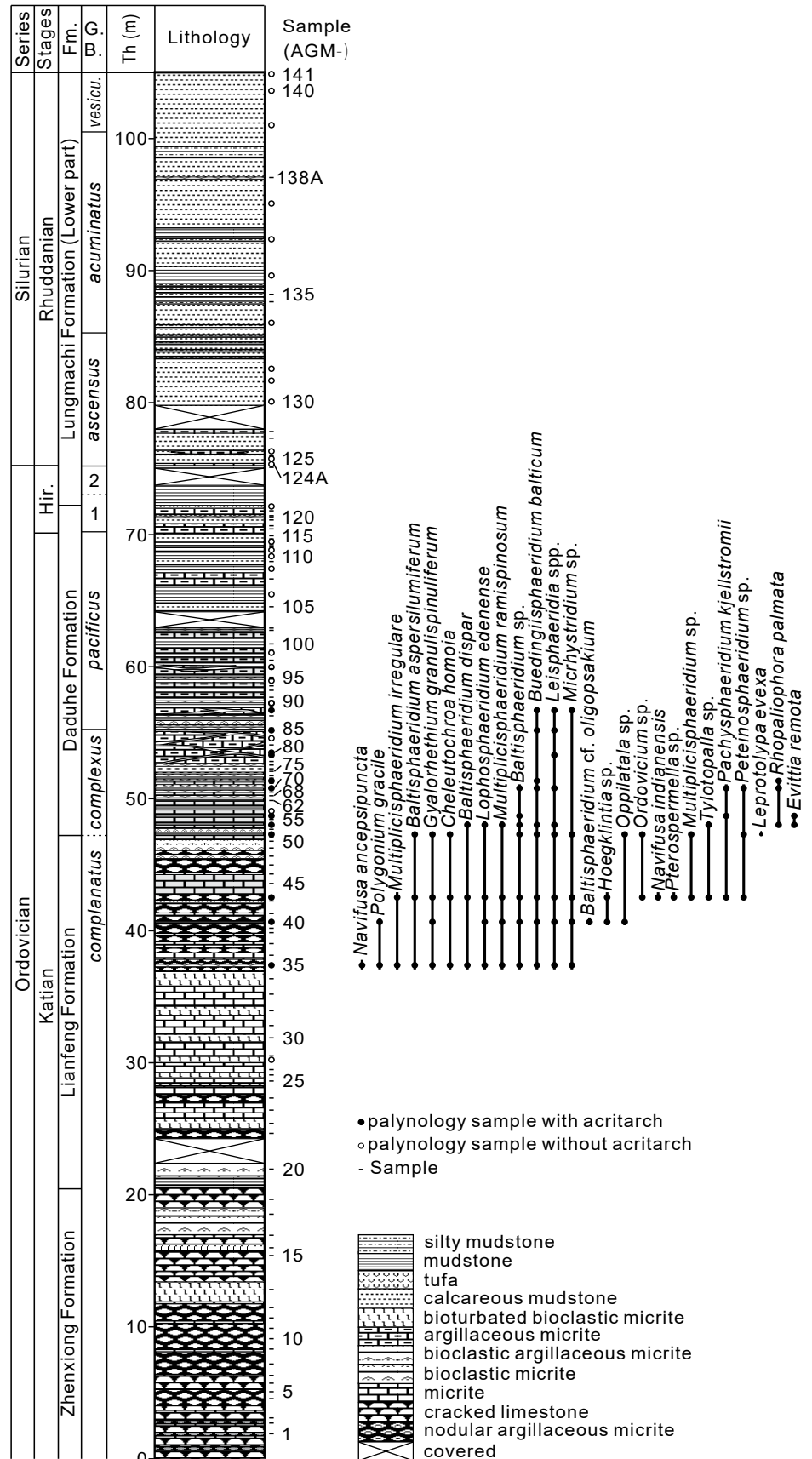
The Wanhe section was the object of comprehensive collections for fossils, geochemical, sedimentary, and stratigraphic studies by Rong and co-workers since 2012 (Tang *et al.* 2017, Chen, D. *et al.* 2022, Chen, Z.Y. *et al.* 2022, Liao *et al.* 2025, Li *et al.* 2025). It is also called the Lizhi section by Tang *et al.* (2017). The Wanhe section is a roadcut section located at Heping (Wanhe) Village of Lianfeng, Yongshan County, Zhaotong City, in northeastern Yunnan (Fig. 1). The section displays Late Ordovician and early Silurian rocks and the lithological succession in ascending order is composed of the Zhenxiong, Lianfeng, Daduhe formations, the Kuanyinchiao Bed, and the Lungmachi Formation (Fig. 2) (Tang *et al.* 2017, Wang *et al.* 2023).

The Zhenxiong Formation was established by Wang *et al.* (2022a) in Shangzhai, Zhenxiong County, and mainly contains limestones or dolomitic limestones. Abundant trace fossils and some long-ranging conodonts have been found in the formation. The Zhenxiong Formation can be correlated with the Pagoda and Taching formations in the other areas of South China, which refer to the early Katian (Wang *et al.* 2022a).

The overlying Lianfeng Formation was established by Wang *et al.* (2022b) in the Wanhe section, Yongshan County. The formation was formerly called the “Linhsiang Formation”. It is composed of dark-gray thin-bedded limestone and nodular argillaceous limestone with one bentonite layer. The Lianfeng Formation can be correlated with other formations with different lithofacies, such as the Linhsiang Formation. The Lianfeng Formation contains several fossil groups, including acritarchs, brachiopods, chitinozoans, conodonts, trace fossils, and trilobites, correlated with the *Dicellograptus complanatus* graptolite Biozone (Tang *et al.* 2017).

The next unit, the Daduhe Formation, was established by the Nanjing Institute of Geology and Paleontology and Sichuan Petroleum Bureau in 1965 (Gao *et al.* 2014) and

Figure 2. Stratigraphical column and acritarch distribution of the Wanhe section. Modified from Tang *et al.* (2017). Legend: 1 – *extraordinarius*; 2 – *persculptus*; Hir. – Hirnantian; *vesicu.* – *vesiculosus*.



subsequently described by Hu (1980) from Jiaodingshan, Hanyuan, Sichuan Province. Tang *et al.* (2017) reinvestigated the Daduhe Formation at the Wanhe section. The Daduhe Formation can be divided into two members: the lower member consists of medium-layered limestone interbedded with calcareous mudstone, and the upper member consists of thick-layered calcareous mudstone intercalated with thick-layered argillaceous limestone. The *Dicellograptus complexus*, *Paraorthograptus pacificus*, and *Metabolograptus extraordinarius* graptolite biozones have been recognized in the Wanhe section and indicate that the Daduhe Formation can be attributed to the late Katian to the early Hirnantian (Tang *et al.* 2017). Several beds of K-bentonite are also found in the Daduhe Formation, and 4 high-precision zircon U-Pb dates have been documented, indicating a late Katian age (Ling *et al.* 2019).

The overlying Hirnantian Kuanyinchiao Bed contains calcareous silty mudstone and middle-layered argillaceous micrite, bioclastic argillaceous micrite, and displays the typical *Hirnantia* Fauna (Tang *et al.* 2017).

The overlying Lungmachi Formation mainly contains gray calcareous mudstone with three layers of dark gray argillaceous micrite lenses, which are considered to be of latest Ordovician to Rhuddanian (Silurian) age (Tang *et al.* 2017).

Material and methods

Thirty-eight samples were collected from shale, mudstone, and siltstone of the Wanhe section, Yongshan, northeastern Yunnan, for palynological analysis (Fig. 2). Five were collected from the Lianfeng Formation, 20 from the Daduhe Formation, and 13 from the lower part of the Lungmachi Formation.

All samples were processed in the Laboratory of Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences, following standard palynological techniques. Fifty grams of each sample were prepared and crushed into soybean-sized pieces. All samples were processed with 10% HCl to remove carbonates, and then with 40% HF to remove silicates. After that, 37% HCl was used to remove CaF₂ in the residues by slightly boiling. The residues were neutralised in distilled water after each acid treatment. The residues were not oxidized or alkali-treated. They were sieved through a 15 µm mesh, and two slides were made for observation under the microscope. All slides were analyzed using a Zeiss Axioscope A1 optical microscope and photographed with a Zeiss Axiocam HRC image capture system. All slides are archived in the laboratory of microfossil paleontology, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences.

Results

The acritarch assemblage from the Wanhe Formation is moderately well-preserved, with specimens being transparent to dark brown in color, which is a preservation type that is comparable to other lower Paleozoic acritarch assemblages from South China. From a total of 38 samples, only 11 samples yielded acritarchs. These are from the upper part of the Lianfeng Formation and the lower part of the Daduhe Formation, from sample AGM 35 to AGM 87 (Fig. 2, Tab. 1). The moderate preservation of the acritarch assemblage from the Wanhe section does not allow the classification at the species level for all specimens. Twenty-six species assigned to 20 genera were identified, including 12 species (about 46% of all species) here classified in open nomenclature. Selected taxa are illustrated in Figs 3, 4. All identified species are listed in alphabetical order below:

- Baltisphaeridium aspersilumiferum* Loeblich & Tappan, 1978 (Fig. 3A)
- Baltisphaeridium dispar* (Turner, 1984) Uutela & Tynni, 1991 (Fig. 3C)
- Baltisphaeridium* cf. *oligopsakium* Loeblich & Tappan, 1978 (Fig. 3B)
- Baltisphaeridium* sp. (Fig. 3E)
- Buedingiisphaeridium balticum* Uutela & Tynni, 1991 (Fig. 3I)
- Cheleutochroa homoia* Turner, 1984 (Fig. 3H)
- Evittia remota* (Deunff, 1955) Lister, 1970 (Fig. 3D)
- Gyalorhethium granulispinuliferum* nomen nudum Delabroye *et al.*, 2011a (Fig. 3J)
- Hoegkintia* sp. (Fig. 3F)
- Leisphaeridia* spp. (Fig. 3K)
- Leprotolypa evexa* Colbath, 1979 (Fig. 3G)
- Lophosphaeridium edenense* Loeblich & Tappan, 1978 (Fig. 3L)
- Micrhystriidium* sp. (Fig. 3M)
- Multiplicisphaeridium irregulare* Staplin *et al.*, 1965 (Fig. 4A)
- Multiplicisphaeridium ramispinosum* Staplin, 1961 (Fig. 4B)
- Multiplicisphaeridium* sp. (Fig. 4C)
- Navifusa ancepsipuncta* Loeblich, 1970 ex Eisenack *et al.*, 1979 (Fig. 4F)
- Navifusa indianensis* Loeblich & Tappan, 1978 (Fig. 4G)
- Oppilatata* sp. (Fig. 4H)
- Ordovicium* sp. (Fig. 4I)
- Pachysphaeridium kjellstromii* Ribecai & Tongiorgi, 1999 (Fig. 4E)
- Peteinosphaeridium* sp. (Fig. 4J)
- Polygonium gracile* Vavrdová, 1966 (Fig. 4K)
- Pterospermella* sp. (Fig. 4L)

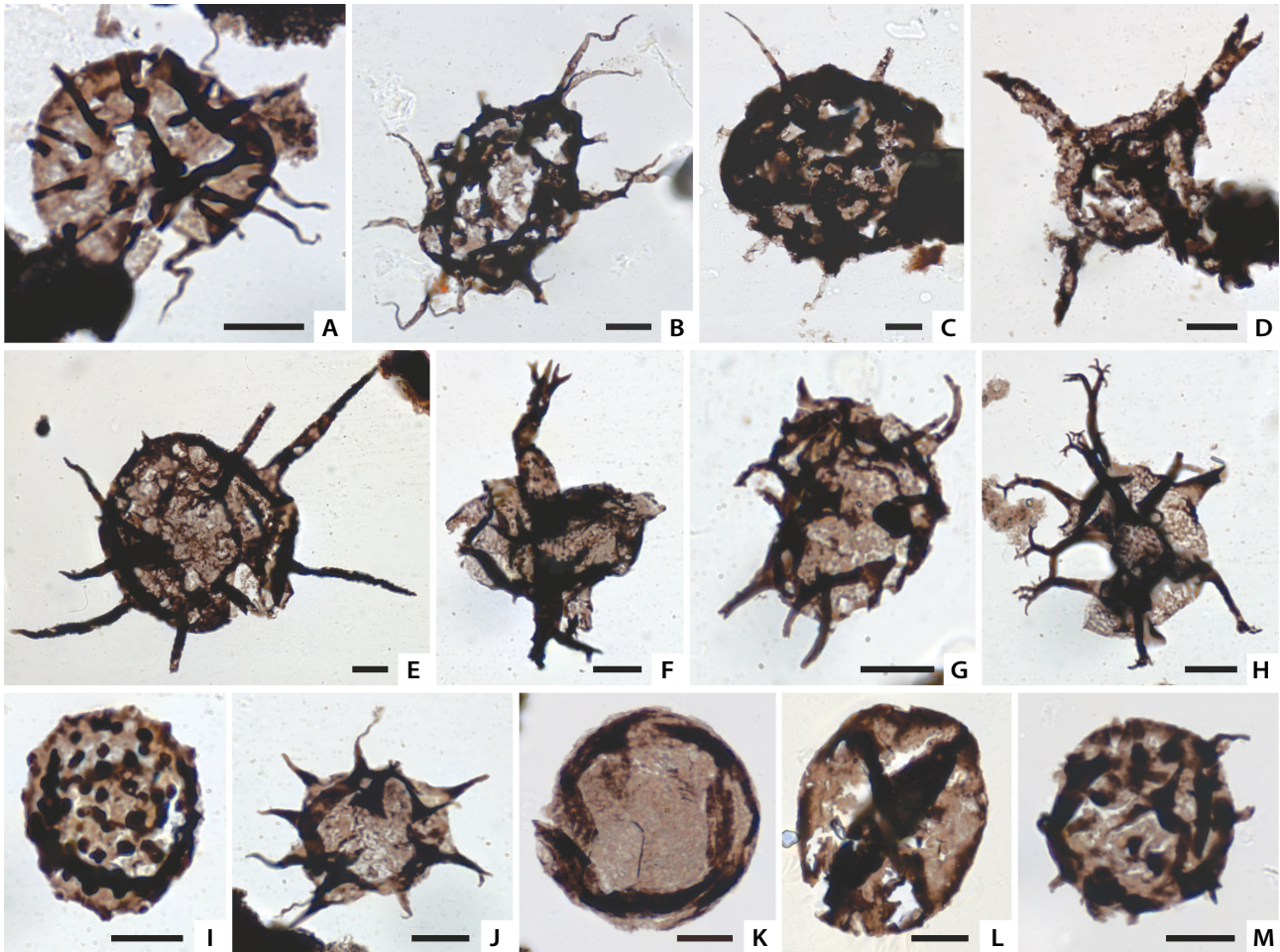


Figure 3. Acritarchs from the Wanhe section, South China. For each illustrated specimen, the following information is given: sample label, slide label, England Finder coordinates, and sample formation. For example, AGM35-1, K59/2, Lianfeng Formation refers to sample AGM35, slide 1, England Finder coordinates K59/2, collected from the Lianfeng Formation. • A – *Baltisphaeridium aspersilumiferum*, AGM35-1, K59/2, Lianfeng Formation. • B – *Baltisphaeridium* cf. *oligopsakium*, AGM41-1, H43, Lianfeng Formation. • C – *Baltisphaeridium dispar*, AGM44-1, D53/1, Lianfeng Formation. • D – *Evittia remota*, AGM54-2, M48, Daduhe Formation. • E – *Baltisphaeridium* sp., AGM52-2, L53/1, Daduhe Formation. • F – *Hoegklingia* sp., AGM44-1, J45/4, Lianfeng Formation. • G – *Leprotolypa evexa*, AGM52-1, M47/3, Daduhe Formation. • H – *Cheleutochroa homoia*, AGM35-1, Q59/4, Lianfeng Formation. • I. *Buedingiisphaeridium balticum*, AGM35-1, M46/4, Lianfeng Formation. • J – *Gyalorhethium granulispinuliferum*, AGM35-1, S50/2, Lianfeng Formation. • K – *Leisphaeridia* spp., AGM35-1, R47/3, Lianfeng Formation. • L – *Lophosphaeridium edenense*, AGM41-2, P57/3, Lianfeng Formation. • M – *Michrhystridium* sp., AGM35-2, E42/3, Lianfeng Formation. Scale bars = 10µm.

Rhopaliophora palmata (Combaz & Péniguel, 1972)
emend. Playford & Martin, 1984 (Fig. 4M)
Tylotopalla sp. (Fig. 4D)

The microflora from the upper part of the Lianfeng Formation contains 23 species attributed to 17 genera (Fig. 2, Tab. 1). It is dominated by the two species *Buedingiisphaeridium balticum* and *Multiplicisphaeridium ramispinosum*. Higher in the stratigraphic succession, 19 species assigned to 16 genera were identified in the lower part of the Daduhe Formation (Fig. 2, Tab. 1). The assemblage from the Daduhe Formation is dominated by *Evittia remota*. Based on the number of species observed, we consider that the diversity of the microflora is relatively high in

the upper Lianfeng Formation and the lowermost Daduhe Formation.

Discussion

Comparison with other acritarch assemblages

Because the preservation of the specimens is only moderate, and as about 46% species remain in open nomenclature status (not identified at the specific level), the comparison of the acritarch assemblages with other areas is limited.

Table 1. Distribution of acritarchs in the studied samples from the Wanhe section, Yongshan, China.

	AGM35	AGM41	AGM44	AGM52	AGM54	AGM56	AGM70	AGM72	AGM79	AGM84	AGM87
<i>Baltisphaeridium aspersilumiferum</i>	x		x	x							
<i>Baltisphaeridium dispar</i>	x		x		x						
<i>Baltisphaeridium cf. oligopsakium</i>		x									
<i>Baltisphaeridium sp.</i>	x	x	x	x	x	x	x				
<i>Buedingiisphaeridium balticum</i>	x	x	x	x	x		x	x		x	x
<i>Cheleutochroa homoia</i>	x		x	x							
<i>Evittia remota</i>					x	x					
<i>Gyalorhethium granulispinuliferum</i>	x	x	x	x							
<i>Hoegklintia sp.</i>		x	x								
<i>Leisphaeridia spp.</i>	x	x	x	x	x		x		x	x	x
<i>Leprotolypa evexa</i>				x							
<i>Lophosphaeridium edenense</i>	x	x	x		x						
<i>Micrhystridium sp.</i>	x	x	x	x							x
<i>Multiplicisphaeridium irregulare</i>	x		x								
<i>Multiplicisphaeridium ramispinosum</i>	x	x	x		x						
<i>Multiplicisphaeridium sp.</i>			x	x							
<i>Navifusa ancepsipuncta</i>	x										
<i>Navifusa indianensis</i>			x								
<i>Oppilatala sp.</i>		x		x							
<i>Ordovicium sp.</i>			x	x							
<i>Pachysphaeridium kjellstromii</i>			x			x	x				
<i>Peteinosphaeridium sp.</i>			x	x			x				
<i>Polygonium gracile</i>	x	x									
<i>Pterospermella sp.</i>			x								
<i>Rhopaliophora palmata</i>					x		x	x			
<i>Tylotopalla sp.</i>			x		x						

China. – Late Ordovician-Silurian acritarch studies from China were mainly reported from South China, North China and Tarim, with only 12 published papers, which is a limited number compared to the Early and Middle Ordovician (Fig. 5).

Yin *et al.* (2023) described acritarch assemblages from the upper Katian Wufeng Formation (Huayinshan, Sichuan Province) and the Hirnantian Kuanyinchiao Formation in Yangzikou (Guizhou Province) and Huanggexi (Yunnan Province) sections. Among the taxa described, only *Buedingiisphaeridium balticum*, *Evittia (Diexallophasis) remota*, and *Polygonium gracile* are also present in our assemblage. The upper Katian assemblage in the Lingfeng Coal section (Huayinshan, Sichuan Province) is reported to be dominated by *Buedingiisphaeridium* by Yin *et al.* (2023), that is also the case in our assemblage. Another acritarch assemblage from South China was recovered by He & Yin (1993) in the Changwu Formation, attributed to

the middle-late Katian (Zhang *et al.* 2019). These authors recognized 47 species, and only one taxon, *Navifusa ancepsipuncta*, is also present in our assemblage. Li *et al.* (2001) reported an acritarch assemblage from the Bohai Bay, North China, from the Fengfeng Formation, referred to the late Sandbian to early Katian, including 16 species of palynomorphs. Most species of this assemblage remain in open nomenclature, making it hard to correlate with other assemblages at the specific level, and only the two genera *Leiosphaeridia* and *Pterospermella* are also present in the Wanhe section. In another paper, Li *et al.* (2006) described 17 genera and 29 species from the Dawangou section, whereas Yan *et al.* (2020) described 36 species and 20 genera from the nearby Dawanxigou and Sishichang sections in the Aksu area. Eleven species recognized in this area are also present in our new assemblage. These are *Baltisphaeridium dispar*, *B. cf. oligopsakium*, *Gyalorhethium granulispinuliferum* nomen

nudum, *Leprotolypa evexa*, *Lophosphaeridium edenense*, *Multiplicisphaeridium irregulare*, *M. ramispinosum*, *N. ancepsipuncta*, *N. indianensis*, *P. gracile*, and *Rhopaliophora palmata*.

Peri-Gondwana. – Some Katian acritarch assemblages have been reported from the Middle East, North Africa, South America, Bohemia and India, that are areas considered to be of the border of the supercontinent Gondwana, and that are often referred to Peri-Gondwana.

Ghavidel-Syooki *et al.* (2011) and Ghavidel-Syooki (2025) reported the acritarch assemblages from the Khoshyeilagh region, southern Caspian Sea, northern Iran. Among the assemblage, *Baltisphaeridium* cf. *oligopsakium*, *Multiplicisphaeridium irregulare*, *M. ramispinosum*, *Navifusa ancepsipuncta*, and *Polygonium gracile* are

also present in the acritarch assemblage from the Wanhe section. Some other acritarch assemblages reported from Iran (Ghavidel-Syooki 2006, 2008, 2016, 2017a, b; Ghavidel-Syooki & Borji 2018; Ghavidel-Syooki & Piri-Kangarshahi 2021), including *B. oligopsakium*, *Evittia remota*, *M. irregulare*, *N. ancepsipuncta* and *P. gracile*, that are also present in the Wanhe section. Paris *et al.* (2007) describe acritarch assemblages from the Taurus Chain and the Border Folds of Turkey, but only *Leprotolypa evexa*, *M. irregulare* and *P. gracile* are also present in our assemblage. Another Katian acritarch assemblage from Turkey was published by Oktay & Wellman (2019), who recognized two acritarch assemblages referred to a Katian–Hirnantian (Acritarch assemblage 1) and Llandovery (Acritarch assemblage 2) age. *B. dispar*, *M. irregulare* and *P. gracile* are the only species present in both the Wanhe

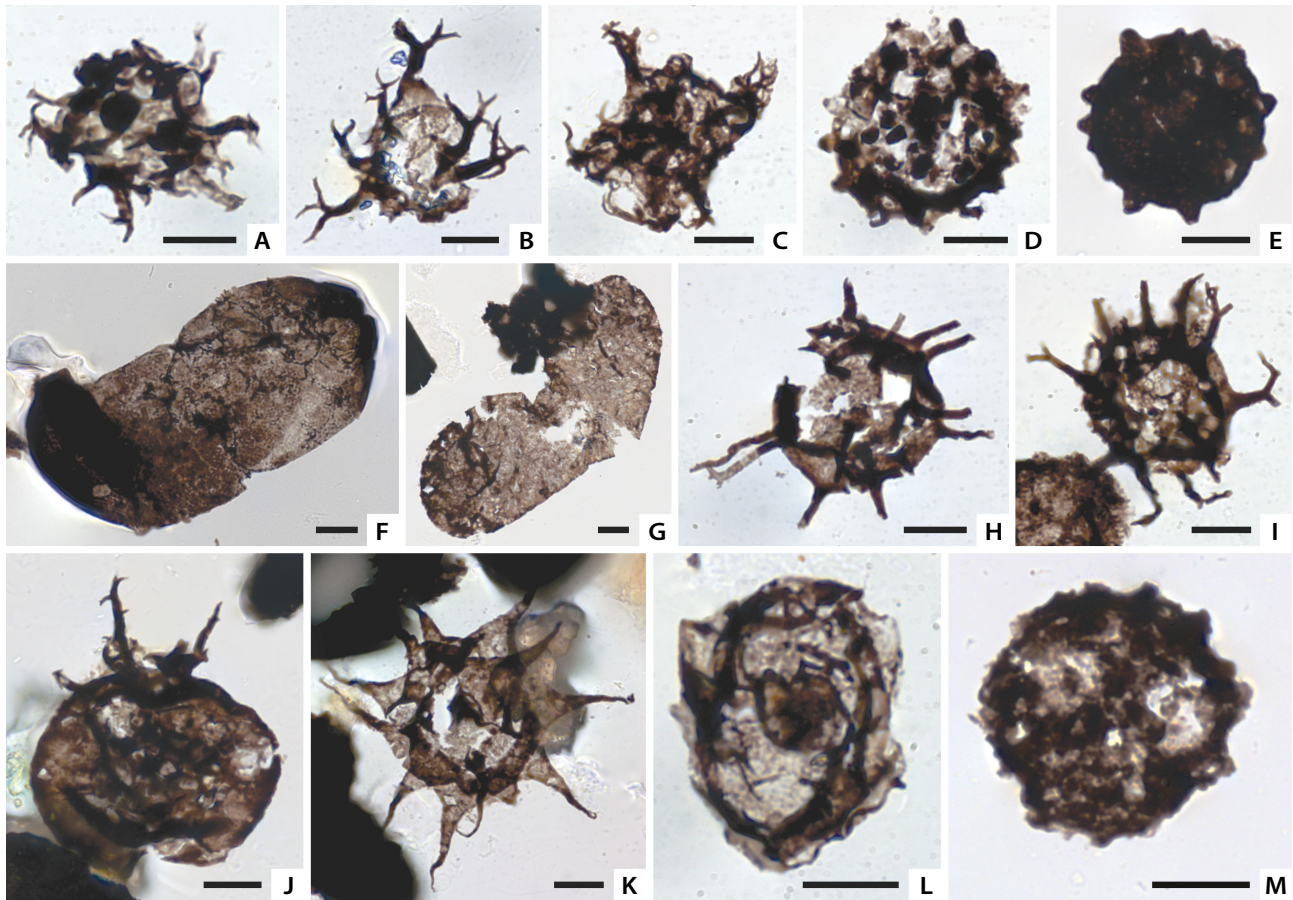


Figure 4. Acritarchs from the Wanhe section, South China. For each illustrated specimen, the following information is given: sample label, slide label, England Finder coordinates, and sample formation. For example, AGM35-1, H51/4, Lianfeng Formation, refers to sample AGM35, slide 1, England Finder coordinates H51/4, collected from the Lianfeng Formation. • A – *Multiplicisphaeridium irregulare*, AGM35-1, H51/4, Lianfeng Formation. • B – *Multiplicisphaeridium ramispinosum*, AGM44-2, Q43/2, Lianfeng Formation. • C – *Multiplicisphaeridium* sp., AGM52-2, O52/4, Daduhe Formation. • D – *Tylotopalla* sp., AGM54-2, J50/4, Daduhe Formation. • E – *Pachysphaeridium kjellstromii*, AGM70-1, R41/2, Daduhe Formation. • F – *Navifusa ancepsipuncta*, AGM35-2, T44, Lianfeng Formation. • G – *Navifusa indianensis*, AGM44-2, G45, Lianfeng Formation. • H – *Oppilatala* sp., AGM52-2, V44/3, Daduhe Formation. • I – *Ordovicium* sp., AGM52-1, R51/3, Daduhe Formation. • J – *Peteinosphaeridium* sp., AGM44-2, T45, Lianfeng Formation. • K – *Polygonium gracile*, AGM41-1, T43/1, Lianfeng Formation. • L – *Pterospermella* sp., AGM44-1, D51/4, Lianfeng Formation. • M – *Rhopaliophora palmata*, AGM72-2, H46/3, Daduhe Formation. Scale bars = 10µm.

section and the Diyarbakır Basin, Turkey. Le Hérisse *et al.* (2015) described an acritarch assemblage with 69 genera and 130 species from Upper Ordovician to lower Silurian strata in the Qusaiba-1 shallow core hole. *L. evexa* and *M. irregulare* are the only taxa from this assemblage present also in the Wanhe section of Katian age.

Vecoli (1999) reported Cambro-Ordovician palynomorph assemblages from several boreholes in Algeria and Tunisia, North Africa. Among them, *E. remota*, *L. evexa*, and *M. ramispinosum* are also present in our Katian assemblage.

Gagnier *et al.* (1996) described the acritarch assemblage from Bolivia and considered it of Katian age with 10 acritarch species, with only *Evittia remota* being also present in the Wanhe section.

Wang *et al.* (2021) preliminarily published the acritarch assemblage from the Pin Formation of the Indian Himalaya, which contained 17 species of Katian age. Among them, only *Multiplicisphaeridium ramispinosum* is also present in our assemblages. Sinha (2022) recognized two palyno-assemblages from the Shiala and Limestone formations in the Tethys Himalaya, India. There are no common species occurring in the India assemblage and the Wanhe assemblage, but the genus *Oppilatala* is present in both areas.

Turner (1984) reported an acritarch assemblage with 62 species attributed to 23 genera from the type Caradoc of the type area of England. Three of the taxa (*Baltisphaeridium dispar*, *Cheleutochroa homoia* and *Navifusa ancepsipuncta*) are also present in our Katian assemblage.

Baltic region. – Most Katian acritarch assemblages from the Baltic region were collected from boreholes. These acritarch assemblages show the highest diversity during the Late Ordovician (Yan *et al.* in press). Uutela & Tynni (1991) reported 332 species and 71 genera from the Middle Ordovician to early Silurian from the Rapla borehole in Estonia, but these high numbers are possibly based on taxonomical splitting. From this Estonian assemblage, the Katian taxa *Baltisphaeridium dispar*, *B. oligopsakium*, *Buedingiisphaeridium balticum*, *Multiplicisphaeridium irregulare*, *Pachysphaeridium kjellstroemii* and *Rhopaliophora palmata* are in common with the assemblage of the Wanhe section. Another Estonian late Katian to Hirnantian acritarch assemblage was described by Delabroye *et al.* (2011b) from the Valga-10 drill core. Five species (*B. aspersilumiferum*, *B. balticum*, *Lophosphaeridium edenense*, *M. irregulare*, and *M. ramispinosum*) are also found in the assemblage from the Wanhe section. Several Late Ordovician acritarch assemblages reported from the boreholes from Sweden (Górka 1987, Badawy *et al.* 2014), with *B. aspersilumiferum*, *B. balticum* and *Polygonium gracile*, being also

present in the Wanhe section. Some new investigations on the Middle–Late Ordovician acritarch assemblages were reported from Sweden and Russia (Rubinstein & Vajda 2023, Raevskaya & Iskül 2024). Rubinstein & Vajda (2023) recognized an acritarch assemblage from the Borensult-1 drillcore of southern Sweden, and among the taxa present, *Cheleutochroa homoia*, *B. dispar*, *L. edenense*, *M. irregulare*, *N. ancepsipuncta*, *P. gracile*, and *R. palmata* are also present in the Wanhe Section. Raevskaya & Iskül (2024) described a palynomorph assemblage from the Lisino-10 Borehole, southwest of St. Petersburg, Russia, with five species (*C. homoia*, *Evittia remota*, *L. edenense*, *M. irregulare*, *N. ancepsipuncta*) being also present in the Wanhe Formation. Several acritarch assemblages from Poland with relatively low diversity (Szczepanik 2000, Trela & Szczepanik 2009, Bednarczyk & Stempień-Sałek 2011, Stempień-Sałek 2011, Sullivan *et al.* 2018), include *C. homoia*, *E. remota*, *L. evexa*, *M. irregulare* and *P. gracile*, that are also present in our assemblage.

North America. – Most studies on Ordovician palynomorph assemblages from North America focused on the Late Ordovician. Wicander *et al.* (1999) reported a Katian assemblage from Pike County, northeastern Missouri, USA, and compared to the assemblage from the Wanhe section, *Baltisphaeridium oligopsakium*, *Lophosphaeridium edenense*, *Multiplicisphaeridium irregulare*, and *Polygonium gracile* are common. Wicander & Playford (2008) describe the Ka4 acritarch assemblage from Delta County, Michigan, USA, characterised by *L. edenense*, *M. irregulare*, and *P. gracile*, which are also common in the Wanhe assemblage. Playford & Wicander (2006) recognized 42 acritarch species from the Sylvan Shale, corresponding to the Richmondian Stage (upper Katian), in the Lawrence Quarry of the Arbuckle Mountains, Oklahoma, USA. The common taxa present in both the Wanhe section and the Lawrence Quarry are *B. oligopsakium*, *Navifusa ancepsipuncta* and *P. gracile*.

Several Late Ordovician acritarch assemblages are also described from Canada. Delabroye *et al.* (2011a) restudied the microphytoplankton from the Vauréal, Ellis Bay and Becscie formations, Anticosti. The Vauréal Formation is of Katian age, and the acritarch taxa in this formation, including *Baltisphaeridium oligopsakium*, *Evittia remota*, *Gyalorhethium granulispinuliferum*, *Lophosphaeridium edenense*, *Multiplicisphaeridium irregulare*, *Navifusa ancepsipuncta* and *Polygonium gracile*, are also common in the Wanhe section. Some other Katian acritarch assemblages are described from southeastern Canada, such as Labrador, Montréal, Québec, and Ottawa (Legault 1982, Martin 1983, Gillespie 1998, Bingham-Kosłowski *et al.* 2019), with some species reported from there (*L. edenense*, *M. irregulare*, *N. ancepsipuncta* and *P. gracile*) also being common in the Wanhe section.

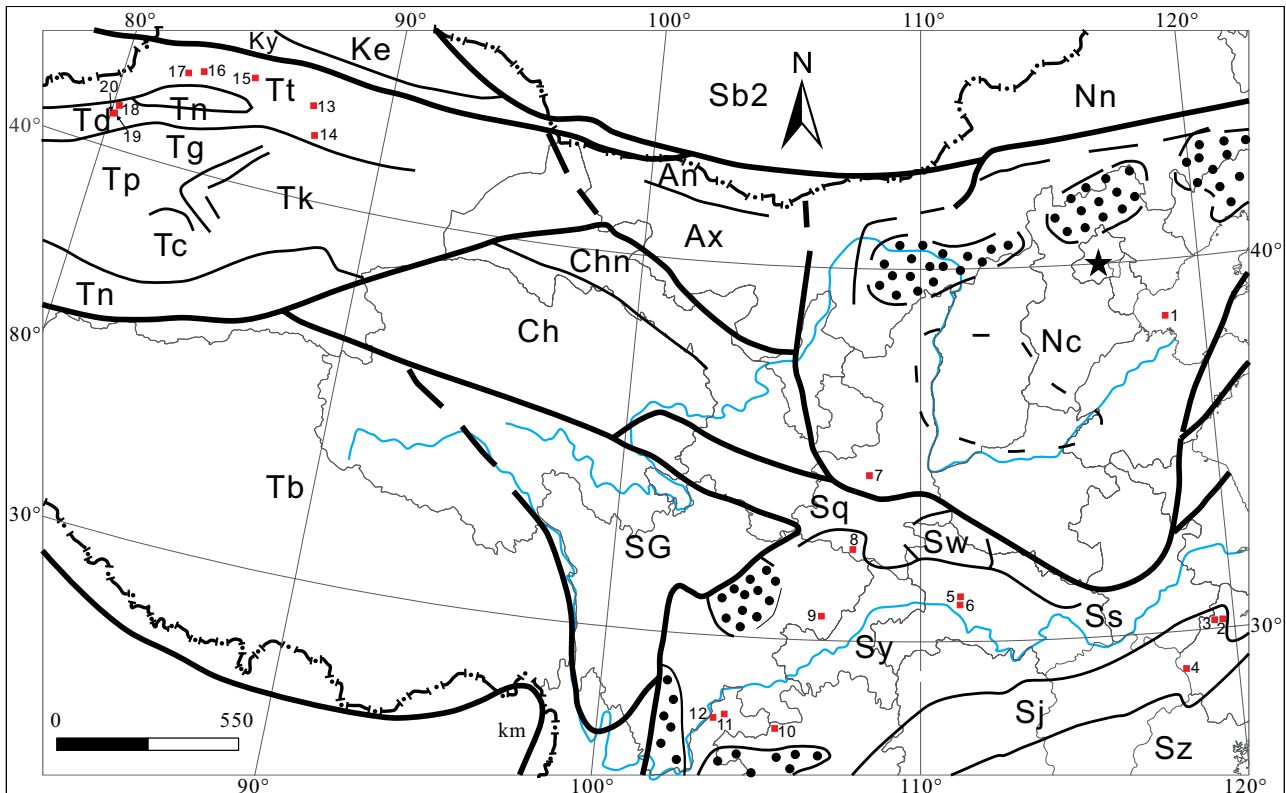


Figure 5. Map of Ordovician tectonic units of China with boundaries of various paleoplates or blocks. Black dots with numbers show sections where Upper Ordovician acritarch assemblages have been reported. Modified from Chen *et al.* (2003), with abbreviations of tectonic units as indicated by Chen *et al.* (2003). Legend: 1 – Bohai (Li *et al.* 2001); 2 – Tangjia (Yin & He 2000); 3 – Yankou (Yan *et al.* 2011); 4 – Wujialong (He & Yin 1993, Yan *et al.* 2011); 5 – Zhenjin (Yan & Li 2007); 6 – Jieling (Yan & Li 2007); 7 – Dongzhuang (Yin *et al.* 1993, Yan *et al.* in press); 8 – Liangjiaqiao (Fu 1986); 9 – Lingfeng coal (Yin *et al.* 2023); 10 – Yanzikou (Yin *et al.* 2023); 11 – Huanggexi (Yin *et al.* 2023); 12 – Wanhe (this study); 13 – QK1 borehole (Li & Wang 1997); 14 – TD1 borehole (Li & Wang 1997); 15 – LN46 borehole (Li & Wang 1997); 16 – YM1 borehole (Li & Wang 1997); 17 – YM2 borehole (Li & Wang 1997); 18 – Sishichang (Yan *et al.* 2020); 19 – Dawangou (Li 1995, Li *et al.* 2006, Yan *et al.* 2020); 20 – Dawanxigou (Yan *et al.* 2020).

Siberia. – Only one paper described a complete acritarch assemblage from the Upper Ordovician from the Tungus basin, Siberia (Raevskaya & Dronov 2014). There is no common species between the acritarch assemblage from the Tungus basin and the Wanhe section, but the genera *Baltisphaeridium*, *Micrhystridium* and *Oppilatala* are common in both.

Biostratigraphical implication

Our acritarch assemblage, reported from the upper Lianfeng and lower Daduhe formations from the Wanhe section, corresponds to an interval that includes the late Katian *Dicellograptus complanatus*, *D. complexus*, and *Paraorthograptus pacificus* graptolite biozones (Tang *et al.* 2017; Wang *et al.* 2022a, b). Ling *et al.* (2019) provided four ID-TIMS U-Pb isotopic dates from K-bentonite zircons from 444.65 ± 0.22 to 442.99 ± 0.17 Ma, which referred to a late Katian to Hirnantian

age of the Daduhe Formation. An uppermost Katian *Amorphognathus ordovicicus* conodont Biozone was recognized and indicated the Ka4 Stage Slice in the Daduhe Formation from the Wanhe section (Chen, Z.Y. *et al.* 2022). Under this high-resolution stratigraphic framework, the acritarch assemblage recovered from the Wanhe section can be attributed to the Ka4.

Wicander *et al.* (1999) and Wicander & Playford (2008) selected several acritarch taxa as biostratigraphical indicators of the Late Ordovician, some of them restricted to the “Ashgill”. Some First Appearance Datum (FADs) of selected acritarchs had the potential to define the Lower and Middle Ordovician stages (Servais *et al.* 2018), but few have been done in the Late Ordovician and further research is needed to clarify the FADs in these time intervals. *Baltisphaeridium aspersilumiferum* was established by Loeblich & Tappan (1978) from the Sylvan Shale, and is considered to be indicative of the upper Katian. This species is also found in the Sandbian and Katian from North America and Batica, and was first

recovered in South China in our assemblage. The species may thus be an index taxon in the Late Ordovician.

Baltisphaeridium dispar was considered a Caradoc (Sandbian to lower Katian) species (Li *et al.* 2006). The species is also present in late Katian and Hirnantian assemblages, distributed in peri-Gondwana, Baltica and North America during the Katian.

Cheleutochroa was first present in late Darriwilian of Estonia (Uutela & Tynni 1991), and mostly reported in Upper Ordovician sediments especially in the Katian (Rubinstein & Vajda 2023). Therefore, this genus can be considered a key taxon for Upper Ordovician stratigraphy. *Cheleutochroa homoia* was first identified from the type area of the Caradoc (Shropshire, England), where it is present in late Sandbian and Katian. More recently, this species was reported from the Borensult-1 borehole, Sweden, by Rubinstein & Vajda (2023) and from the Lisino-10 borehole, Russia, by Raevskaya & Iskül (2024) in Sandbian. *Cheleutochroa homoia* is also present in the Grabowiec-6 borehole, Poland, in the Katian (Sullivan *et al.* 2018).

Gyalorhethium granulispinuliferum was established in an unpublished Ph.D. study by Delabroye (2010) who published the name as a nomen nudum later (Delabroye *et al.* 2011a). The species was only discovered from Anticosti and China in the Late Ordovician, and its FAD occurred at the top of the Sargan Formation from Tarim (Yan *et al.* 2020).

Leprotolypa evexa was first described by Colbath (1979) from the Eden shale, which is referred to the early Katian. *Leprotolypa evexa* is distributed worldwide during the Late Ordovician, and its FAD occurred at the base of the Sandbian in the Yichang area (Yan & Li 2007).

Lophosphaeridium edenense was also established by Loeblich & Tappan (1978) from the Eden Shale. The species first occurred in South China at the base of the Sandbian (Yan & Li 2007). It is also present in Tarim and North America, then extends to North China (Yan *et al.* in press) and Baltica (Delabroye *et al.* 2011b) in the Katian and is discovered only in North America (Delabroye *et al.* 2011a) and Baltica (Delabroye *et al.* 2011b) during the Hirnantian.

Our acritarch assemblage from the Wanhe section contains *Baltisphaeridium aspersilumiferum*, *B. dispar*, *B. cf. oligopsakium*, *Buedingiisphaeridium balticum*, *Gyalorhethium granulispinuliferum*, *Hoegklintia* sp., *Leprotolypa evexa*, *Lophosphaeridium edenense*, *Multiplicisphaeridium irregulare*, *M. ramispinosum*, *Navifusa ancepsipuncta*, *Ordovicium* sp., which indicate the Late Ordovician age, and *Evittia remota*, *Oppilatala* sp., *Tylotopalla* sp., which are so far considered as Silurian taxa. Additional studies, including detailed taxonomical revisions, are needed to clarify the biostratigraphical potential of these acritarch taxa, that most probably can be used for international correlation in the future.

Paleogeographical implications

After a pronounced acritarch provincialism during the Early and Middle Ordovician, acritarch assemblages were considered cosmopolitan after the late Darriwilian, but Delabroye *et al.* (2011b) suggested two paleophytoprovinces in the Late Ordovician during the late Katian to Hirnantian. A new paleogeographical analysis implied that the three plates from China (South China, North China and Tarim) have close geographical affinities during the Katian (Yan *et al.* in press).

Although South China is considered to be located near the equator in the Late Ordovician (Torsvik & Cocks 2017), the diversity of the acritarch assemblage from the Wanhe section is relatively low in the Katian. The Wanhe assemblage, containing *Baltisphaeridium* and ‘giant’ acritarchs of the genus *Hoegklintia*, provides indications that this acritarch association is similar to that of Laurentian and Baltican assemblages of Delabroye *et al.* (2011b). On the other hand, the relatively low diversity, with few netromorph acritarchs (*Navifusa*), provides a similarity to the Gondwanan and “peri-Gondwanan” assemblages (Delabroye *et al.* 2011b).

Paleoenvironmental implication

The Wanhe section in Yongshan is located southwest of the Upper Yangtze Sea and near the oldland in the Late Ordovician. Based on the sedimentological research, the Wanhe section was in the mixed siliciclastic-carbonate lithofacies belt, which implied a relatively deep water setting (Wang *et al.* 2022b). The brachiopod *Trimurellina*–*Kassinella* Association referred to Benthic Assemblage (BA) 5 was discovered in the sample AGM 100 in the middle part of the Daduhe Formation, and the *Manosia* Community referred to BA4 at the top of the Daduhe Formation (Rong & Huang 2019). Based on the brachiopod assemblages, a deep water to shallow water transit occurs from the Daduhe Formation to the Kuanyinchiao bed in the Wanhe section (Rong & Huang 2019). Recently, this bathymetry was confirmed by the presence of a deep-water linguliform brachiopod (Chen, D. *et al.* 2022).

Li (2021) discussed the depositional characteristics of Darriwilian to Katian in South China and pointed out that the Wanhe section shows a relatively shallow water environment in the Lianfeng Formation (“Linhsiang Formation”) and a deeper water environment in the Daduhe Formation. A transgression occurred during the late Katian, and the sea level dropped in the latest Katian to Hirnantian in the Wanhe section. Our study indicates that the acritarch assemblage from the Wanhe section is dominated by *Buedingiisphaeridium balticum*, *Multi-*

placisphaeridium ramispinosum in the upper part of the Lianfeng Formation and by *Evittia remota* in the lower part of the Daduhe Formation, which may be affected by these environmental changes.

Chen, Z.Y. *et al.* (2022) noticed that the conodont assemblage from the Daduhe Formation represents the *Hamarodus brevirameus*–*Dapsilodus mutatus*–*Scabardella altipes* (HDS) Biofacies, which normally occurred in middle–low latitude areas. The HDS Biofacies is generally discovered with two cool-water brachiopod communities (Chen, Z.Y. *et al.* 2022). In more recent paleogeographic reconstruction, South China is located near the equator during the Late Ordovician (Torsvik & Cocks 2017), so a cold tongue model was used to explain these distributions of fossils in the late Ordovician (Jin *et al.* 2018). The acritarch assemblage is dominated by *Evittia remota* in the Daduhe Formation. Except for the occurrence in China, *Evittia remota* was also found in middle-high latitude areas, such as Avalonia (Martin *et al.* 1970), Saxothuringia (Heuse 1994), Bohemia (Konzalová-Mazancová 1969), South America (Gagnier *et al.* 1996, Rubinstein & Vaccari 2004), North Africa (Vecoli 1999) and the Middle East (Al-Hadidy 2007, Ghavidel-Syooki 2008) and in relative low latitudes, such as Baltoscandia (Samuelsson *et al.* 2001; Masiak *et al.* 2003, 2020; Stempień-Sałek 2011), North America (Martin 1980, Delabroye *et al.* 2011a), in localities around 20° S in the southern hemisphere, based on several paleogeographical reconstructions (Torsvik & Cocks 2017, Scotese 2021). Delabroye *et al.* (2011a) noticed the abundance of *Evittia remota* was enhanced, as well as that of the “synglacial assemblages” in the Anticosti Island across the Ordovician–Silurian boundary. Similarly, the cold tongue model can also explain the high abundance of *Evittia remota* present in the late Katian from the Wanhe section of South China.

Conclusions

Late Ordovician acritarch reports remain rare, in particular from China. Here, we describe for the first time a Katian palynomorph assemblage from the Wanhe section in northeastern Yunnan, South China. A total of 26 acritarch species assigned to 20 genera were identified from 11 samples collected from the upper Lianfeng Formation and lower Daduhe Formation, with 12 species being classified in open nomenclature.

The acritarch assemblage from the Wanhe section, together with graptolites and conodonts, can be attributed to a late Katian (Ka4) age. Some acritarch taxa in the Wanhe section have the potential for biostratigraphic correlation during the Late Ordovician, but detailed taxonomical revisions at a global level are needed to strengthen this potential.

The Katian acritarch assemblage shows a close geographical affinity between South China, North China and Tarim.

A transgression occurred in the late Katian, and a sea-level drop occurred in the latest Katian to Hirnantian throughout the section. The change of acritarch assemblages in the Wanhe section may have been affected by the transgression in the late Katian. The dominance of *Evittia remota*, a taxon widespread across high to low paleolatitudes, is consistent with the “equatorial cold-water tongue” model, linking its distribution to Late Ordovician climate fluctuations.

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