



# Palynological analysis of the lower member of the Hongguleleng Formation and discussion of the Frasnian/Famennian boundary in Western Junggar, NW China

Zhen Shen <sup>a,b</sup>, Philippe Steemans <sup>c</sup>, Yiming Gong <sup>b,\*</sup>, Ruiwen Zong <sup>b</sup>, Thomas Servais <sup>d</sup>

<sup>a</sup> College of Resources and Environment, Shanxi University of Finance and Economics, Taiyuan 030006, China

<sup>b</sup> State Key Laboratory of Biogeology and Environmental Geology, School of Earth Sciences, China University of Geosciences, Wuhan 430074, China

<sup>c</sup> EDDy Lab, Department of Geology, University of Liege, B18 Sart Tilman, B-4000, Liege, Belgium

<sup>d</sup> Université de Lille, CNRS, UMR 8198 Evo-Eco-Paleo, F-59000 Lille, France

## ARTICLE INFO

### Article history:

Received 2 November 2020

Received in revised form 28 July 2021

Accepted 3 August 2021

Available online 8 August 2021

### Keywords:

Miospores

Acritarchs

Late Devonian

Hongguleleng Formation

NW China

Central Asian Orogenic Belt

## ABSTRACT

Palynological investigations have been carried out on samples from the Upper Devonian Hongguleleng Formation of Western Junggar, Xinjiang, NW China. In total, 26 miospore species belonging to 19 genera and 28 acritarch species assigned to 19 genera have been recognized from the lower member of the Hongguleleng Fm. in the Bulongguoer section. The palynofloral assemblages, in particular the miospore taxa, are similar to those from the eastern European early Famennian *Corbulispora vimineus*–*Geminispora vasjamica* (VV) and *Cyrtospora cristifer*–*Diaphanospora zadonica* (CZ) miospore biozones, albeit quantitatively and qualitatively depauperate. The miospore assemblage zone is also consistent with the previous zonal schemes in light of brachiopod and conodont fauna assemblages, as well as carbon isotope geochemistry, that indicates a correspondence to the *Palmatolepis crepida* conodont Biozone. Part of the earliest Famennian *Corbulispora vimineus*–*Geminispora vasjamica* (VV) (more or less equivalent to the *Palmatolepis triangularis* conodont Biozone) miospore Biozone is most likely to be missing in the Hongguleleng Fm. of the Bulongguoer section. The palynostratigraphy and sedimentary sequence in Western Junggar are very similar to those from some other regions of western and eastern Europe, which increases the knowledge of the evolution of the paleoclimate, paleogeography and regional sedimentary environment of the Central Asian Orogenic Belt (CAOB), Eastern European Platform, and Laurussia.

© 2021 Elsevier B.V. All rights reserved.

## 1. Introduction

The Hongguleleng Formation of the Bulongguoer section in Western Junggar, NW Xinjiang, China, has attracted much attention due to its well-exposed Upper Devonian lithological units and abundant fossils, such as conodonts (Zhao, 1986; Xia, 1996; Wang et al., 2016), brachiopods (Ma et al., 2011), rugose corals (Liao and Cai, 1987), ammonoids (Zong et al., 2015), trace fossils (Fan and Gong, 2016), and ostracods (Song et al., 2017b). Multiple geochemical proxies, as well as lithological and facies analyses have also been discussed around the Devonian–Carboniferous (D/C) and Frasnian–Famennian (F/F) boundaries in the Bulongguoer section (e.g. Zhao and Wang, 1990; Xia, 1997; Chen et al., 2009; Ma et al., 2011; Carmichael et al., 2014, 2016; Suttner et al., 2014; Wang et al., 2016; Zong et al., 2015, 2017; Zong and Ma, 2018). Nevertheless, there is still no unanimous agreement on the chronostratigraphic framework for the Hongguleleng Fm., and the debate about the position of the F/F boundary in Western Junggar is still ongoing.

Devonian palynological studies in China have mainly been concentrated on the South China plate (Li et al., 2002; Shen et al., 2020), where more than half of the palynological publications have been published over the past few decades (e.g., Gao, 2015; Lu, 1995, 1997; Wang, 1996; Ouyang, 2000). The palynological studies in other regions, such as NW Xinjiang, Western Yunnan, and the Hinggan areas, are still relatively sparse. In fact, the general poor preservation and high thermal maturation of the samples are making it difficult to conduct research in these regions. Until now, palynological reports out of the Bulongguoer section in other sections of the Hongguleleng Fm. are still rare. The pioneer work for the Hongguleleng Fm., concerning miospore and acritarch assemblages from the Bulongguoer section of Western Junggar, was carried out by Lu and Wicander (1988). Lu (1999) systematically described the palynomorphs from the overlying Heishantou Fm., whereas the palynological assemblages of the underlying strata from the upper part of the Hujiersite Fm. (Emsian–Frasnian) from this region were subsequently studied by Xu et al. (2014). More recently, Stachacz et al. (2021) analyzed palynologically and ichnologically the Hongguleleng (from the Bulongguoer and Haer sections) and the overlying Heishantou formations in more detail. The presence of the miospore

\* Corresponding author.

E-mail address: [yimgong@cug.edu.cn](mailto:yimgong@cug.edu.cn) (Y. Gong).

species *Grandispora gracilis* and *Teichertospora torquata* enabled the identification of the wider *Teichertosproa torquata*–*Grandispora gracilis* miospore Biozone from the F/F transitional interval (Stachacz et al., 2021), but the precise position of the F/F boundary remains uncertain.

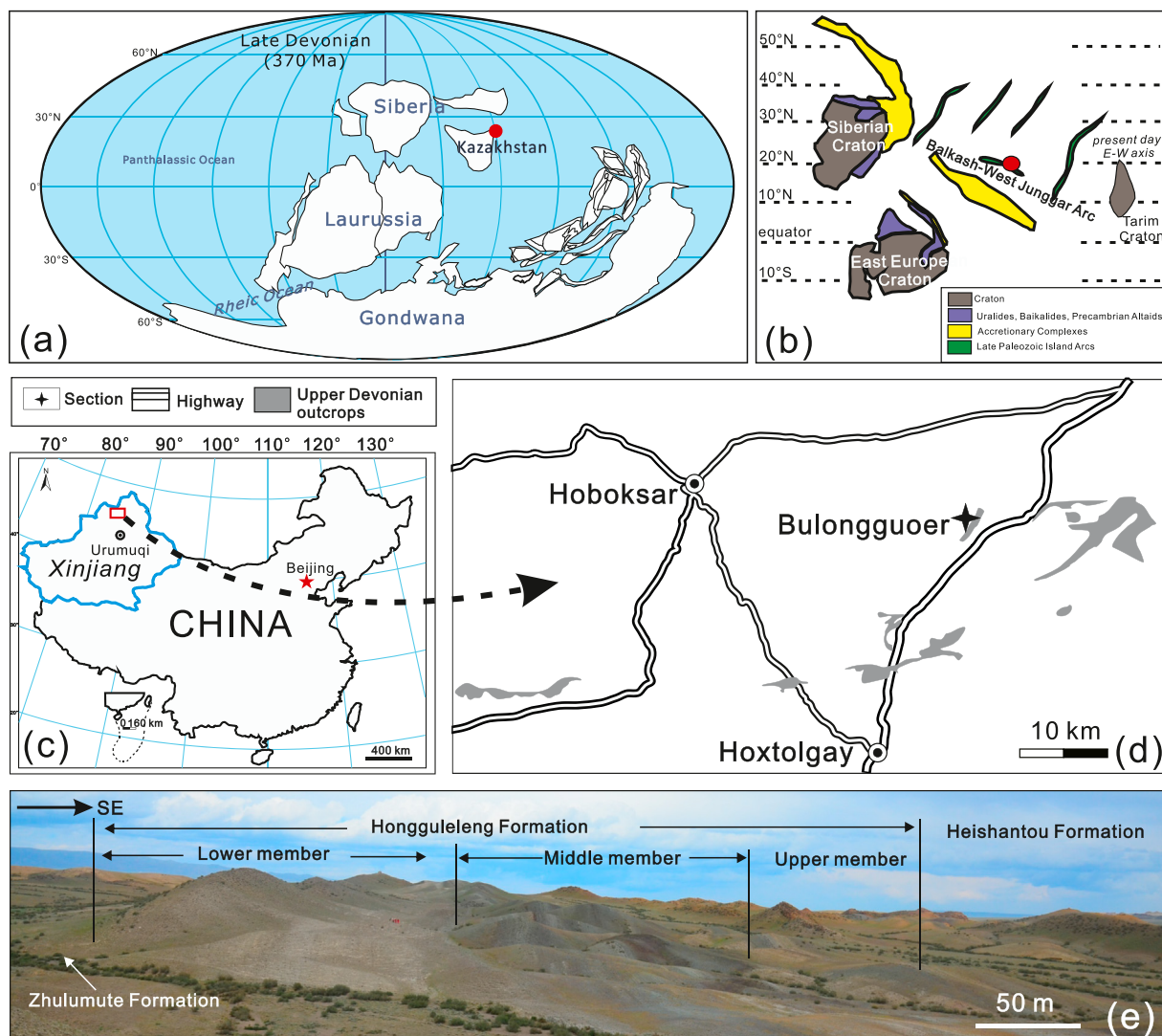
During the last two years, palynological samples were collected from the Bulongguoer section in Western Junggar (Fig. 1). Fifteen samples yielded well-preserved palynomorphs including miospore and phytoplankton (acritarchs and prasinophytes) assemblages. The palynologically depauperate samples provide important biostratigraphic information and allow a comparison with sections from other regions of the world. The objective of the present paper is to precise the position of the F/F boundary in this area in more detail, and to compare its sedimentary background with other regions at the global level, by studying the newly collected microfloral assemblages in the Hongguleleng Fm. of the Bulongguoer section.

## 2. Geological setting and stratal section descriptions

The Western Junggar (Fig. 1) is an important part of the Central Asian Orogenic Belt (CAOB). It is lying between the Siberian Craton on the North and the North China-Tarim Craton in the South (Jahn et al.,

2000; Chen and Arakawa, 2005; Cocks and Torsvik, 2007; Windley et al., 2007). Devonian to Early Carboniferous strata are well-exposed in Western Junggar; these include the Middle to Upper Devonian Hujiersite Fm. (Xu et al., 2014), the Frasnian dominated Zhulumute Fm., the Famennian Hongguleleng Fm., and the Lower Carboniferous Heishantou Fm. (Cai, 2000; Ma et al., 2017; Zong et al., 2020).

The material investigated in the present study was collected along the stratotype of the Hongguleleng Fm. from Bulongguoer (46°45'10.26"N; 86°08'20.70"E; Fig. 1), which has paleontologically been studied previously by many authors (see Suttner et al., 2014 and references therein). There are obviously different opinions on the age of the Hongguleleng Fm. and the contact relationship between the Hongguleleng Fm. and the underlying Zhulumute Fm. In the Bulongguoer section, the upper part of the Zhulumute Fm. is composed of cross-bedded sandstone and minor conglomerate of terrestrial origin, bearing quite common plant fossils including *Callixylon newberryi*, *Lepidodendropsis rhombica*, *Leptophloeum rhombicum*, and *Xinicaulis lignescens* (Cai, 1989; Ma et al., 2011; Xu et al., 2017; Zheng et al., 2020). Towards the top, there is a covered interval of several meters between the two formations. During the past few years, two ditches were dug by Ma et al. (2011), one of



**Fig. 1.** (a): Late Devonian paleogeographic map (modified from Boucot et al., 2013), showing the location of the Kazakhstan Plate where palynological samples have been collected; (b): Late Devonian tectonic model of the study area (shown by red circle), indicating an amalgamating cluster of island arcs and accretionary complexes. Figure modified from Xiao et al. (2010); (c): the geographic location in Xinjiang, NW China; (d): Location of the studied section and Upper Devonian outcrops of Western Junggar; (e): panoramic view of the Bulongguoer section.

which was deep enough to reveal the contact of the parallel unconformity. A layer of loose sandstone weathering in about 25 cm was discovered at the top of the Zhulumute Fm. (Ma et al., 2011; Ma et al., 2013).

The Hongguleleng Fm. was lithostratigraphically divided into three members by Hou et al. (1993), and this division has been widely used in the subsequent studies. Based on the investigation of several sections of the Hongguleleng Fm., Ma et al. (2013, 2017) divided the Hongguleleng Fm. into five members within different sections in ascending order as follows: the lower member (Saerba member, Longkou member, and Duguer member), the middle member (Wulan member), and the upper member (Chasi member). The lower member is made of gray, gray-yellow bioclastic limestones intercalated with calcareous conglomerates, siliceous mudstones, mudstone-shales, or marlstones; the middle member consists of variegated fine-grained volcanoclastic rocks; and the upper member is composed of gray-green, gray-yellow bioclastic limestones and calcareous-pelitic clastic rocks. In the present study, the sampling was mainly focused on the lower member of the Hongguleleng Fm. from the Bulongguoer section.

### 3. Materials and methods

Fifty-one samples were prepared using standard palynological methods (Wood et al., 1996) for the recovery of palynomorphs at the microfossil laboratory of China University of Geosciences (Wuhan), of which 15 yielded taxonomically differentiated assemblages with identifiable palynomorphs (Fig. 2). The process involved treatment in HCl-HF-HCl, followed by heavy liquid separation. Selected samples were bleached tentatively using fuming nitric acid. Samples were then neutralized with distilled H<sub>2</sub>O between each of the acid treatments. The residues were finally sieved through 50 and 15 μm meshes and the residue was transferred to Lille University, France, where slides have been mounted. The palynomorphs were photographed with a Zeiss Axio Imager microspectrophotometer equipped with oil immersion objectives. Generally, the bottom samples, BL-L-5.5, BLG-3, BL-L-14.5, BL-L-17.5, BLG-4, were dominated by miospores, while the remaining samples were dominated by phytoplankton taxa. The palynomorphs are not very well preserved, with the organic material being exposed to high temperatures. The phytoplankton taxa are usually brown in color, and appears to be better preserved than the dark

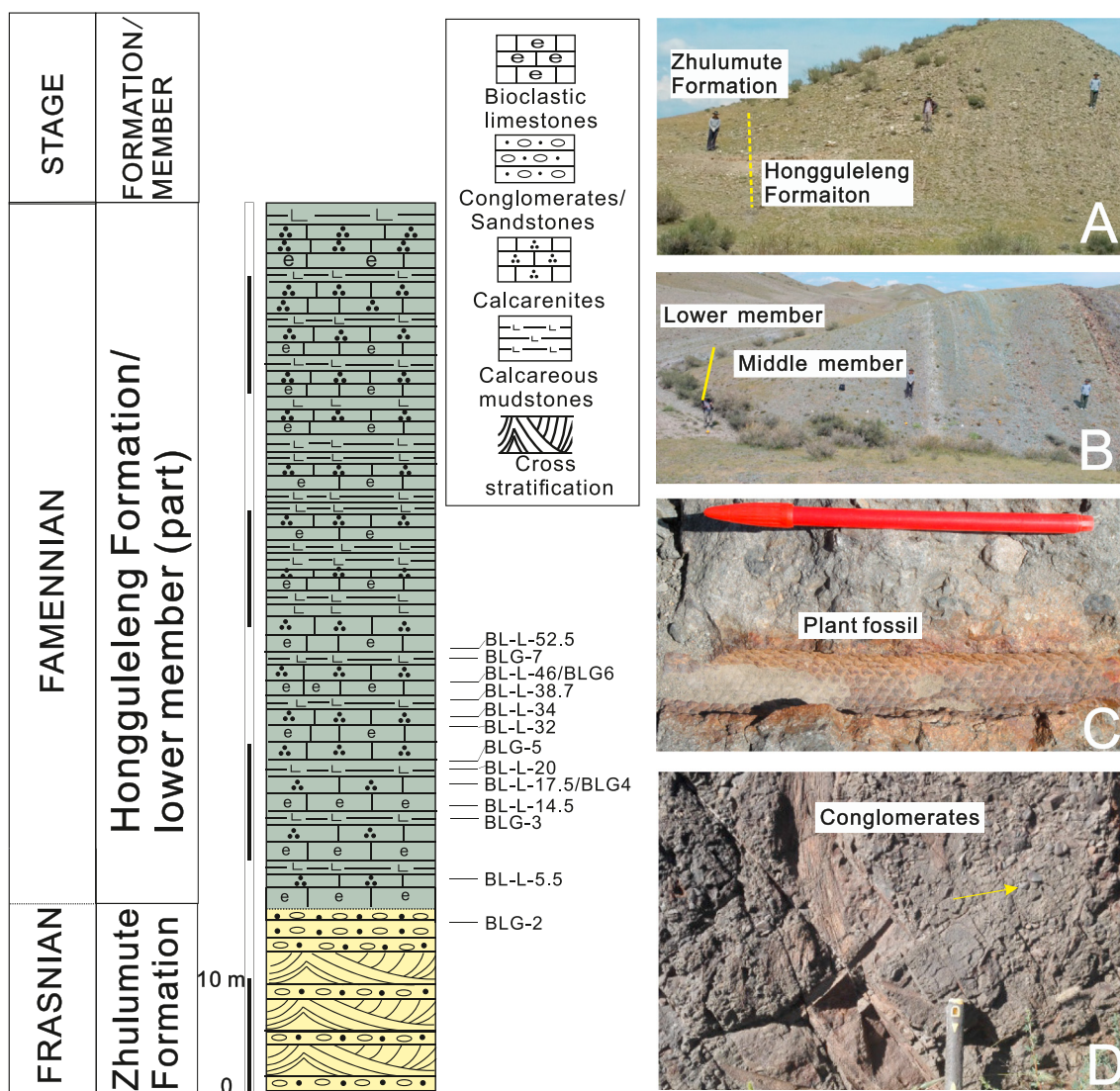


Fig. 2. Simplified geological section of the uppermost Zhulumute Fm. and the lower member of the Hongguleleng Fm. in the Bulongguoer section with the productive sample numbers marked. The division scheme of the Hongguleleng Fm. is derived from Ma et al. (2017). A, position of the boundary between the Zhulumute and Hongguleleng formations in the Bulongguoer section; B, position of the boundary between the lower and middle members of the Hongguleleng Fm. in the Bulongguoer section; C, plant fossil from the Zhulumute Fm.; D, conglomerates from the upper part of the Zhulumute Fm. All photographs used here were taken in August 2018.



brown terrestrial miospores. The palynological slides are deposited in the collections of the College of Resources and Environment, Shanxi University of Finance and Economics.

#### 4. Palynological results

The discussion of miospore biostratigraphy in this paper is primarily based on the palynological samples collected from the lower member of the Hongguleleng Fm. from the Bulongguoer section. Unfortunately, two barren samples were obtained from the Zhulumute Fm., the absence of palynomorphs being probably due to weathering. The quantitatively and qualitatively depauperate palynomorphs occurring in the lower member of the Hongguleleng Fm. are poorly preserved with a high thermal alteration, sometimes making it difficult to accurately identify the specimens. Fortunately, however, the emergence of some index taxa in the lowermost part of the lower member of the Hongguleleng Fm. makes it possible to precise the age of the lower member of this formation.

The *torquata-gracilis* (TG) miospore Biozone has been broadly used in the Old Red Sandstone Continent and adjacent regions (Richardson and McGregor, 1986; Fig. 3) from the latest Frasnian to the late early Famennian transition, which is approximately equivalent to the lower *Palmatolepis triangularis* Biozone to the middle *Scaphignathus velifer* Biozone in terms of conodont zonation, i.e., the newest *Palmatolepis subperlobata* or *Palmatolepis triangularis* Biozone to the *Palmatolepis rugosa trachytera* Biozone (Rickard, 1975; Richardson and McGregor, 1986; Spalletta et al., 2017). The TG Biozone can also be tentatively correlated with several standard miospore biozones with narrower ranges in eastern and western Europe (Fig. 3; Streel et al., 1987; Avkhimovitch et al., 1993). More recently, the appearance of *Teichertospora torquata* and *Grandispora gracilis* in the lower member of the Hongguleleng Fm., distinguished by Stachacz et al., 2021, enabled the identification of the TG miospore Biozone from the F/F transition.

Paleogeographically, Western Junggar, located in the Central Asian Orogenic Belt, was very close to the Eastern European Platform (Fig. 1, b). Among the miospore floras that have been distinguished from eastern Europe, the following taxa have also been identified from the Hongguleleng Fm. of Western Junggar (Plate 1): *Corbulispora vimineus*,

*Converrucosporites curvatus* var. *medius*, *Dictyotriletes famenensis*, *Geminospora vasjamica*, *Lophozonotriletes* cf. *furssenkoi*, and *Lophozonotriletes lebedianensis*.

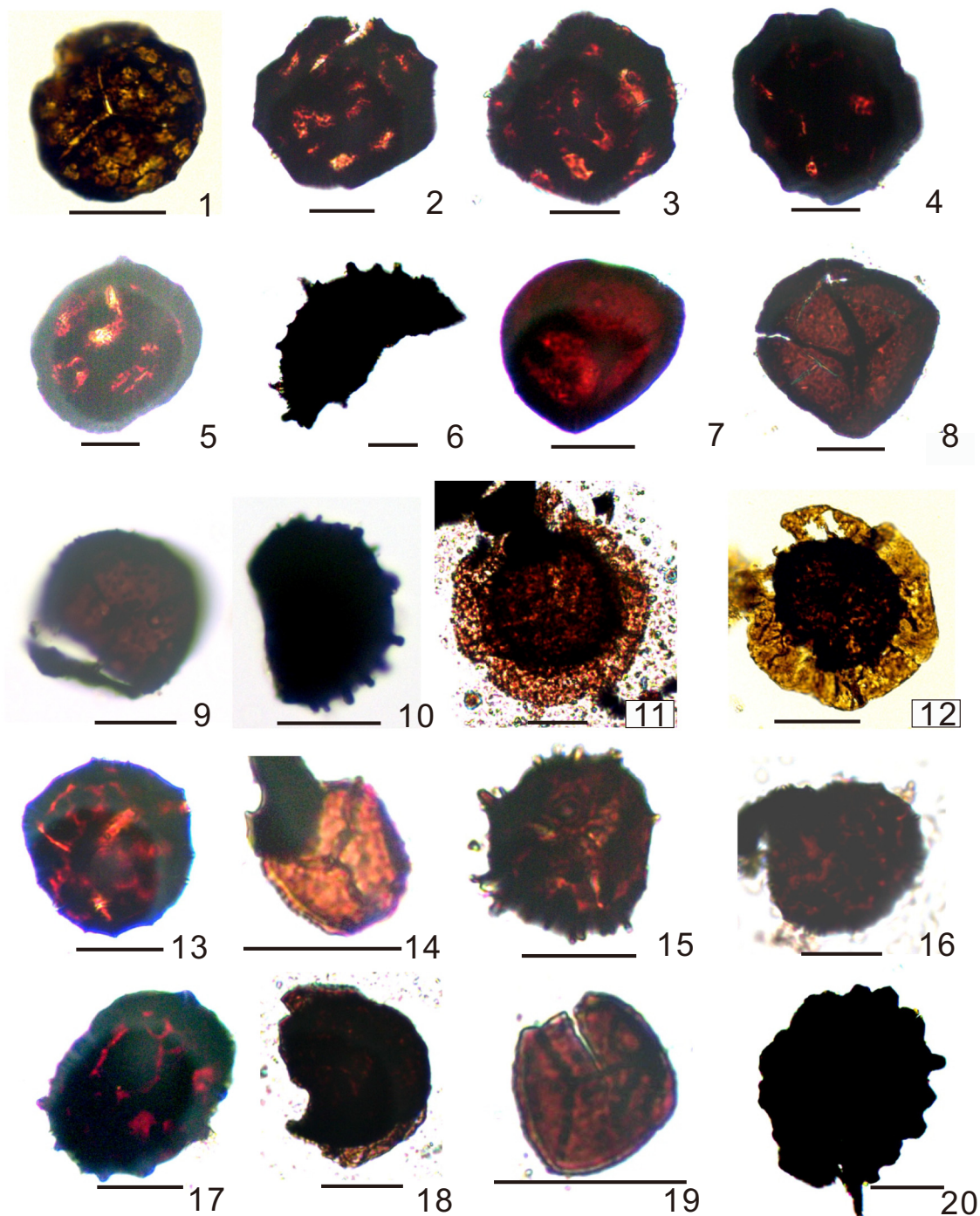
The miospore composition from the lowermost part of the lower member of the Hongguleleng Fm. is rather similar to the eastern European *Corbulispora vimineus*–*Geminospora vasjamica* (VV) Biozone and the upper *Cyrtospora cristifer*–*Diaphanospora zadonica* (CZ) Biozone described by Avkhimovitch et al. (1993).

*Corbulispora vimineus* (sample BL-L-5.5), the index species of the VV Biozone, is recorded in the lowermost part of the Hongguleleng Fm. (Plate 1). According to Avkhimovitch et al. (1993), *C. vimineus* first appeared in the VV Biozone (Fig. 4). In addition, important taxa such as *G. vasjamica*, *L. cf. furssenkoi*, and *C. curvatus* var. *medius* could also be distinguished in the samples BL-L-14.5 and BL-L-17.5, respectively. Such species are typical taxa in the two biozones of eastern Europe, having a relatively short duration. Nevertheless, it remains difficult to accurately compare the Chinese assemblages with the miospore biozonation of eastern European, because specimens are not sufficiently well-preserved. The miospore assemblages from the lowermost Hongguleleng Fm. correspond probably to the eastern European VV or/and CZ biozones. The appearance of *D. famenensis* and *L. lebedianensis* in sample BL-L-20 suggests that the presence of the characteristic species at the lower part of the lower member of the Hongguleleng Fm. might be correlated to the eastern European CZ Biozone. The two species were previously reported in the eastern European GM Subzone (belonging to the *Cyrtospora cristifer*–*Diaphanospora zadonica* Biozone, CZ Biozone) and the upper *Lagenosporites immensus* (Im) Biozone (Avkhimovitch et al., 1993, pl. 19, fig. 13; pl. 21, fig. 2), respectively (Fig. 4).

Regarding the phytoplankton, it is generally considered that paleolatitudes, paleocurrents, paleoecologic conditions (such as water temperature, water chemistry, water depth, distance from shoreline, etc.) and physical barriers may have affected the composition of organic-walled phytoplankton assemblages (Tyson, 1995; Le Hérisse and Gourvenec, 1995; Tongiorgi et al., 1995; Le Hérisse et al., 1997; Li and Servais, 2002; Li et al., 2004; Playford, 2003; Molyneux et al., 2013; Shen et al., 2019). Even in the contemporaneous sequences, the composition of phytoplankton in different regions may not be the

CHRONO-STRATI-GRAPHY	LITHOSTRATI-GRAPHY	CONODONT ZONATION (Ziegler and Sandberg, 1990)	MIOspore ZONATION		
			EASTERN EUROPE (Avkhimovitch et al., 1993)		OLD RED SANDSTONE CONTINENT (Richardson and McGregor, 1986; Streel, 2009)
LATE DEVONIAN	FAMENNIAN	<i>rhomboidea</i>	<i>L. immensus</i> Im		<i>Teichertospora torquata</i> - <i>Grandispora gracilis</i>  TG
		<i>crepida</i>	<i>C. cristifera</i> - <i>D. zadonica</i> CZ	Za GM	
	<i>triangularis</i>	<i>C. vimineus</i> - <i>G. vasjamica</i> VV			
FRASNIAN	Zhulumute Formation	<i>linguiformis</i>	<i>C. deliquescens</i> - <i>V. evlanensis</i> DE		<i>R. bricei</i> - <i>C. acanthaceus</i> BA
		<i>rhenana</i>			

Fig. 3. Correlation of Upper Devonian miospore biozones with conodont biozones and lithostratigraphy. Strip fields indicate the range of the sedimentological gap.



**Plate I.** Famennian miospores from the lower member of the Hongguleng Fm. in the Bulongguoer section. Scale bar = 20  $\mu\text{m}$ . **1:** *Dictyotriletes* sp., sample BLG6-7; **2–3:** *Corbulispora vimineus* (Nekriata) Obukhovskaya et Nekriata, 1983, sample BL-L-5.5-3 and BL-L-5.5-4; **4–5:** *Knoxisporites dedaleus* (Naumova) Streeel, 1977, sample BL-L-5.5-5 and BL-L-5.5-6; **6:** *Raistrickia* cf. *incompleta* Lu, 1981, sample BL-L-14.5-1; **7–8:** *Geminospora vasjamica* (Tchibrikova) Obukhovskaya et Nekriata, 1983, sample BL-L-14.5-2 and BL-L-46-99; **9:** *Grandispora gracilis* (Kedo) Streeel in Becker et al., 1974, sample BL-L-14.5-4; **10:** *Raistrickia* ? *multipartica* Hoffmeister, Staplin et Malloy, 1955, sample BL-L-14.5-5; **11:** *Spelaotriletes* sp., sample BL-L-17.5-1; **12:** *Auroraspora solisortus* Hoffmeister, Staplin et Malloy, 1955, sample BLG5-5; **13:** *Converrucosisporites curvatus* (Naumova) Turnau var. *medius*, Kedo, 1957?, sample BL-L-17.5-3; **14:** *Leotriletes* sp., sample BL-L-20-1; **15:** *Pustulatisporites pullus* (Naumova) Obukhovskaya, 1993, sample BL-L-5.5-12; **16:** *Lophozotriletes* sp., sample BL-L-20-0; **17:** *Lophozonotriletes lebedianensis* Naumova, 1953, sample BL-L-20-4; **18:** *Auroraspora* cf. *macra* Sullivan, 1968, sample BL-L-46-95; **19:** *Geminospora* sp., sample BL-L-46-100; **20:** *Lophozonotriletes* cf. *furszenkoi* Nekriata, 1974, sample BL-L-14.5-3.

same, which is the result of dissimilar paleoecologic or paleo-environmental conditions, or disparate taxonomic and nomenclatural interpretations among different authors (e.g., Wicander and Playford, 2013). Up to now, no global phytoplankton biozonation scheme has been proposed, although regional biozonations have been proposed in

the past (e.g., Molyneux et al., 1996; Le Hérisse et al., 2000; Filipiak, 2005).

The phytoplankton recovered from the lowermost part of the Hongguleng Fm. are of lower quantity, but also of lower diversity than the miospores from the same interval. Although the stratigraphic

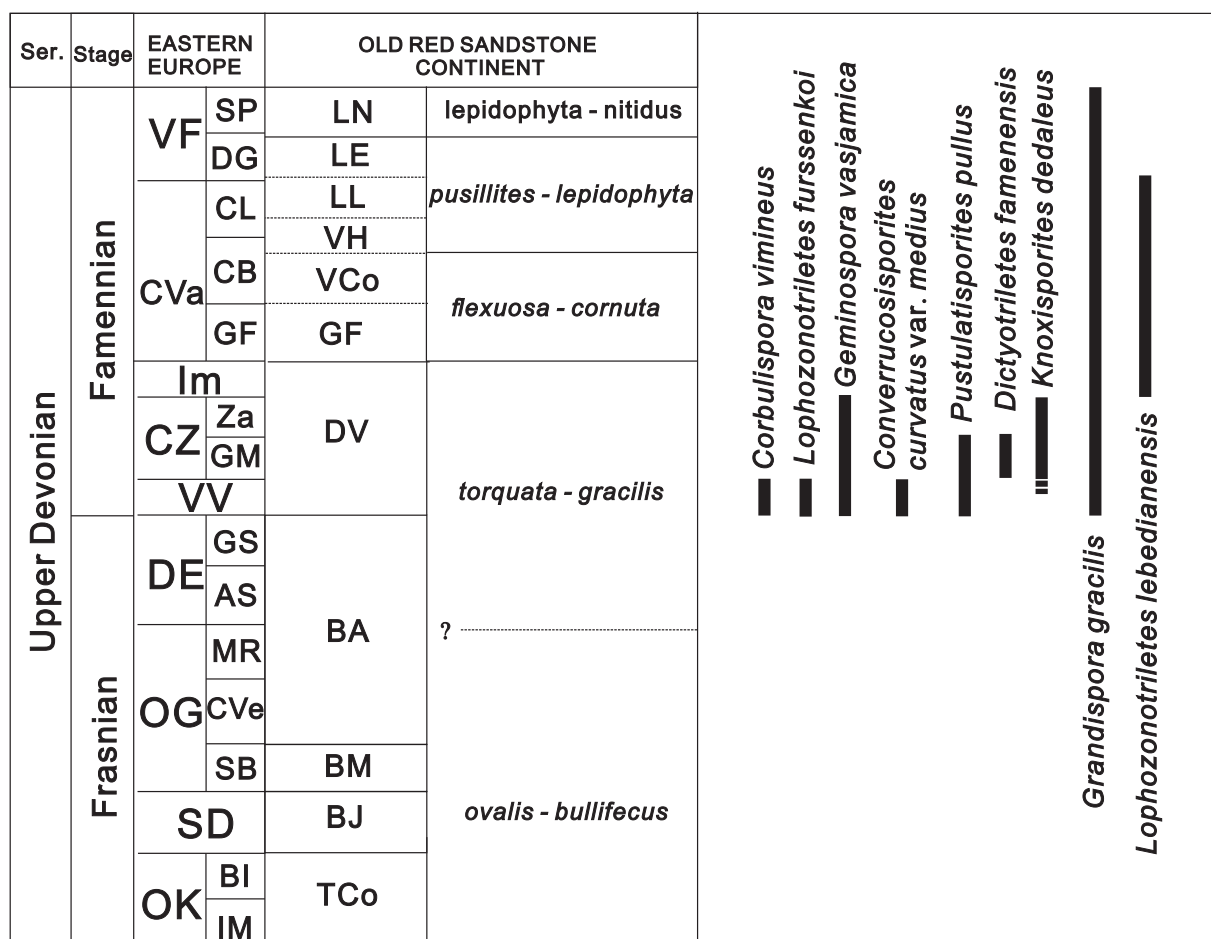


Fig. 4. Stratigraphic ranges of selected key miospore species identified in the investigated samples from the Bulongguoer section and approximate correlation of the miospore biozones of the Upper Devonian from eastern Europe (Avkhimovitch et al., 1993), and the Old Red Sandstone Continent (Streeel et al., 1987; Richardson and McGregor, 1986; Streeel, 2009).

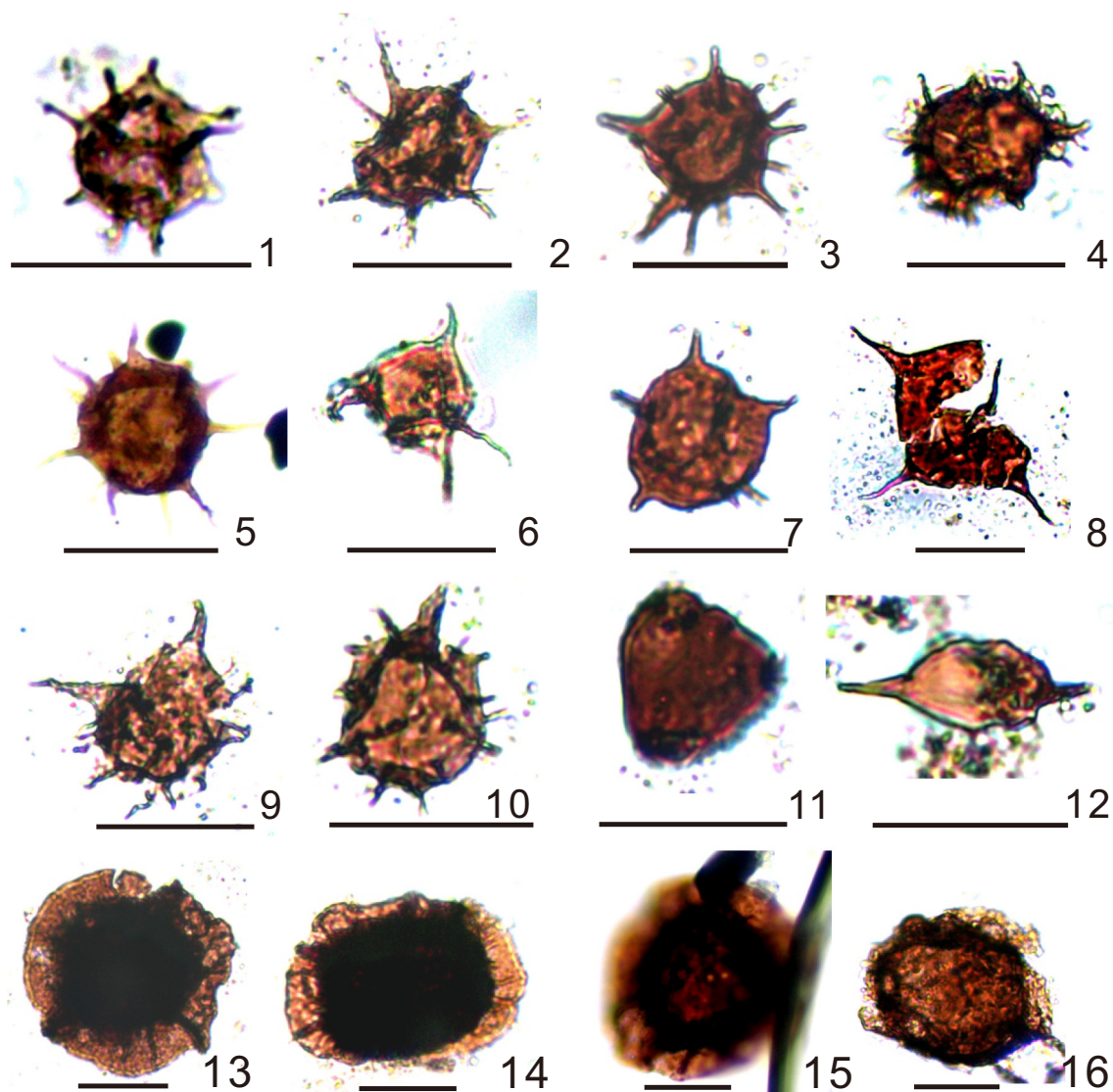
ranges recorded elsewhere in the world of several phytoplankton species recorded in this study commences in the Middle or even Early Devonian, many taxa identified are restricted to the Late Devonian at a global level. The Hongguleleng Fm. phytoplankton assemblage (Plates II, III) indeed points to a Late Devonian, especially Famennian age (Fig. 5). Among the common and cosmopolitan phytoplankton species identified in the present study, a few are restricted to the Late Devonian, although some of them have also been reported from the Mississippian (Fig. 5). These taxa include *Cymatiosphaera rhodana* Wicander and Loeblich, 1977, *Crassiangulina tessellata* Jardiné, Combaz, Magloire, Peniguel et Vachey, 1974, *Dictyotidium granulatum* Playford and Dring, 1981, *Estiastra culcita* Wicander, 1974, *Gorgonisphaeridium plerispinosum* Wicander, 1974, *Lophosphaeridium segregum* Playford, 1981, *Micrhystridium flexibile* Wicander, 1974, *Micrhystridium wepionense* (Stockmans and Willièere) Lu and Wicander, 1988, *Polydrixium lagoviense* Górka, 1974, *Solisphaeridium spinoglobosum* (Staplin) Wicander, 1974, and *Unellium piriforme* Rauscher, 1969. However, a few taxa are so far stratigraphically limited to the Famennian, providing a useful biostratigraphic information: *Crassiangulina tessellata*, *Cymatiosphaera rhodana*, *Estiastra culcita*, and *? Polydrixium lagoviense*. Most of these taxa need, however, a careful taxonomic and biostratigraphic revision.

Among the taxa recorded in the phytoplankton assemblage, *Estiastra culcita* Wicander, 1974 was previously mentioned from the Famennian Chagrín Shale, Ohio and Illinois Basin, U.S.A. (Wicander, 1974; Wicander and Playford, 2013). The discovery of this species in the Western

Junggar might be the first report outside Laurussia, South America and Iberia. Another species *Crassiangulina tessellata* Jardiné, Combaz, Magloire, Peniguel et Vachey, 1972, has been regarded as characteristic of peri-Gondwana localities, because it was possibly restricted to high paleolatitudinal regions of the margin of Gondwana, such as Iran (Ghavidel-Syooki, 2001), Portugal (Pereira et al., 2008, 2018), Lybia (Moreau-Benoit, 1984; Streeel et al., 1988), and Bolivia (Vavrdová et al., 1991) (Fig. 6). It seems not to be distributed in lower paleolatitudes during the Late Devonian (Molyneux et al., 2013). However, this latter taxon is possibly a senior synonym of *Veryhachium improcerum* Wicander and Loeblich, 1977. Although Wicander and Loeblich (1977) discussed the morphological differences between their newly established species *Veryhachium improcerum*, recorded from Indiana, U.S.A. and the holotype of *C. tessellata*, it can be assumed that, based on morphological characteristics, at least some specimens of *Veryhachium improcerum* (Wicander and Loeblich, 1977) can be considered to be synonymous of *C. tessellata*. The paleogeographic distribution of *C. tessellata* was therefore not only limited to the peri-Gondwanan border, but has probably a wider distribution, at least into the Kazakhstan Plate and Laurussia. *Crassiangulina tessellata* may well have been dispersed into lower paleolatitudes during the Late Devonian.

Globally, the phytoplankton assemblage of the Illinois Basin displays the closest similarity to that from the Famennian Hongguleleng Fm. (Fig. 6) (Wicander and Playford, 2013). In addition to the taxa that have been reported by Lu and Wicander (1988) and Stachacz et al. (2021), there are a number of stratigraphically long-range Devonian





**Plate II.** Famennian phytoplankton from the lower member of the Hongguleleng Fm. in the Bulongguoer section. Scale bar = 20  $\mu\text{m}$ . **1–3:** *Micrhystridium stellatum* Deflandre, 1945, sample BL-L-17.5-1; BL-L-46-5; BL-L-46-4; **4:** *Centrosphaeridium lecythium* Wicander et Playford, 1985, sample BL-L-34-1; **5:** *Solisphaeridium spinoglobosum* (Staplin) Wicander, 1974, sample BL-L-17.5-2; **6:** *Dorsennidium europaeum* (Stockmans et Willièrè, 1962) Sarjeant and Stancliffe 1994, sample BL-L-5.5-1; **7:** *Micrhystridium wepionense* (Stockmans and Willièrè) Lu et Wicander, 1988, sample BL-L-46-7; **8:** *Veryhachium lairdi* (Deflandre) Deunff, 1959, sample BL-L-46-14; **9:** *Unellium winslowiae* Rauscher, 1969, sample BL-L-46-12; **10:** *Unellium piriforme* Rauscher, 1969, sample BL-L-46-11; **11:** *Crassianguлина tessellata* Jardiné, Combaz, Magloire, Peninguel et Vachey, 1972, sample BL-L-46-2; **12:** *Leiofusa* sp., sample BL-L-20-7; **13–14:** *Pterospermella capitana* Wicander, 1974, sample BL-L-46-8; BL-L-20-3; **15:** *Muraticaeae enteichia* Wicander, 1974, sample BL-L-14.5-1; **16:** cf. *Divietipellis robusta* Wicander, 1974, sample BL-L-32-1.

taxa that have been found in the Hongguleleng Fm.; these include *Centrosphaeridium lecythium* Wicander and Playford, 1985, *Daillydium pentaster* (Staplin) Playford, 1981, *Gorgonisphaeridium evexispinosum* Wicander, 1974, *Pterospermella capitana* Wicander, 1974, *Dorsennidium europaeum* (Stockmans et Willièrè, 1962) Sarjeant and Stancliffe 1994, and *V. lairdii* (Deflandre) Deunff, 1959.

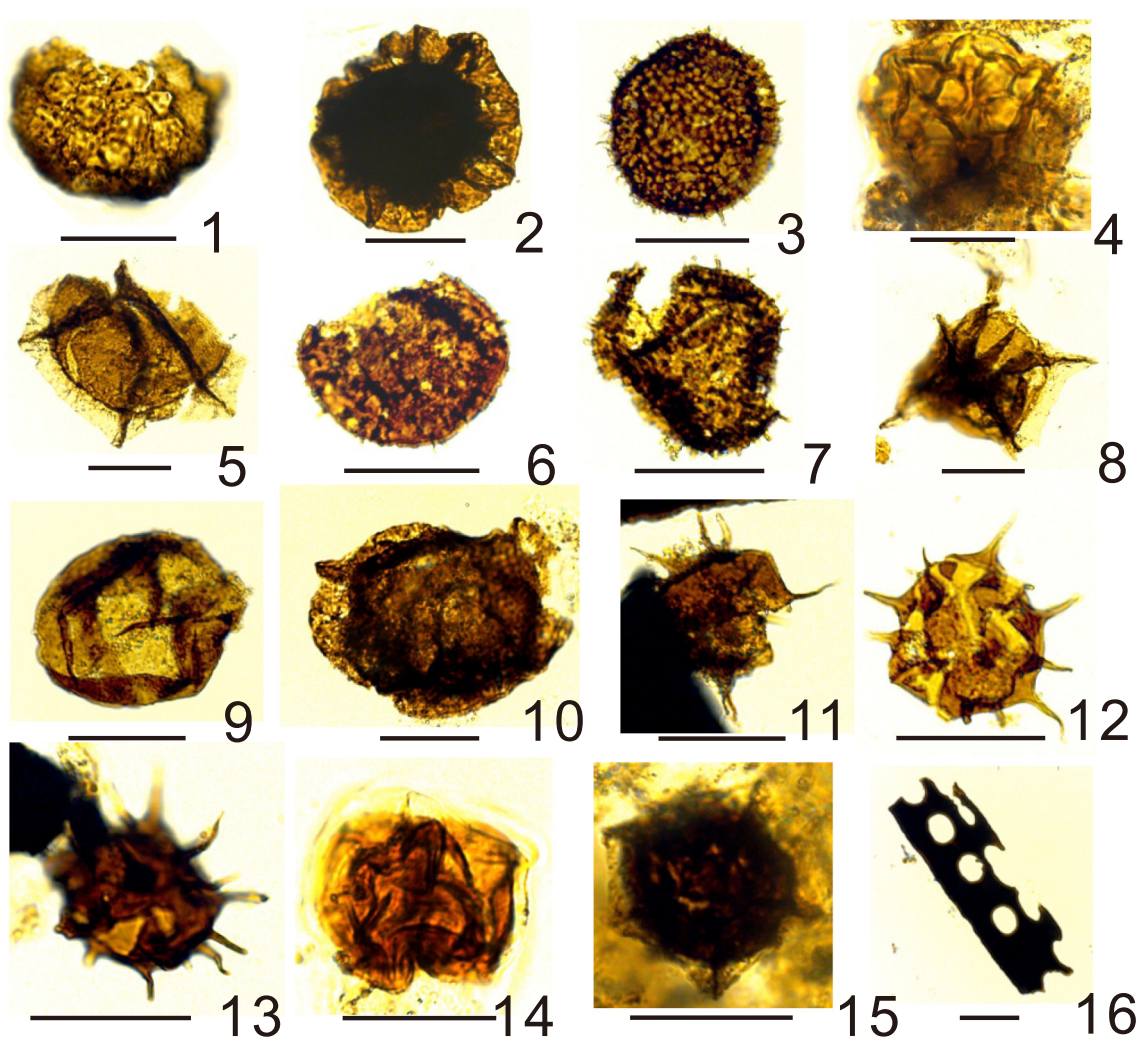
## 5. Discussion

### 5.1. Age implication of the lower member of the Hongguleleng Formation

Opinions differ regarding the age of the Hongguleleng Fm. Previous studies have exhibited that the age of the Hongguleleng Fm. was ranging from the Famennian to the early Carboniferous (Zhao, 1986; Zhao and Wang, 1990; Xia, 1996), while several authors believed that there were at least upper Frasnian strata at the bottom of the Hongguleleng Fm. (Xia, 1997; Chen et al., 2009; Suttner et al., 2014; Wang et al., 2016).

According to the palynological samples from the lower member of Hongguleleng Fm. in Bulongguoer section, Lu and Wicander (1988) indicated that the acritarch assemblage belonged to the late Frasnian-Famennian, and they considered that it was fairly similar to the assemblages from Belgium and North America. Despite this, these authors admitted that the miospores are very poorly preserved and difficult to compare with the coeval assemblages from Europe, North America, and other regions of China.

In western Europe, Streele (2009) renamed the previous miospore IV (latest Frasnian) and V (earliest Famennian) (Streele et al., 1987) biozones as the *Rugospora bricei*–*Cymbosporites acanthaceus* (BA) and *Knoxisporites dedaleus*–*Diducites versabilis* (DV) biozones (Fig. 4), respectively. In Western Junggar, *Knoxisporites dedaleus* (Plate I, 4–5) has been identified from sample BL-L-5.5 in the lowermost part of the Hongguleleng Fm., according to the discussion concerning western Europe, the *K. dedaleus* FOB (First Occurrence Biohorizon) should fit into the *triangularis* Biozone or even higher in the Famennian (Streele,



**Plate III.** Famennian palynomorphs from the lower member of the Hongguleleng Fm. in the Bulongguoer section. Scale bar = 20  $\mu$ m. **1:** *Dictyotidium granulatum* Playford and Dring, 1981, sample BLG5-7; **2:** *Pterospermella capitata* Wicander, 1974, sample BLG6-1; **3:** *Gorgonisphaeridium evexispinosum* Wicander, 1974, sample BLG4-1; **4:** *Cymatiosphaera rhodana* Wicander et Loeblich, 1977, sample BLG7-1; **5:** *Polyedryxium cf. ambitum* Wicander et Wood, 1981, sample BLG5-9; **6–7:** *Gorgonisphaeridium plerispinosum* Wicander, 1974, samples BLG5-14 and BLG5-15; **8:** *Polyedryxium pharaonis* (Deunff) Playford, 1977, sample BLG5-8; **9:** *Leiosphaeridia* sp., sample BLG2-1; **10:** *Divietipellis robusta* Wicander, 1974, sample BLG3-2; **11:** *Michystridium cf. pascheri* Stockmans et Willière, 1962, sample BLG5-3; **12–13:** *Michystridium flexibile* Wicander, 1974, samples BLG5-1 and BLG5-4; **14:** ? *Polyedryxium lagoviense* Górka, 1974, sample BLG5-5; **15:** *Daillyidium pentaster* (Staplin) Playford and Dring, 1981, sample BLG6-2; **16:** A plant tracheid fragment, sample BLG5-16.

2009). The other typical Famennian to Tournaisian (Tn1) species, such as *Diducites poljessicus*, can be recovered in the lowermost sample of the Hongguleleng Fm. (sample BLG-L-14.3; Plate IV, 12) as well. *Diducites poljessicus* first appeared in the early Famennian (Van Veen, 1980; Becker et al., 1974; Loboziak and Strel, 1981). Therefore, the lower member of the Hongguleleng Fm. should be of early Famennian age.

In terms of proportions, the organic material in the lowermost samples of the Hongguleleng Fm. is dominated by terrestrial microfloras represented by important taxa characteristic for the lower Famennian VV and CZ miospore Biozone, where important taxa, for instance *Corbulispora vimineus*, *Geminospora vasjamica*, *Dictyotrites famenensis*, have been observed (Fig. 7; Plate I). The appearance of *D. famenensis* and *L. lebedianensis* indicates that the earliest Famennian deposits (corresponding to the lower part of the VV miospore Biozone) may be missing in the lowermost part of the Hongguleleng Fm.

The conodont assemblages from the Hongguleleng Fm. of the Bulongguoer section reported by Zhao and Wang (1990) contain taxa that indicate the Famennian *crepida* to *marginifera* conodont biozones (Ziegler and Sandberg, 1990). However, Xia (1996) considered that

the lower member of the Hongguleleng Fm. was roughly equivalent to a conodont biozone spanning an interval from the Frasnian upper *Pa. rhenana* to the Famennian *crepida* biozones. More recently, Zhang (2019) reinvestigated the conodont assemblages of the lower member of the Hongguleleng Fm. Based on the presence of several significant Famennian taxa, such as *Palmatolepis prima* and *Ancyrognathus bifurcates*, Zhang (2019) supported Zhao and Wang's (1990) view that the lower member of the Hongguleleng Fm. did not contain any typical Frasnian conodont taxa and considered that the F/F boundary is not present in the Hongguleleng Fm.

The presence of corals and brachiopods in the lower member of the Hongguleleng Fm. is consistent with the Famennian age (Zong et al., 2017). In terms of brachiopods, the benthic brachiopod fauna from the Hongguleleng Fm. is characterized by an association of productids, rhynchonellids, and cyrtospiriferid spiriferids, and the absence of atrypides (an important group in pre-Famennian strata) (Ma et al., 2011). Five brachiopod assemblages of Famennian age have been established by Zong et al. (2016) based on new material from the Hongguleleng Fm. and the overlying Heishantou Fm. in western Junggar. In ascending order, they are: the *Caenanoplia?* aff. *logani*



Taxa	DEVONIAN						
	LOWER			MIDDLE		UPPER	
	Lochkovian	Pragian	Emsian	Eifelian	Givetian	Frasnian	Famennian
<b>MIOSPORE</b>							
<i>Aneurospora greggsii</i>							→ ?
<i>Auroraspora macra</i>							→ ?
<i>Auroraspora solisortus</i>							→ ?
<i>Corbulispora vimineus</i>							→ ?
<i>Converrucosporites curvatus</i> var. <i>medius</i>							→ ?
<i>Cymbosporites</i> sp. cf. <i>C. magnificus</i>							→ ?
<i>Dictyotrilletes famenensis</i>							→ ?
<i>Diducites poljessica</i>							→ ?
<i>Geminospora punctata</i>							→ ?
<i>Grandispora gracilis</i>							→ ?
<i>Geminospora vasjamica</i>							→ ?
<i>Knoxisporites dedaleus</i>							→ ?
<i>Lophozonotriletes</i> cf. <i>L. fursenkoi</i>							→ ?
<i>Lophozonotriletes lebedianensis</i>							→ ?
<i>Raistrickia</i> cf. <i>incompleta</i>							→ ?
<i>Raistrickia</i> ? <i>multipertica</i>							→ ?
? <i>Acanthotriletes hacquebardii</i>							→ ?
<i>Pustulatisporites pullus</i>							→ ?
<b>PHYTOPLANKTON</b>							
<i>Cymatiosphaera rhodana</i>							→ ?
<i>Crassiangulina tessellata</i>							→ ?
<i>Centrasphaeridium lecythium</i>							→ ?
<i>Dictyotidium granulatum</i>							→ ?
<i>Daillyidium pentaster</i>							→ ?
<i>Divietipellis robusta</i>							→ ?
<i>Estiastra culcita</i>							→ ?
<i>Gorgonisphaeridium plerispinosum</i>							→ ?
<i>Gorgonisphaeridium evexispinosum</i>							→ ?
<i>Lophosphaeridium segregum</i>							→ ?
<i>Micrhystridium flexibile</i>							→ ?
<i>Micrhystridium pascheri</i>							→ ?
<i>Micrhystridium stellatum</i>							→ ?
<i>Micrhystridium wepionense</i>							→ ?
<i>Muraticaea enteichia</i>							→ ?
<i>Polyedryxium</i> cf. <i>ambitum</i>							→ ?
? <i>Polyedryxium lagoviense</i>							→ ?
<i>Polyedryxium pharaonis</i>							→ ?
<i>Pterospermella capitata</i>							→ ?
<i>Solisphaeridium spinoglobosum</i>							→ ?
<i>Dorsennidium europaeum</i>							→ ?
<i>Veryhachium lairdi</i>							→ ?
<i>Veryhachium trispinosum</i>							→ ?
<i>Unellium winslowiae</i>							→ ?
<i>Unellium piriforme</i>							→ ?

Fig. 5. Stratigraphic ranges of selected miospore and phytoplankton species from the Hongguleleng Fm. Dashed lines indicate uncertainty of range limits; arrows denote ranges extending into the Silurian and Mississippian.

assemblage, the *Paleospirifer*–*Megalopterorhynchus* assemblage, which can be divided into the *Cyrtospirifer sulcifer* subassemblage and the *Rugaltarostrium* subassemblage, the *Ambocoelia?* cf. *unionensis* assemblage, the *Austrospirifer?* sp. assemblage, and the *Syringothyris*–*Spirifer* assemblage, which corresponds to the standard Famennian conodont biozone starting upwardly from the *crepida* Biozone (Zong et al., 2016). The distribution of the brachiopods suggests that the lower member of the Hongguleleng Fm. is consistent with the evidence of the conodont biozonation of Zhao and Wang (1990), where the earliest Famennian *triangularis* conodont Biozone is missing.

Regarding geochemical research, Suttner et al. (2014) analyzed the lithology and facies, conodont biostratigraphy and geochemical data in the Bulongguoer section. The authors believed that the basal limestone beds of the so-called “Hongguleleng Fm.” belong to the late Frasnian *linguiformis* conodont Biozone, and that the Frasnian–Famennian transition is located 2.7 m above the formation boundary, based on the first occurrence of *Palmatolepis triangularis*. A prominent positive excursion of  $\delta^{13}\text{C}$  is occurring at the base of the Hongguleleng Fm. across the F/F boundary (the *linguiformis*–*triangularis* zonal boundary) increasing from  $-5.72\%$  to maximum values of  $+0.62\%$ . Suttner et al. (2014) also explained that the high covariance of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  ( $r^2 = 0.98$ ) at the base of the Hongguleleng Fm. indicates that the isotope signal may be diagenetic and not a primary signal of marine chemistry (Suttner et al., 2014). At about the same time Carmichael et al. (2014) analyzed

the geochemical proxies from the uppermost 1 m of the Zhulumute Fm. to the basal 6 m of the Hongguleleng Fm. in the Bulongguoer section and recognized the Upper Kellwasser Anoxia Event, with a 2‰ positive  $\delta^{13}\text{C}$  excursion at the “F/F boundary.”

Recently, the carbon and oxygen isotopes of the Bulongguoer section have been restudied by Zong et al. (2017). After considering the diagenesis on the lower part of the lower member, the new trend of  $\delta^{13}\text{C}$  result is strikingly similar to that of Suttner et al. (2014) and Carmichael et al. (2014). However, there is no significant positive excursion signal at the base of the Hongguleleng Fm. Interestingly, this variation trend of  $\delta^{13}\text{C}$  in the lower member of the Hongguleleng Fm. can be compared with that from coeval conodont zones from central Hunan Province, South China (*Pa. crepida*–*Pa. rhomboidea* conodont biozones).

In summary, multiple evidence, including works from microfloral assemblages, indicates that the F/F boundary may not exist in the Hongguleleng Fm., and that even the earliest Famennian strata, corresponding to the *Pa. triangularis* Biozone may be missing in Western Junggar (Fig. 3; Ma et al., 2017; Zong et al., 2017).

## 5.2. The F/F transitional eustatic regression and its response

Despite the fact that the cause of the Late Devonian F/F biotic crisis is still controversially debated, many authors believe that the significant climatic cooling, which may have resulted in short-term glacial phases

Localities	<i>Crassianguina tessellata</i>	<i>Diclyotidium granulatum</i>	<i>Cymatiosphaera rhodana</i>	<i>Daillyidium pentaster</i>	<i>Dvietipellis robusta</i>	<i>Estiastra calcita</i>	<i>Gorgonispheeridium evexipinosum</i>	<i>Lophospheeridium segregum</i>	<i>Microhystridium pascheri</i>	<i>Microhystridium flexibile</i>	<i>Microhystridium stellatum</i>	<i>Cymatospheera anera</i>	<i>Microhystridium wepionense</i>	<i>Pterosperma capitata</i>	<i>Polyedrixium lagoviense</i>	<i>Polyedrixium pharaonis</i>	<i>Solisphaeridium spinoglobosum</i>	<i>Unellium winslowiae</i>	<i>Unellium piriforme</i>	<i>Veryhachium trispinosum</i>	<i>Dorsemmidium europaeum</i>	<i>Veryhachium lairdi</i>	References
Carnarvon Basin, Australia	x	x					x	x							x	x		x				Playford, 1981 Playford and Dring, 1981	
Alberta, southern Saskatchewan, Canada			x								x					x	x		x			Staplin, 1961 Playford and McGregor, 1993	
Esfahan and Tabas, Iran			x								x					x	x		x			Hashemi and Playford, 1998 Ghavidel-Syooki, 2001	
Hakkari Province, Turkey	x	x					x	x			x								x			Higgs et al., 2002	
South Portuguese Zone, Portugal	x		x								x								x	x		Pereira et al., 2008	
Northeast Libya, Libya	x										x						x					Moreau-Benoit, 1984 Streel et al., 1988	
Titikaka Lake and Bermejo, Bolivia	x										x						x					Vavrdová et al., 1991 Wicander et al., 2011	
Algerian Sahara, Algeria			x																			Jardiné et al., 1974	
Dinant Basin, Belgium			x											x								Martin, 1984 Martin, 1981	
Belgium												x						x	x			Stockmans and Williére, 1962	
Illinois, Ohio, Iowa, Indiana, U.S.A.			x				x	x		x		x	x				x					Wicander, 1974 Wicander and Loeblich, 1977 Wicander and Playford, 2013 Wicander and Playford, 1985	
Holy Cross Mountains, Poland	x							x	x		x			x			x	x	x	x	x	Filipiak, 2005 Filipiak, 2009 Marynowski et al., 2010	
Nyalam, Tibet, China			x				x	x	x		x				x	x				x		Górka, 1974 Gao, 1986	

**Fig. 6.** Comparison of selected phytoplankton from the Hongguleleng Fm. with other published Upper Devonian acritarch assemblages from Australia (Playford, 1981; Playford and Dring, 1981), Canada (Playford and McGregor, 1993; Staplin, 1961), Iran (Ghavidel-Syooki, 2001; Hashemi and Playford, 1998), Turkey (Higgs et al., 2002), Portugal (Pereira et al., 2008), Libya (Moreau-Benoit, 1984; Streel et al., 1988), Bolivia (Vavrdová et al., 1991; Wicander et al., 2011), Belgium (Martin, 1981, 1984; Stockmans and Williére, 1962), U.S.A. (Wicander, 1974; Wicander and Loeblich, 1977; Wicander and Playford, 1985, 2013), Poland (Filipiak, 2005, 2009; Górka, 1974; Marynowski et al., 2010) and China (Gao, 1986), respectively.

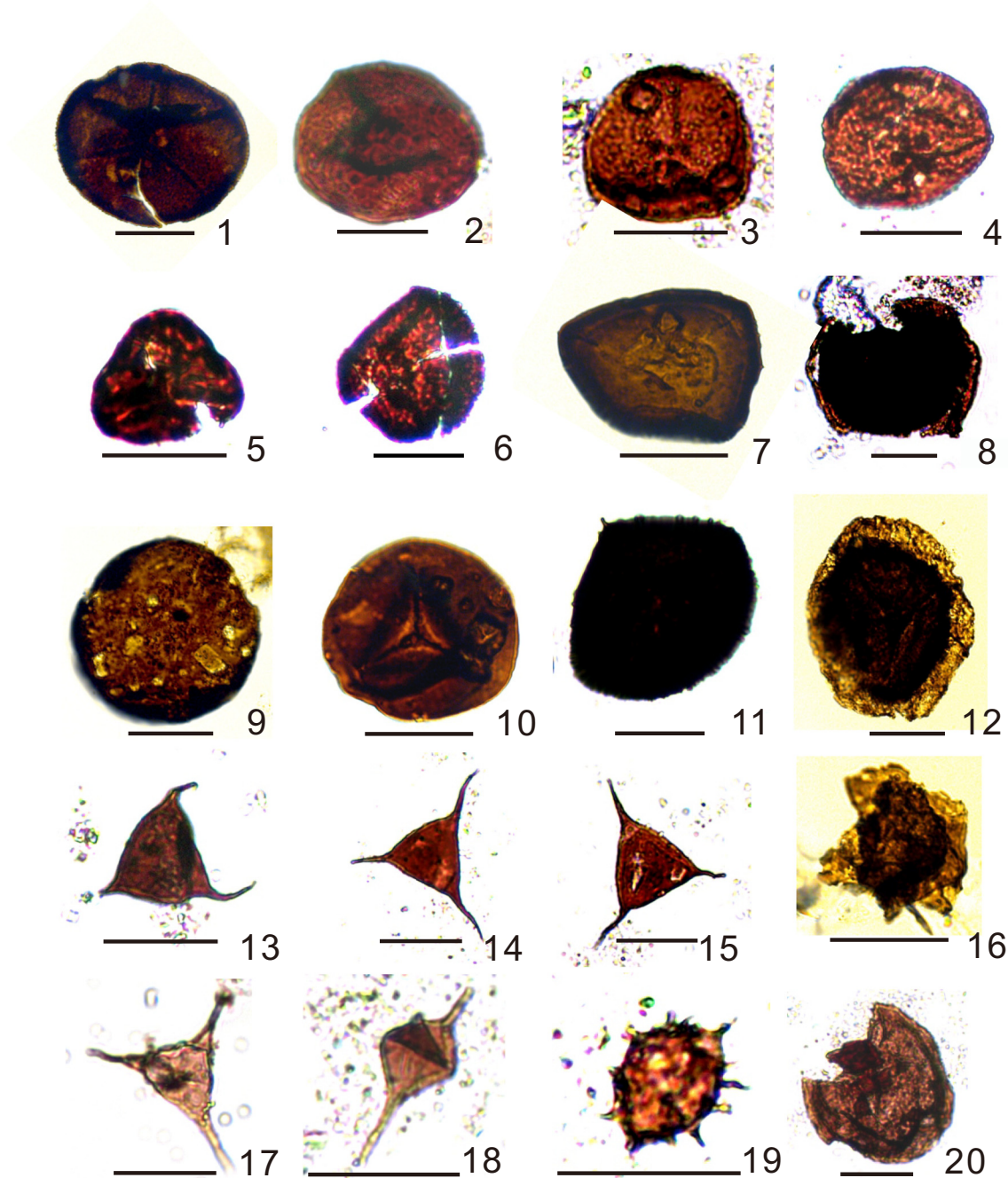
(Streel et al., 2000) and regression (Johnson et al., 1985; Ma et al., 2016), is one of the major drivers of the F/F event (Song et al., 2017a; Huang et al., 2018). A large-scale regression occurred globally in the latest Frasnian (Veimarn et al., 1997; Muchez et al., 1996; Ma et al., 2016), resulting in a hiatus that has been recorded in central North America (Day, 1998), Poland (Racki et al., 2002), Germany (Piecha, 2002), France (Loboziak and Streel, 1981), Southern Siberia (Gutak et al., 2011), western Russia (Filipiak and Krawczyński, 2018), and Western Junggar.

In southern Poland, high-resolution biostratigraphic studies confirmed the occurrence of a third-order sequence boundary in the F/F transition in an active synsedimentary tectonic setting, marked by erosional discontinuities, hardgrounds and brecciation or omission surfaces (Racki et al., 2002). In the Volga region, the lowest part of the Famennian succession is always absent in the Central Devonian Field, Russia (Obukhovskaya et al., 2000), and a prominent paraconformity (or even disconformity) is suggested to be at the boundary level over the central and western part of the East European Platform (Tikhomirov, 1995; Alekseev et al., 1996; Nikishin et al., 1996; Mantsurova, 2003; Zatoń et al., 2014; Filipiak and Krawczyński, 2018). Filipiak and Zbukova (2006) focused on the palynostratigraphy of the Frasnian-Famennian boundary from the Central Devonian Field, western Russia. The research confirmed the existence of a sedimentological

gap between the Livny and Zadonsk horizons, including all of the Volgrad horizon, the depositional break near the F/F transition caused the loss of *Corbulispora viminea*-*Geminispora vasjamica* (VV) miospore Biozone (Filipiak and Zbukova, 2006; Filipiak and Krawczyński, 2018).

In the Boulonnais area, France, and at Senzeilles, Belgium, a dolomitic bed is exposed in the Hydrequent Fm. near the F-F boundary. The last spore assemblage from the uppermost part of the Hydrequent Fm. containing taxa such as *Knoxisporites dedaleus*, *K. cf. hederatus*, *Auroraspora hyalina*, *A. macra*, and *Diducites plicabilis*, is very different from the lower part, implying the presence of a possible sediment gap or condensation between the dolomitic bed and these samples (Loboziak and Streel, 1981). Therefore, the uppermost part of the Hydrequent Fm. corresponds to the *P. crepida* Biozone, and there is likely to be a depositional hiatus in the Boulonnais between the miospore assemblages IV and V (Streel et al., 1987; Streel, 2009), which is probably caused by the eustatic regression at the end of the Frasnian age.

In the semi-restricted and restricted platform facies of Dushan, Guizhou Province, South China, the Yaosuo Fm. near the F/F boundary interval is characterized by thick to massive dolomitic limestones and dolostones in some intervals with two erosive surfaces occurring at the bottom and lower part of the dolomitic bed (Wang and Chen, 1999). Similarly, the eustatic sea-level regression happened in



**Plate IV.** Famenian miospores (1–12) and phytoplankton (13–20) from the lower member of the Hongguleleng Fm. in the Bulongguoer section. Scale bar = 20  $\mu\text{m}$ . **1:** *Aneurospora greggsii* (McGregor) Streeel in Becker, Bless, Streeel et Thorez, 1974, sample BLG6-6; **2:** *Dictyotriletes famenensis* Naumova, 1953, sample BL-L-20-6; **3–4:** *Aneurospora* spp., samples BL-L-46-97 and BL-L-46-93; **5:** *Camarazonotriletes* sp., sample BL-L-46-98; **6:** *Cymbosporites* cf. *magnificus* (McGregor) McGregor et Camfield, 1982, sample BL-L-46-96; **7:** *Geminospira punctata* Owens, 1971, sample BLG6-1; **8:** *Auroraspora macra* Sullivan, 1968, sample BL-L-46-94; **9:** ? *Tholisporites* sp., sample BLG5-13; **10:** *Retusotriletes* sp., sample BLG6-11; **11:** ? *Acanthotriletes hacquebardii* Playford, 1964, sample BL-L-5.5-5; **12:** *Diducites poljessica* (Kedo) emend. Van Veen, 1981, sample BLG3-1; **13–15:** *Veryhachium trispinosum* (Eisenack, 1938) Stockmans et Willièere, 1962, sample BL-L-38.7-1; BL-L-46-16; BL-L-52.5-1; **16:** *Estiastra culcita* Wicander, 1974, sample BLG3-2; **17:** *Dorsennidium europaeum* (Stockmans et Willièere, 1962)

Hunan Province, South China also caused a sedimentary hiatus at the top of the Wujiayang Fm., that is dominated by the near-shore sandy facies in the Leimingqiao section, and at the top of the Laojiangchong Fm., dominated by subtidal mixed carbonate and argillaceous facies in the Qiziqiao section, which led to the absence of the earliest Famenian *Yunnanella* interval in both sections. Therefore, the F/F boundary is also not present in the concerned sections (Ma et al., 2016).

The Western Junggar is located in the CAOB, where the Upper Devonian is mainly composed of the Frasnian Zhulumute Fm., and the Famenian Hongguleleng Fm. Regarding the lithological sequence, the Zhulumute Fm. is composed of sandstones, gravel sandstones, tuffaceous sandstones, and conglomerates as a whole, with rich plant stem fossils discovered frequently at outcrops (Cai, 1989; Xu et al., 2017; Zheng et al., 2020), which was thought to represent a fluvial environment (e.g., Zheng et al., 2020). The overlying lower member of the



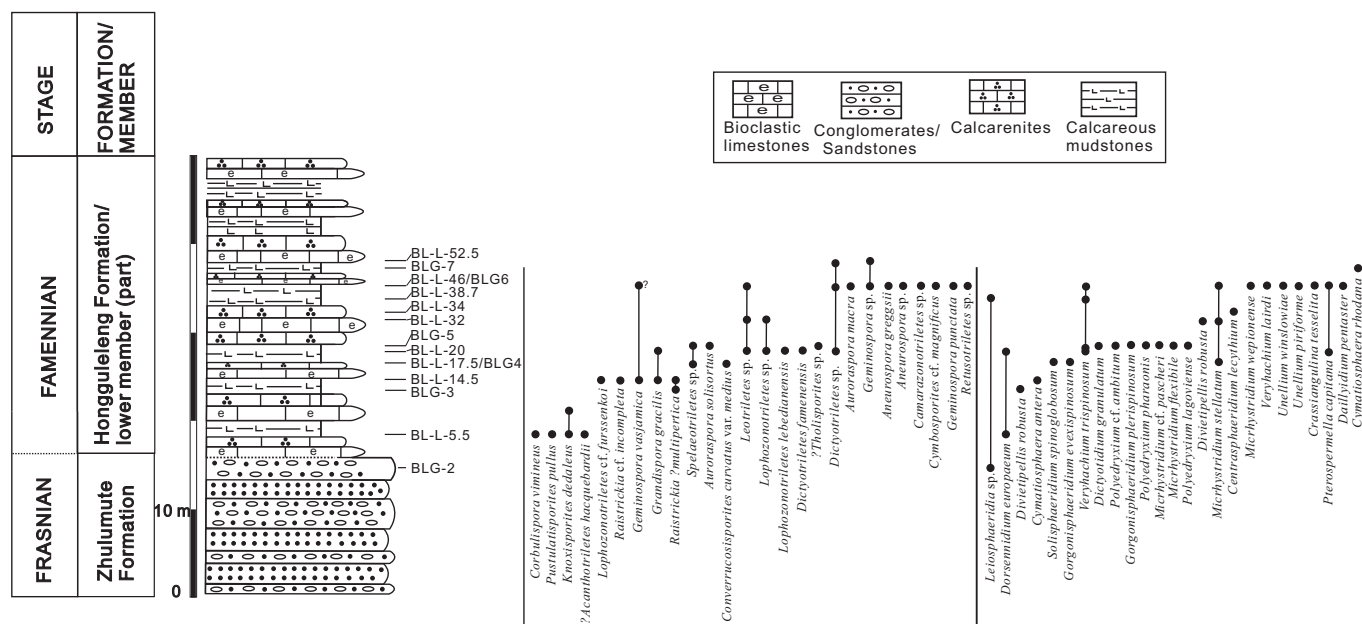


Fig. 7. Range chart of miospores and phytoplankton species in the investigated samples.

Hongguleleng Fm., deposited in a shallow marine sedimentary environment, is composed mainly of bioclastic limestones, variegated siliceous claystones, tuffaceous siltstones and fine-grained sandstones. A layer of thin-bedded bioclastic or shelly limestone appears at the bottom of the Hongguleleng Fm., representing a saltatory type sea-level change, which is characterized by a rapid and high-magnitude sea-level fluctuation in a very short time. As mentioned previously, two ditches were dug to reveal the contact of the parallel unconformity, where a layer of loose sandstone, approximately 25 cm thick, has been found at the top of the Zhulumute Fm. (e.g., Ma et al., 2011), which indicates that a depositional loss (i.e., an erosional surface) occurred in Western Junggar. In the Wulankeshun section, approximately 100 km from the Bulongguoer section, the lowermost Hongguleleng Fm. was deposited in a shallow sedimentary environment. Wang et al. (2016) believed that the latest Frasnian regression may have caused the intermittent sedimentary discontinuity in this area, although it is still unclear whether this discontinuity is widespread in Western Junggar. According to the latest data adopted by the International Commission on Stratigraphy, the absolute age threshold for the F/F boundary is between 370.6 and 373.8 Ma. More recently, the new radio-isotopic (U–Pb) ages provided some precision for the placement of the F/F boundary in Western Junggar to be within the upper part of Zhulumute Fm. (Zheng et al., 2020).

## 6. Conclusion

The newly discovered palynomorphs at the lower member of the Hongguleleng Fm. can be attributed to the early Famennian. The composition of the miospore assemblage corresponding to the eastern European *Corbulispora vimineus*–*Geminosporea vasyamica* (VV) and *Cyrtospora cristifer*–*Diaphanospora zadonica* (CZ) miospore biozones is roughly equivalent to the *Pa. crepida* conodont Biozone. The elements of the assemblage may be compared widely with coeval miospore taxa from eastern Europe, and western Europe. Despite the fact that the microfloras are very poorly preserved and more detailed palynological studies are still needed, there is now sufficient evidence, in addition to the previous biostratigraphy works based on brachiopods and conodonts, as well as  $\delta^{13}\text{C}$  geochemical data, to indicate that the earliest Famennian miospore zone (i.e., the lower part of the VV Biozone, also

known as the conodont *Pa. triangularis* Biozone) is most likely to be missing from the lower member of the Hongguleleng Fm.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

This work was financially supported by the National Natural Science Foundation of China [grant numbers 41872034, 41702006, 41290260]. P.S. is financed by the National Fund of Scientific Research. The authors grateful to Dr. Xinsong Zhang (Fuzhou University) for a valuable discussion. Sylvie Regnier (Lille University) helped with sample preparation. The manuscript greatly benefited from the comments and suggestions of the editor Michael Stephenson and reviewer Paweł Filipiak (University of Silesia in Katowice, Poland) and another anonymous reviewer.

## Appendix A. Alphabetic listing of miospore and phytoplankton species, used in the text and explanations of figures

### A.1. Miospore taxa

- ?*Acanthotriletes hacquebardii* Playford, 1964
- Aneurospora greggsii* (McGregor) Strel in Becker, Bless, Strel et Thorez, 1974
- Aneurospora* spp.
- Auroraspora macra* Sullivan, 1968
- Auroraspora solisortus* Hoffmeister, Staplin et Malloy, 1955
- Camarazonotriletes* sp.
- Converrucosporites curvatus* (Naumova) Turnau var. *medius*, Kedo, 1957
- Corbulispora vimineus* (Nekriata) Obukhovskaya et Nekriata, 1983
- Cymbosporites* cf. *magnificus* (McGregor) McGregor et Camfield, 1982
- Dictyotriletes famenensis* Naumova, 1953
- Diducites poljessica* (Kedo) emend. Van Veen, 1981
- Geminosporea punctata* Owens, 1971

*Geminospora vasjamica* (Tchibrikova) Obukhovskaya et Nekriata, 1983

*Geminospora* sp.

*Grandispora gracilis* (Kedo) Streele in Becker et al., 1974

*Knoxisporites dedaleus* (Naumova) Streele, 1977

*Leotriletes* sp.

*Lophozonotriletes* cf. *furssenkoi* Nekriata, 1974

*Lophozonotriletes lebedianensis* Naumova, 1953

*Lophozonotriletes* sp.

*Pustulatisporites pullus* (Naumova) Obukhovskaya, 1993

*Raistrickia* cf. *incompleta* Lu, 1981

*Raistrickia* ? *multipectica* Hoffmeister, Staplin et Malloy, 1955

*Retusotriletes* sp.

*Spelaeotriletes* sp.

?*Tholisporites* sp.

## A.2. Phytoplankton taxa

*Centrasphaeridium lecythium* Wicander et Playford, 1985

*Crassianguilina tessellata* Jardiné, Combaz, Magloire, Peniguel et Vachey, 1972

*Cymatiosphaera rhodana* Wicander et Loeblich, 1977

*Dailyidium pentaster* (Staplin) Playford and Dring, 1981

*Dictyotidium granulatum* Playford and Dring, 1981

*Divietipellis robusta* Wicander, 1974

*Dorsennidium europaeum* (Stockmans et Willièrè, 1962) Sarjeant and Stancliffe 1994

*Estiastra culcita* Wicander, 1974

*Gorgonisphaeridium evexispinosum* Wicander, 1974

*Gorgonisphaeridium plerispinosum* Wicander, 1974

*Leiofusa* sp.

*Leiosphaeridia* sp.

*Lophosphaeridium segregum* Playford, 1981

*Micrhystridium stellatum* Deflandre, 1945

*Micrhystridium wepionense* (Stockmans and Willièrè) Lu et Wicander, 1988

*Micrhystridium* cf. *pascheri* Stockmans et Willièrè, 1962

*Micrhystridium flexibile* Wicander, 1974

*Muraticaea enteichia* Wicander, 1974

*Polyedryxium* cf. *ambitum* Wicander et Wood, 1981

*Polyedryxium pharaonis* (Deunff) Playford, 1977

?*Polyedryxium lagoviense* Górka, 1974

*Pterospermella capitana* Wicander, 1974

*Solisphaeridium spinoglobosum* (Staplin) Wicander, 1974

*Unellium winslowiae* Rauscher, 1969

*Unellium piriforme* Rauscher, 1969

*Veryhachium lairdi* (Deflandre) Deunff, 1959

*Veryhachium trispinosum* (Eisenack, 1938) Stockmans et Willièrè, 1962

*Veryhachium* sp.

## References

- Alekseev, A.S., Kononova, L.L., Nikishin, A.M., 1996. The Devonian and Carboniferous of the Moscow syncline (Russian Platform): stratigraphy and sea-level changes. *Tectonophysics* 268, 149–168.
- Avkhimovitch, V.I., Tchibrikova, E.V., Obukhovskaya, T.G., Nazarenko, A.M., Umnova, V.T., Raskatova, L.G., Mantsurova, V.N., Loboziak, S., Streele, M., 1993. Middle and Upper Devonian miospore zonation of Eastern Europe. *Bull. Centres Rech. Explor. Prod. Elf-Aquitaine* 17, 79–147.
- Becker, G., Bless, M.J., Streele, M., Thorez, J., 1974. Palynology and ostracod distribution in the Upper Devonian and basal Dinantian of Belgium and their dependence on sedimentary facies. *Mededelingen-Rijks Geologische Dienst* 25 (2), 9–99.
- Boucot, A.J., Chen, X., Scotese, C.R., Morley, R.J., 2013. Phanerozoic paleoclimate: an atlas of lithologic indicators of climate. *SEPM Concepts in Sedimentology and Paleontology* No. 11. SEPM. Society for Sedimentary Geology, Tulsa, p. 478.
- Cai, C., 1989. Two Callixylon species from Upper Devonian of Junggar Basin, Xinjiang. *Acta Palaeontol. Sin.* 28, 571–578.
- Cai, C., 2000. Non-marine Devonian of China. In: Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences (Eds.), *Stratigraphical Studies in China* (1979–1999). Science and Technology University Press, Hefei, pp. 95–128 (in Chinese).
- Carmichael, S.K., Waters, J.A., Suttner, T.J., Kido, E., DeReuil, A.A., 2014. A new model for the Kellwasser Anoxia Events (Late Devonian): Shallow water anoxia in an open oceanic setting in the Central Asian Orogenic Belt. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 399, 394–403.
- Carmichael, S.K., Waters, J.A., Batchelor, C.J., Coleman, D.M., Suttner, T.J., Kido, E., Moore, L.M., Chadimová, L., 2016. Climate instability and tipping points in the Late Devonian: Detection of the Hangenberg Event in an open oceanic island arc in the Central Asian Orogenic Belt. *Gondwana Res.* 32, 213–231.
- Chen, B., Arakawa, Y., 2005. Elemental and Nd–Sr isotopic geochemistry of granitoids from the West Junggar foldbelt (NW China), with implications for Phanerozoic continental growth. *Geochim. Cosmochim. Acta* 69 (5), 1307–1320.
- Chen, X.Q., Mawson, R., Suttner, T.J., Talent, J.A., Fryda, J., Mathieson, D., Molloy, P., Berykova, S., 2009. Late Devonian (latest Frasnian–Famennian) faunas from the ‘Hongguleng Formation’ and the FF-boundary in northern Xinjiang, NW China. *Berichte des Institutes für Erdwissenschaften, Karl-Franzen-Universität Graz* 14, 18–20.
- Cocks, L.R.M., Torsvik, T.H., 2007. Siberia, the wandering northern terrane, and its changing geography through the Palaeozoic. *Earth Sci. Rev.* 82, 29–74.
- Day, J., 1998. Distribution of latest Givetian–Frasnian Atrypida (Brachiopoda) in central and western North America. *Acta Palaeontol. Pol.* 43 (2), 205–240.
- Fan, R.Y., Gong, Y.M., 2016. Ichnological and sedimentological features of the Hongguleng Formation (Devonian–Carboniferous transition) from the western Junggar, NW China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 448, 207–223.
- Filipiak, P., 2005. Late Devonian and early Carboniferous acritarchs and prasinophytes from the Holy Cross Mountains (central Poland). *Rev. Palaeobot. Palynol.* 134, 1–26.
- Filipiak, P., 2009. Lower Famennian phytoplankton from the Holy Cross Mountains, Central Poland. *Rev. Palaeobot. Palynol.* 157, 326–338.
- Filipiak, P., Krawczyński, W., 2018. Palynological and microfacies analysis of the Famennian part of the Russkiy Brod Quarry section, Central Devonian Field, Russia. *Rev. Palaeobot. Palynol.* 249, 50–60.
- Filipiak, P., Zbukova, D.V., 2006. Palynostratigraphy of the Frasnian–Famennian boundary deposits from the Central Devonian Field, western Russia and comparisons with adjacent areas. *Rev. Palaeobot. Palynol.* 138 (2), 109–120.
- Gao, L.D., 1986. Late Devonian and early Carboniferous acritarchs from Nyalam county, Xizang (Tibet), China. *Rev. Palaeobot. Palynol.* 47, 17–30.
- Gao, L.D., 2015. The Late Devonian–Early Carboniferous miospore zonation in the lower Yangtze Valley, China and the Devonian–Carboniferous boundary. *Acta Geoscient. Sin.* 36, 7–21 in Chinese with English abstract.
- Ghavidel-Syooki, M., 2001. Palynostratigraphy and paleogeography of the Late Devonian in northeastern Esfahan City, central Iran. In: Goodman, D.K., Clarke, R.T. (Eds.), *Proceedings of the IX International Palynological Congress, Houston, Texas, USA, 1996*. American Association of Stratigraphic Palynologists Foundation, pp. 37–51.
- Górka, H., 1974. Quelques informations sur une association d’acritarches du Famennien de Pologne. *Rev. Palaeobot. Palynol.* 18, 131–135.
- Gutak, J.M., Antonova, V.A., Ruban, D.A., 2011. Diversity and richness of the Devonian terrestrial plants in the Southeastern Mountainous Altay (Southern Siberia): Regional versus global patterns. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 299, 240–249.
- Hashemi, H., Playford, G., 1998. Upper Devonian palynomorphs of the Shishtu Formation, Central Iran Basin, east-central Iran. *Palaeontogr. Abt. B* 246, 115–212.
- Higgs, K.T., Finucane, D., Tunbridge, I.P., 2002. Late Devonian and early Carboniferous microfloras from the Hakkari Province of southeastern Turkey. *Rev. Palaeobot. Palynol.* 118, 141–156.
- Hou, H.F., Lane, N.G., Waters, J.A., Maples, C.G., 1993. Discovery of a new Famennian echinoderm fauna from the Hongguleng Formation of Xinjiang, with redefinition of the formation. In: Yang, Z.Y. (Ed.), *Stratigraphy and Paleontology of China*. vol. 2. Geological Publishing House, Beijing, pp. 1–18.
- Huang, C., Joachimski, M.M., Gong, Y.M., 2018. Did climate changes trigger the late Devonian Kellwasser Crisis? Evidence from a high-resolution conodont record from South China. *Earth Planet. Sci. Lett.* 495, 174–184.
- Jahn, B.M., Wu, F., Chen, B., 2000. Granitoids of the Central Asian Orogenic Belt and continental growth in the Phanerozoic. *Trans. R. Soc. Edinb. Earth Sci.* 91, 181–193.
- Jardiné, S., Combaz, A., Magloire, L., Péniguel, G., Vachey, G., 1974. Distribution stratigraphique des acritarches dans le Paléozoïque du Sahara algérien. *Rev. Palaeobot. Palynol.* 18, 99–129.
- Johnson, J., Klapper, G., Sandberg, C.A., 1985. Devonian eustatic fluctuations in Euramerica. *Geol. Soc. Am. Bull.* 96, 567–587.
- Le Hérisse, A.L., Gourvennec, R., 1995. Biogeography of upper Llandovery and Wenlock acritarchs. *Rev. Palaeobot. Palynol.* 86, 111–133.
- Le Hérisse, A.L., Gourvennec, R., Wicander, R., 1997. Biogeography of Late Silurian and Devonian acritarchs and prasinophytes. *Rev. Palaeobot. Palynol.* 98, 105–124.
- Le Hérisse, A., Servais, T., Wicander, R., 2000. Devonian acritarchs and related forms. *Courier-Forschungsinstitut senckenberg* 220, 195–205.
- Li, J., Servais, T., 2002. Ordovician acritarchs of China and their utility for global palaeobiogeography. *Bull. Soc. Géol. France* 173, 399–406.
- Li, J., Servais, T., Brocke, R., 2002. Chinese Paleozoic acritarch research: review and perspectives. *Rev. Palaeobot. Palynol.* 118, 181–193.
- Li, J., Servais, T., Yan, K., Zhu, H.C., 2004. A nearshore–offshore trend in acritarch distribution from the Early–Middle Ordovician of the Yangtze Platform, South China. *Rev. Palaeobot. Palynol.* 130, 141–161.
- Liao, W.H., Cai, T.C., 1987. Sequence of Devonian rugose coral assemblages from northern Xinjiang. *Acta Palaeontol. Sin.* 26 (6), 689–707 (in Chinese with English abstract).
- Loboziak, S., Streele, M., 1981. Synthèse palynostratigraphique de l’intervalle Givétien–Famennien du Boulonnais (France). *Biostratigr. Paléozoïque* 7, 71–77.

- Lu, L.C., 1995. Miospores from Shaodong Member at Jieliang Section of Hunan, China and their geological age. *Acta Palaeontol. Sin.* 34, 40–52 (in Chinese with English summary).
- Lu, L.C., 1997. Microflora from Shaodong Member at Jieliang section, Hunan, China. *Acta Palaeontol. Sin.* 36, 187–206 (in Chinese with English abstract).
- Lu, L.C., 1999. On the miospore assemblages of the Heishantou Formation at Aherbruckomha in Horboksar, Xinjiang, with additional reference to the transition stratum from Devonian to Carboniferous. *Palaeozoic Fossils in Northern Xinjiang*. Nanjing University Press, pp. 1–141 (in Chinese with English summary).
- Lu, L.C., Wicander, R., 1988. Upper Devonian acritarchs and spores from the Hongguleleng Formation, Hefeng District in Xinjiang, China. *Rev. Esp. Micropaleontol.* 20, 109–148.
- Ma, X.P., Zong, P., Sun, Y.L., 2011. The Devonian (Famennian) sequence in the western Junggar area, Northern Xinjiang, China. *SDS Newslett.* 26, 44–49.
- Ma, X.P., Zong, P., Zhang, Y.B., Zhang, M.Q., Xue, J.Z., 2013. Subdivision of Famennian (Late Devonian) strata in the northwest border of the Junggar Basin, Xinjiang, Northwestern China. *Earth Sci. Front.* 20 (6), 255–268 (in Chinese with English abstract).
- Ma, X.P., Gong, Y.M., Chen, D.Z., Racki, G., Chen, X.Q., Liao, W.H., 2016. The Late Devonian Frasnian–Famennian Event in South China – patterns and causes of extinctions, sea level changes, and isotope variations. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 448, 224–244.
- Ma, X.P., Zhang, M.Q., Zong, P., Zhang, Y.B., Lü, D., 2017. Temporal and spatial distribution of the Late Devonian (Famennian) strata in the northwestern border of the Junggar Basin, Xinjiang, Northwestern China. *Acta Geol. Sin.* 91 (4), 1413–1437.
- Mantsurova, V.N., 2003. The Frasnian Famennian boundary in the Volgograd Volga region by palynological data. *Acta Paleontol. Sin.* 42 (1), 22–30.
- Martin, F., 1981. Acritarches du Famennien inférieur à Villers-sur-Lesse (Belgique). *Bull. Inst. R. Sci. Nat. Belg. Sci. Terre* 52, 1–49.
- Martin, F., 1984. Acritarches du Frasnien Supérieur et du Famennien Inférieur du bord meridional du Bassin de Dinant (Ardenne belge). *Bull. Inst. R. Sci. Nat. Belg. Sci. Terre* 55, 1–57.
- Marynowski, L., Filipiak, P., Zatoń, M., 2010. Geochemical and palynological study of the Upper Famennian Dasberg event horizon from the Holy Cross Mountains (central Poland). *Geol. Mag.* 147, 527–550.
- Molyneux, S.G., Le Hérisse, A., Wicander, R., 1996. Paleozoic phytoplankton. In: Jansonius, J., McGregor, D.C. (Eds.), *Palynology: Principles and Applications*. vol. 2. American Association of Stratigraphic Palynologists Foundation, pp. 493–529.
- Molyneux, S.G., Delabroye, A., Wicander, R., Servais, T., 2013. Biogeography of early to mid Palaeozoic (Cambrian–Devonian) marine phytoplankton. *Geological Society, London, Memoirs* 38, 365–397.
- Moreau-Benoit, A., 1984. Acritarches et chitinozoaires du Dévonien moyen et supérieur de Libye occidentale. *Rev. Palaeobot. Palynol.* 43, 187–216.
- Muñoz, P., Boulvain, F., Dreesen, R., Hou, H.F., 1996. Sequence stratigraphy of the Frasnian–Famennian transitional strata: a comparison between South China and southern Belgium. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 123, 289–296.
- Nikishin, A.M., Ziegler, P.A., Stephenson, R.A., Cloetingh, S., Furne, A.V., Fokin, P.A., Ershov, A.V., Bolotov, S.N., Korotaev, M.V., Alekseev, A.S., Gorbachev, V.I., Shipilov, E.V., Lankreijer, A., Bembina, E.Y., Shalimov, I.V., 1996. Late Precambrian to Triassic history of the east European Craton – dynamics of sedimentary basin evolution. *Tectonophysics* 268, 23–63.
- Obukhovskaya, T.G., Avkhimovitch, V.I., Streef, M., Loboziak, S., 2000. Miospores from the Frasnian–Famennian Boundary deposits in eastern Europe (The Pripyat Depression, Belarus and the Timan–Pechora Province, Russia) and comparison with Western Europe (Northern France). *Rev. Palaeobot. Palynol.* 112, 229–246.
- Ouyang, S., 2000. Succession of late Palaeozoic palynological assemblages in Jiangsu. *J. Stratigr.* 24, 230–235 (in Chinese with English abstract).
- Pereira, Z., Matos, J.X., Fernandes, P.M.C., Oliveira, J.T., 2008. Palynostratigraphy and systematic palynology of the Devonian and carboniferous successions of the south Portuguese Zone, Portugal. *Instituto Nacional de Engenharia, Tecnologia e Inovação* 1–181.
- Pereira, Z., Fernandes, P., Matos, J.X., Jorge, R.C.G.S., Oliveira, J.T., 2018. Stratigraphy of the Northern Pulo do Lobo Domain, SW Iberia Variscides: A palynological contribution. *Geobios* 51, 491–506.
- Piecha, M., 2002. A considerable hiatus at the Frasnian/Famennian boundary in the Rhinish shelf region of northwest Germany. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 181, 195–211.
- Playford, G., 1981. Late Devonian Acritarchs from the Gneudna formation in the Western Carnarvon basin, Western Australia. *Geobios* 14, 145–171.
- Playford, G., 2003. Acritarchs and prasinophyte phycmata: a short course. *American Association of Stratigraphic Palynologists Foundation* 41, 1–46.
- Playford, G., Dring, R.S., 1981. Late Devonian acritarchs from the Carnarvon Basin, Western Australia. *Special Paper in Palaeontology* 27, 1–78.
- Playford, G., McGregor, D.C., 1993. Miospores and organic-walled microphytoplankton of Devonian–Carboniferous boundary beds (Bakken Formation), Williston Basin, southern Saskatchewan: a systematic and stratigraphic appraisal. *Geol. Surv. Can. Bull.* 445, 1–107.
- Racki, G., Racka, M., Matyja, H., Devleeschouwer, X., 2002. The Frasnian/Famennian boundary interval in the South Polish–Moravian shelf basins: integrated eventstratigraphical approach. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 181, 251–297.
- Rauscher, R., 1969. Presence d'une forme nouvelle d'Acritarches dans le Dévonien de Normandie. *Compte Rendu de l'Académie des Sciences de Paris, Series D* 268, 34–36.
- Richardson, J.B., McGregor, D.C., 1986. Silurian and Devonian spore zones of the Old Red Sandstone continent and adjacent regions. *Geol. Surv. Can. Bull.* 364, 1–79.
- Rickard, L.V., 1975. Correlation of the Silurian and Devonian rocks in New York State. *New York State Museum and Science Service, Map and Chart Series No. 24*. University of the State of New York and State Education Department, Albany, p. 16.
- Shen, Z., Song, J., Servais, T., Gong, Y., 2019. Late Devonian palaeobiogeography of marine organic-walled phytoplankton. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 531, 108706.
- Shen, Z., Monnet, C., Cascales-Miñana, B., Gong, Y.M., Dong, X.H., Kroeck, D., Servais, T., 2020. Diversity dynamics of Devonian terrestrial palynofloras from China: Regional and global significance. *Earth Sci. Rev.* 200, 102967.
- Song, H., Song, H., Algeo, T.J., Tong, J., Romaniello, S.J., Zhu, Y., Chu, D., Anbar, A.D., 2017a. Uranium and carbon isotopes document global-ocean redox-productivity relationships linked to cooling during the Frasnian–Famennian mass extinction. *Geology* 45, 887–890.
- Song, J.J., Crasquin, S., Gong, Y.M., 2017b. Ostracods of the Late Devonian Frasnian/Famennian transition from Western Junggar, Xinjiang, NW China. *Alcheringa* 41, 250–276.
- Spalletta, C., Perri, M.C., Over, D.J., Corradini, C., 2017. Famennian (upper devonian) conodont zonation: revised global standard. *Bull. Geosci.* 92, 31–57.
- Stachacz, M., Kondas, M., Filipiak, P., Ma, X.P., 2021. Environment and age of the Upper Devonian–Carboniferous Zhulumute and Hongguleleng Formations (Junggar Basin, NW China): Ichnological and palynological aspects. *Acta Geol. Sin.* 95 (3), 724–739.
- Staplin, F.L., 1961. Reef-controlled distribution of Devonian microplankton in Alberta. *Palaeontology* 4, 392–424.
- Stockmans, F., Willièvre, Y., 1962. Hystrichosphères du Dévonien belge (Sondage de Wépion). *Bulletin de la Société belge de géologie, de paléontologie et d'hydrologie* 71, 83–99.
- Streef, M., 2009. Upper Devonian miospore and conodont zone correlation in western Europe. *Geol. Soc. Lond., Spec. Publ.* 314 (1), 163–176.
- Streef, M., Higgs, K., Loboziak, S., Riegel, W., Steemans, P., 1987. Spore stratigraphy and correlation with faunas and floras in the type marine Devonian of the Ardenne–Rhenish regions. *Rev. Palaeobot. Palynol.* 50 (3), 211–229.
- Streef, M., Paris, F., Riegel, W., Vanguetaine, M., 1988. Acritarch, Chitinozoan and Spore Stratigraphy from the Middle and Upper Devonian subsurface of Northeast Libya. *Garyounis Univ. Publ.* 41, 111–128.
- Streef, M., Caputo, M.V., Loboziak, S., Melo, J.H.G., 2000. Late Frasnian–Famennian climates based on palynomorph analyses and the question of the Late Devonian glaciations. *Earth-Sci. Rev.* 52, 121–173.
- Suttner, T.J., Kido, E., Chen, X.Q., Mawson, R., Waters, J.A., Frýda, J., Mathieson, D., Molloy, P.D., Pickett, J., Webster, G.D., Frýdová, B., 2014. Stratigraphy and facies development of the marine Late Devonian near the Boulongour Reservoir, northwest Xinjiang, China. *J. Asian Earth Sci.* 80, 101–118.
- Tikhomirov, S.V., 1995. Etapy osadkonakopleniâ devona Russkoj platformy i obščie voprosy razvitiâ i stroeniâ stratisfery. *Nedra, Moskva*, p. 445 (in Russian).
- Tongiorgi, M., Yin, L.M., Milia, A.D., 1995. Arenigian acritarchs from the Daping section (Yangtze Gorges area, Hubei Province, Southern China) and their palaeogeographic significance. *Rev. Palaeobot. Palynol.* 27, 94–100.
- Tyson, R.V., 1995. *Sedimentary Organic Matter. Organic Facies and Palynofacies*. Chapman and Hall, p. 615.
- Van Veen, P.M., 1980. Aspects of Late Devonian and Early Carboniferous palynology of southern Ireland, IV morphological variation within *Diducites*, a new formgenus to accommodate camerate spores with two-layered outer wall. *Rev. Palaeobot. Palynol.* 31, 261–287.
- Vavrdová, M., Isaacson, P.E., Diaz-Martinez, E., Bek, J., 1991. Palinología del límite Devónico–Carbonífero en torno al Lago Titikaka, Bolivia: Resultados preliminares. *Revista Técnica de Yacimientos petrolíferos Fiscales Bolivianos* 12, 303–313.
- Veimarn, A.B., Kuzmin, A.V., Kononova, L.L., Baryshev, V.N., Vorontzova, T.N., 1997. Geological events at the Frasnian/Famennian boundary on the territory of Kazakhstan, Urals and adjacent regions of the Russian plate. In: House, M.R., Ziegler, W. (Eds.), *On Sealevel Fluctuations in the Devonian*. vol. 199. CFS Courier Forschungsinstitut Senckenberg, pp. 37–50.
- Wang, Y., 1996. Miospore assemblages from the Shaodong and Mengkung'ao Formations at Xikuangshan, Central Hunan with discussion on Devonian–Carboniferous boundary. *Acta Micropalaeontol. Sin.* 13, 13–42 (in Chinese with English abstract).
- Wang, Y., Chen, H.D., 1999. New Data on the Frasnian–Famennian Event Boundary in the Dushan Area, South Guizhou. *J. Stratigr.* 23, 26–30.
- Wang, Z.H., Becker, R.T., Aboussalam, Z.S., Hartenfels, S., Joachimski, M., Gong, Y.M., 2016. Conodont and carbon isotope stratigraphy near the Frasnian/Famennian (Devonian) boundary at Wulankeshun, Junggar Basin, NW China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 448, 270–297.
- Wicander, R., 1974. Upper Devonian–Lower Mississippian acritarchs and prasinophycean algae from Ohio. *U.S.A. Palaeontogr. Abt. B* 148, 9–43.
- Wicander, E.R., Loeblich, A.R., 1977. Organic-walled microphytoplankton and its stratigraphic significance from the Upper Devonian Antrim Shale, Indiana, U.S.A. *Palaeontogr. Abt. B* 160, 129–165.
- Wicander, R., Playford, G., 1985. Acritarchs and spores from the Upper Devonian Lime Creek Formation, Iowa, U.S.A. *Micropaleontology* 31, 97–138.
- Wicander, R., Playford, G., 2013. Marine and terrestrial palynofloras from transitional Devonian–Mississippian strata, Illinois Basin, U.S.A. *Bol. Geol. Miner.* 124, 589–637.
- Wicander, R., Clayton, G., Marshall, J.E.A., Troth, I., Racey, A., 2011. Was the latest Devonian glaciation a multiple event? New palynological evidence from Bolivia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 305, 75–83.
- Windley, B.F., Alexeiev, D., Xiao, W., Kröner, A., Badarch, G., 2007. Tectonic models for accretion of the Central Asian Orogenic Belt. *J. Geol. Soc. Lond.* 164, 31–47.
- Wood, G.D., Gabriel, A.M., Lawson, J.C., 1996. Palynological techniques – Processing and microscopy. In: Jansonius, J., McGregor, D.C. (Eds.), *Palynology: Principles and Applications 1*. American Association Stratigraphic Palynologist Foundation, Dallas, Texas, pp. 29–50.
- Xia, F.S., 1996. New knowledge on the age of Hongguleleng Formation in Northwestern margin of Junggar Basin, Northern Xinjiang. *Acta Micropalaeontol. Sin.* 13 (3), 277–285 (in Chinese with English abstract).



- Xia, F., 1997. Marine microfaunas (bryozoans, conodonts and microvertebrate remains) from the Frasnian–Famennian interval in northwestern Junggar Basin of Xinjiang in China. *Beitr. Paläontol.* 22, 91–207.
- Xiao, W., Huang, B., Han, C., Sun, S., Li, J., 2010. A review of the western part of the Altai: a key to understanding the architecture of accretionary orogens. *Gondwana Res.* 18, 253–273.
- Xu, H.H., Marshall, J.E.A., Wang, Y., Zhu, H.C., Berry, C.M., Wellman, C.H., 2014. Devonian spores from an intra-oceanic volcanic arc, West Junggar (Xinjiang, China) and the palaeogeographical significance of the associated fossil plant beds. *Rev. Palaeobot. Palynol.* 206, 10–22.
- Xu, H.H., Berry, C.M., Stein, W.E., Wang, Y., Tang, P., Fu, Q., 2017. Unique growth strategy in the Earth's first trees revealed in silicified fossil trunks from China. *Proc. Natl. Acad. Sci.* 114, 12009–12014. <https://doi.org/10.1073/pnas.1708241114>.
- Zatoń, M., Zhuravlev, A.V., Rakociński, M., Filipiak, P., Borszcz, T., Krawczyński, W., Wilson, M.A., Sokiran, E.V., 2014. Microconchid-dominated cobbles from the Upper Devonian of Russia: opportunism and dominance in a restricted environment following the Frasnian–Famennian biotic crisis. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 401, 142–153.
- Zhang, X.S., 2019. Late Devonian Conodont Biostratigraphy, Event Stratigraphy and Chemostratigraphy in South China and Western Junggar, NW China. China University of Geoscience, Wuhan, pp. 1–443 (in Chinese with English abstract).
- Zhao, Z.X., 1986. Conodonts and age of the “Hebukehe” Formation at Aerjiati Hill, northern Xinjiang. *Xinjiang Petrol. Geol.* 7 (3), 89–107 (in Chinese).
- Zhao, Z.X., Wang, C.Y., 1990. Age of the Hongguleleng Formation in the Junggar basin of Xinjiang. *J. Stratigr.* 14 (2), 145–146 (in Chinese).
- Zheng, D., Chang, S.C., Algeo, T., Zhang, H., Wang, B., Wang, H., Wang, J., Feng, C., Xu, H., 2020. Age constraint for an earliest Famennian forest and its implications for Frasnian–Famennian boundary in West Junggar, Northwest China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 552, 109749.
- Ziegler, W., Sandberg, C.A., 1990. The late Devonian standard conodont zonation. *Courier Forschungsinstitut Senckenberg* 121, 1–115.
- Zong, P., Ma, X.P., 2018. Spiriferide brachiopods from the Famennian (Late Devonian) Hongguleleng Formation of western Junggar, Xinjiang, northwestern China. *Palaeoworld* 27, 66–89.
- Zong, P., Becker, R.T., Ma, X.P., 2015. Upper Devonian (Famennian) and Lower Carboniferous (Tournaisian) ammonoids from western Junggar, Xinjiang, northwestern China—stratigraphy, taxonomy and palaeobiogeography. *Palaeobiodiv. Palaeoenviron.* 95, 159–202.
- Zong, P., Ma, X., Xue, J., Jin, X., 2016. Comparative study of late Devonian (Famennian) brachiopod assemblages, sea level changes, and geo-events in northwestern and southern China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 448, 298–316.
- Zong, P., Ma, X.P., Zhang, M.Q., Zhang, Y.B., Lü, D., 2017. Comparative Study of Famennian Carbon Isotope Characteristics of Junggar, Xinjiang and Central Hunan, South China. *Acta Sci. Nat. Univ. Pekin.* 53 (5), 843–861 (in Chinese with English abstract).
- Zong, R.W., Wang, Z.H., Fan, R.Y., Song, J.J., Zhang, X.S., Shen, Z., Gong, Y.M., 2020. New knowledge on the Hongguleleng Formation and Devonian–Carboniferous boundary in western Junggar, Xinjiang. *Acta Geol. Sin.* 98 (8), 2460–2475. <https://doi.org/10.19762/j.cnki.dizhixuebao.2019000> (in Chinese with English abstract).