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Palynological assemblages from Hongguleleng Formation of Western Junggar, Northwest China and their correlation with conodont zonation

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Abstract

The Upper Devonian Hongguleleng Formation is a significant stratigraphic unit near the Frasnian/Famennian and Devonian/Carboniferous boundaries of the Kazakhstan Paleoplate. However, its age is still under debate. A new palynostratigraphic analysis was conducted at the Gennaren section to provide a more accurate biostratigraphic assignment. In this study, we identified 43 species belonging to 26 spore genera, including those in open nomenclature. Despite the poor preservation of the palynofloras, the spore taxa were categorized into two assemblages. Assemblage I is established at the lower part of the lower member of the Hongguleleng Formation, containing *Cornispora varicornata*, cf. *Auroraspora pseudocrista*, and *Cyrtospora cristifera*. Assemblage II is from the upper part of the lower member of the Hongguleleng Formation, including *Grandispora cornuta*, *Grandispora famennensis* var. *famennensis*, *Grandispora* cf. *famennensis* var. *minutus*, *Grandispora microseta*, and *Rugospora radiata*. These assemblages are compared with the Western European DV Oppel Zone (lower-middle Famennian), and the GF to VCo Oppel zones. The assemblages are equivalent to the conodont *crepida–rhomboidea* and *marginifera* to Lower *trachytera* zones (middle-upper Famennian).

Keywords: Palynostratigraphy; Devonian/Carboniferous boundary; Famennian; Hongguleleng Formation; Western Junggar

1. Introduction

Western Junggar is currently located in northern Xinjiang, Northwest China. However, during Late Devonian, this area was part of the Kazakhstan Plate within the Central Asian Orogenic Belt (CAOB). The Upper Devonian and Lower Carboniferous strata found in this region are of great significance, because they recorded the globally famous Kellwasser and Hangenberg events. The Zhulumute Formation of the Frasnian, the Hongguleleng Formation of Famennian, and the Heishantou Formation of Early Carboniferous, are well-exposed in Western Junggar region (Lu, 1999; Ma et al., 2017; Zheng et al., 2020; Zong et al., 2020; Stachacz et al., 2021). However, due to its isolation from other continental shelf areas, biostratigraphic studies of conodonts, which are predominantly endemic

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and missing in many intervals (Wang et al., 2016), are a challenge for age determination. As a result, the age of the Hongguleleng Formation is still under debate. Although earlier studies suggested an early Famennian to Early Carboniferous age for the formation (Zhao, 1986; Zhao and Wang, 1990; Xia, 1996), others indicated a latest Frasnian age for the lower member of the Hongguleleng Formation (Xia, 1997; Chen et al., 2009; Carmichael et al., 2014, 2016; Suttner et al., 2014; Wang et al., 2016). Recently, U-Pb dates provided some evidence for setting the Frasnian/Famennian (F/F) boundary within the upper part of Zhulumute Formation in Western Junggar (Zheng et al., 2020). Zhang et al. (2021) confined the lower member of the Hongguleleng Formation within the *Pa. rhomboidea* Zone to the *Pa. marginifera marginifera* Zone, of early Famennian.

During the Late Devonian, the Kazakhstan Paleoplate was located far from the South China Paleoplate (Fig. 1C), and its palynological research was relatively poor (e.g., Gao and Zhong, 1984; Chen and Ouyang, 1985, 1987; Li et al., 1987; Gao, 1990; Xu and Gao, 1991, 1994; Wang, 1996; Lu, 1997). Lu and Wicander (1988) identified spore and acritarch assemblages, assigned the lower member of the Hongguleleng Formation to late Frasnian–Famenian at the Bulongguoer section, a well-studied stratotype section located approximately 13 km northwest of our Gennaren section (Fig. 1). Stachacz et al. (2021) recently examined the Late Devonian to Early Carboniferous Bulongguoer and Haer (Gennaren area) sections for ichnological and palynological studies. The occurrence of spore *Teichertospora torquate*, together with *Grandispora gracilis*, suggests a comparability with Richardson and McGregor (1986)'s *Teichertospora torquata–Grandispora gracilis* (TG) Zone of North America and Europe, from the F/F interval. However, correlation with the spore zones identified by Avkhimovitch et al. (1993a) in Eastern European is tentative (Stachacz et al., 2021).

Shen et al. (2021) investigated the spore and acritarch content from the bottom of the lower member of the Hongguleleng Formation in the Bulongguoer section. This study identified a palynoflora assemblage from the bottom of the Hongguleleng Formation. The assemblage was assigned to the early Famennian miospore *Corbulispora viminea–Geminospora vasjamica* (VV) and *Cyrtospora cristifer–Diaphanospora zadonica* (CZ) miospore zones from Eastern Europe, corresponding to the *crepida* conodont Zone.

No palynological zonation has been established since 1980s from the Hongguleleng Formation to correlate with

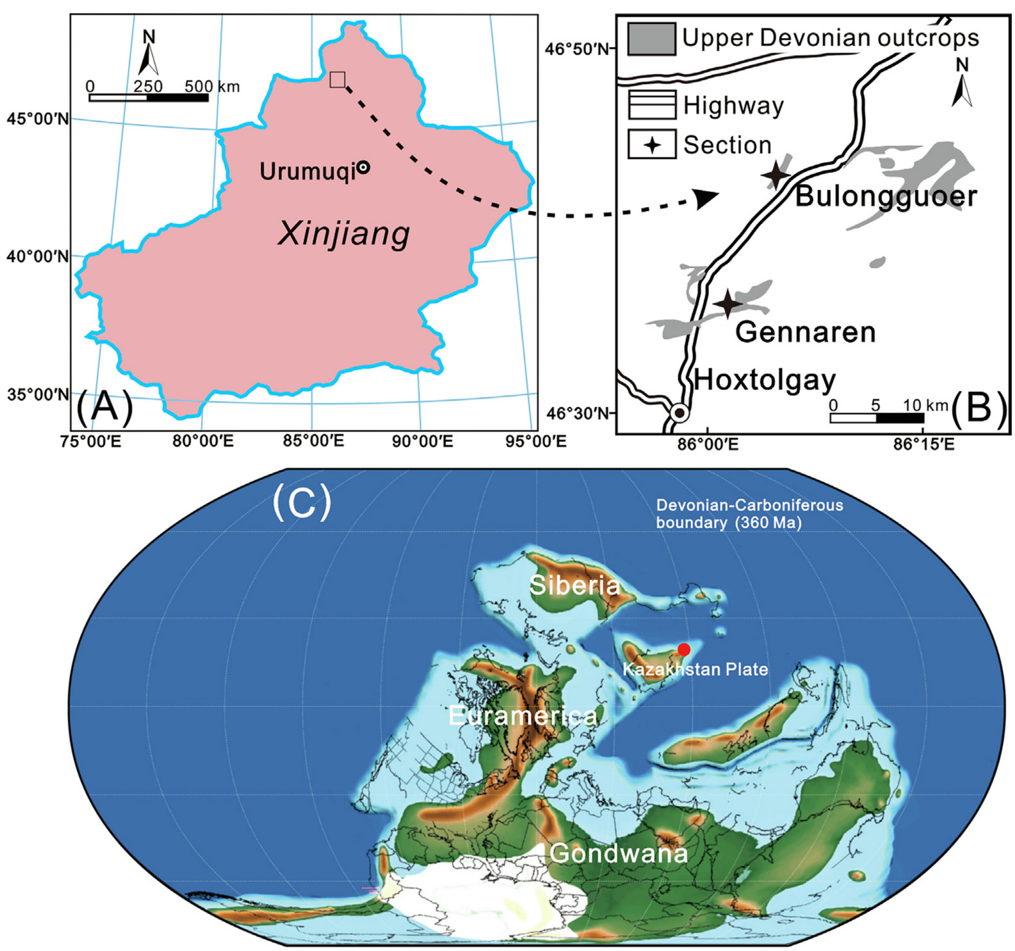

Fig. 1. (A) Location of the study area (red box) in Xinjiang, China. (B) Location of the study section and the Upper Devonian outcrops in Western Junggar. (C) Late Devonian paleogeographic map (modified from Scotese, 2021), indicating the paleogeographic location of the sample locality.

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the brachiopod and conodont zones of the formation (e.g., Zhao and Wang, 1990; Zong et al., 2016). There is a significant barren interval between the upper part of the lower member and middle to upper member of the Hongguleleng Formation.

The present research investigates miospores in the Hongguleleng Formation located in the Gennaren section. The main objective is to identify the spore taxa in the studied samples, to establish the biostratigraphic age throughout the section, and to establish the correlation with other biostratigraphic zones.

2. Tectonic settings and stratigraphy

The Western Junggar is a significant Paleozoic volcanic arc in the CAOB (Windley et al., 2007; Xiao et al., 2008). It is also an important part of the Kazakhstan Paleoplate, particularly during the Devonian and Early Carboniferous (Xiao et al., 2010; Ma et al., 2017; Fig. 1).

The Hongguleleng Formation is distributed at the northwest edge of the Junggar Basin and is a representative deposition of the Upper Devonian in northern China. The Devonian and Carboniferous strata originate from the volcanic arc and are widely distributed and well-exposed (Buckman and Aitchison, 2004; Gong and Zong, 2015). They comprise fossil-rich clastic rocks and carbonate deposits (e.g., Hou et al., 1979, 1993; Ma et al., 2017).

This study focuses on material collected from the Hongguleleng Formation well-exposed in the Gennaren section. The section includes, in ascending order, the Zhulumute Formation, the Hongguleleng Formation, and the Heishantou Formation. The Hongguleleng Formation has been divided into three members and has been widely adopted by previous studies (e.g., Hou et al., 1993; Fan and Gong, 2016; Ma et al., 2017; Zong and Ma, 2018; Zong et al., 2020). The contact relationship between the Hongguleleng Formation and the overlying Heishantou Formation is well established. However, the contact relationship between Hongguleleng Formation and Zhulumute Formation has long been considered a conformity due to the coverage problem. Recent work has shown a thin layer of mud debris approximately 2.5 cm thick between the two formations, indicating a disconformity (Fig. 2b).

Studies on ammonoids (Zong et al., 2014, 2021), brachiopods (Ma et al., 2011; Zong and Ma, 2012, 2018), trilobites (Zong et al., 2020), palynology (Shen et al., 2021; Stachacz et al., 2021), and conodonts (Zhao and Wang, 1990; Xia, 1996; Chen et al., 2009; Wang et al., 2016; Zhang et al., 2021) made significant progress in the area, while the position of the F/F and Devonian/Carboniferous (D/C) boundaries remains highly controversial.

3. Material and methods

Ninety-nine palynological samples were collected from the Gennaren section. The detailed sampling levels are indicated in Fig. 3. To process all the samples, standard HCl-HF-HCl acid maceration (Wood et al., 1996) was used in the laboratory. The samples were then separated using heavy liquid separation, followed by sieving with 15 μm and 50 μm meshes to remove the finest mineral matter. Afterward, the organic residue was evaluated by strew mounting on microscope slides and viewed using a light microscope. There were 14 positive samples contained spores. However, the preservation of the palynomorphs was moderate to poor, with the organic material being exposed to high temperatures. All figured specimens are housed in the Resources and Environment Department, Shanxi University of Finance and Economics.

4. Palynomorph assemblages and palynostratigraphy

The present study summarizes the stratigraphic range of palynomorphs recovered in the Hongguleleng Formation at the Gennaren section. We also compare these data with formal miospore zonations described from other regions, for instance, Western Europe (following Streel et al., 1987), Eastern Europe (Avkhimovitch et al., 1993a, 1993b), Old Red Sandstone Continent (ORSC) (Richardson and McGregor, 1986), and Pomerania (Stempień-Sałek, 2002). However, the marked quantitative and qualitative differences of the studied assemblages made it challenging to employ the widely used miospore biozone schemes mentioned above in 1. Introduction.

Since the lithology was sometimes unfavorable for the preservation of palynological material, the spore assemblage obtained was often limited to local beds, and the significant thickness of intervals was barren. Eventually, 14 palynological samples yielding poorly preserved spores were selected. The present research will deal with miospore taxa only. The acritarch taxa will be published later in a separate paper. Fig. 3 presents the distribution of the samples. The age of the palynomorph assemblages is constrained by conodonts (e.g., Zhao and Wang, 1990; Zhang et al., 2021), miospores (e.g., Shen et al., 2021), brachiopods (e.g., Ma et al., 2011), trilobites (Zong et al., 2020), and ammonoids (Zong et al., 2014, 2021), all obtained from Bulongguoer section.

In this study, the lower member of the Hongguleleng Formation was tentatively divided into two distinct assemblages: Assemblage I and Assemblage II. Fig. 4 presents the correlation of the two assemblages with standard miospore and international conodont zonal schemes. Selected spore taxa are displayed in Figs. 5–7. Fig. 8 shows the final correlation of the three members of the Hongguleleng Formation with the two spore assemblages and conodont zonal schemes. The following sections describe the two assemblages in ascending stratigraphic order, and a list of complete names is provided in Appendix A.

4.1. Assemblage I

The assemblage's lower boundary is unknown, the Assemblage I was distinguished from samples GNR2 to

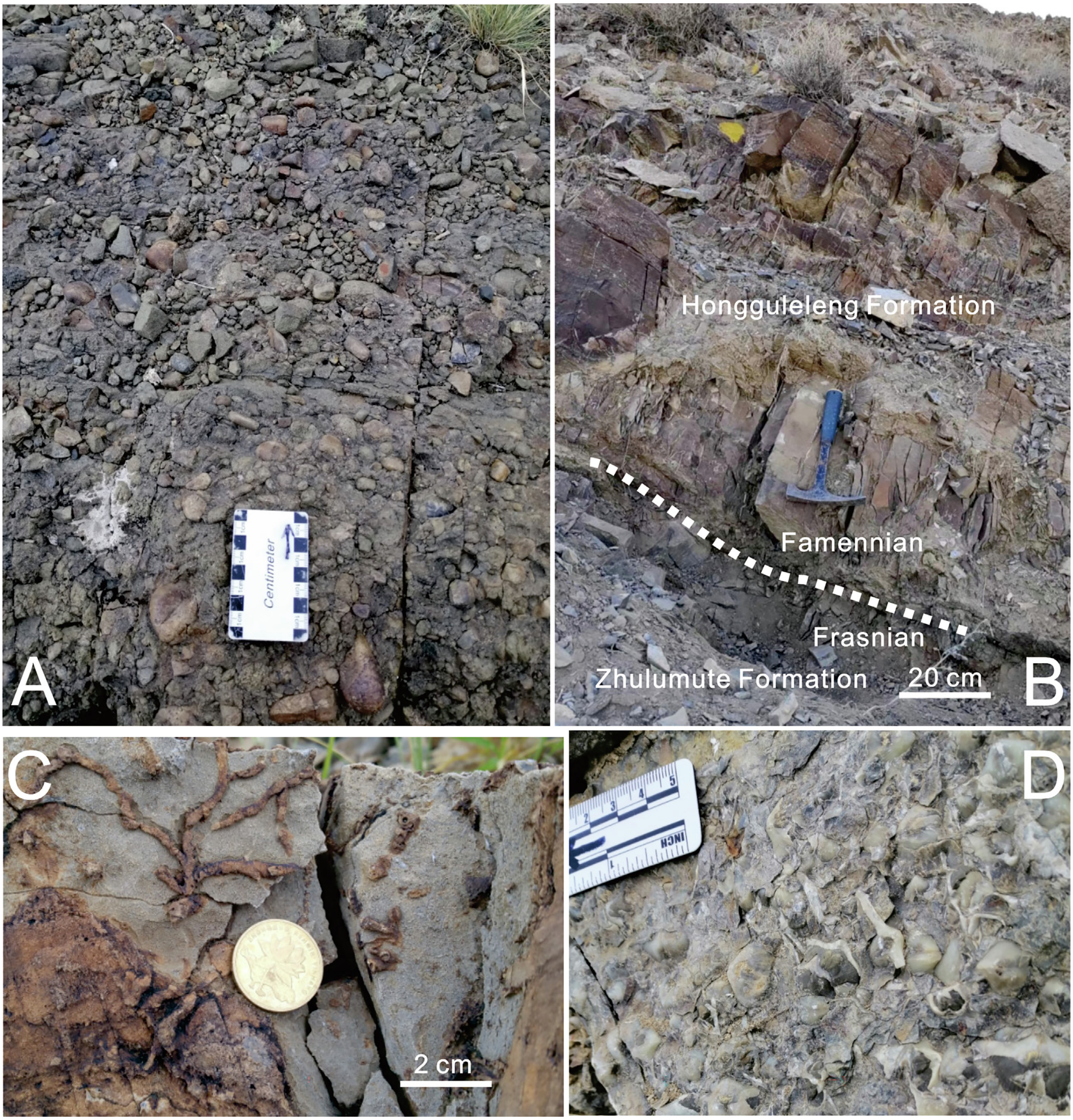

Fig. 2. Lithologic, boundary, and biotic aspects of the Zhulumute Formation and Hongguleleng Formation at the Gennaren section. (A) A conglomerate at the upper part of the Zhulumute Formation. (B) Frasnian–Famennian boundary in the Gennaren section, dotted line showing also the position of the boundary between the Zhulumute Formation and Hongguleleng Formation. (C) Trace fossils from the lower member of the Hongguleleng Formation. (D) Bioclastic limestone with numerous brachiopod shells from the lower member of the Hongguleleng Formation.

GNR10 (‘GNR’ is the abbreviation for the ‘Gennaren’ section). The sample at 20.8 m in the section (GNR8) contains the most abundant and diverse spore taxa. This assemblage is characterized by the appearance of cf. *Auroraspora pseudocrista*, *Cornispora varicornata*, *Cyclogranisporites isostictus*, *Cyrtospora cristifera*, and *Hymenozonotriletes argutus*. Besides, there are undetermined species, such as *Archaeoperisaccus* sp., cf. *Auroraspora* sp. 1, *Auroraspora* sp. 2, cf. *Cristatisporites* sp. 1, cf. *Cristatisporites* sp. 2, cf. *Densosporites* sp. 1, cf. *Densosporites* sp. 2., *Diducites* sp. 1, *Discernisporites* sp., *Emphanisporites* sp., *Grandispora* sp., *Knoxisporites* sp., *Leotriletes* cf. *ornatus*, *Punctatisporites* sp. 1, cf. *Teichertospora* sp. 1, and *Verrucosisporites* sp.

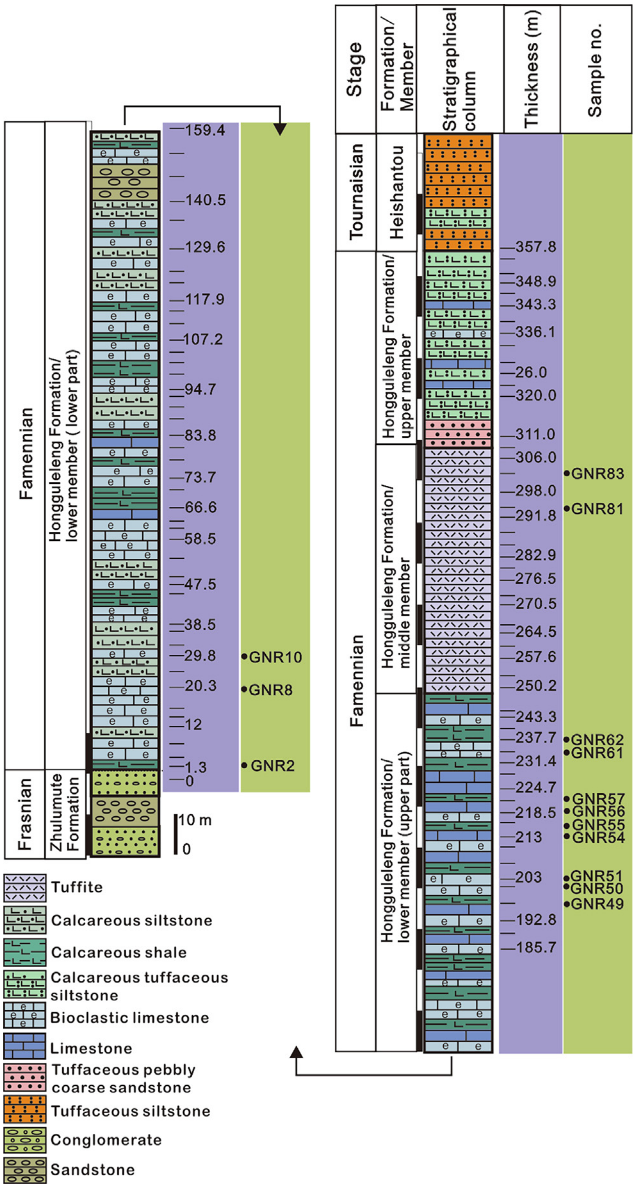

Fig. 3. Stratigraphy of the Hongguleleng Formation in the Gennaren section, showing location of the positive samples (14 positive samples with "GNR").

4.2. Assemblage II

This assemblage was identified from samples GNR49 to GNR62, and it includes several spore taxa newly discovered from the Kazakhstan Plate, such as *Grandispora cornuta*, *Grandispora famennensis* var. *famennensis*, *Grandispora* cf. *famennensis* var. *minutus*, *Grandispora microseta*, cf. *Rugospora radiata*, and cf. *Tergobulasporites immensus*. Additionally, the species *Aneurospora greggsii*, *Auroraspora macra*, *Diducites* sp. 2, *Lophotriletes linguaeformis*, cf. *Punctatisporites famennensis*, *Punctatisporites* sp. 2, *Punctatisporites* sp. 3, *Punctatisporites* sp. 4, and *Teichertospora* sp. 2 were recorded, which were accompanied by *Convolutispora* sp., *Diducites* cf. *mucronatus*, *Latosporites* sp., *Punctatisporites* sp., and cf. *Raistrickia* sp. 5.

5. Palynological stratigraphic correlation with the conodont and brachiopod biostratigraphy in Western Junggar

5.1. The age of the lower member of the Hongguleleng Formation

The research on the Hongguleleng Formation has been ongoing for over 40 years since the first paper was published in 1979 by Hou et al. (1979). While many papers dedicate their attention to this formation, the lower member has received the most attention compared to the middle and upper members. When discussing the conodont content, the biostratigraphy of the lower member of the Hongguleleng Formation revolves around two key points: 1) Whether the base of the formation contains the latest Frasnian conodont *linguiformis* Zone; and 2) Whether the top of the lower member of the formation contains the international conodont *trachyptera* Zone.

According to the occurrence of *Ancyrognathus bifurcates*, *Icriodus cornutus*, *Palmatolepis minuta*, *Pa. glabra pectinate*, *Polygnathus semicostatus*, and other taxa, from Zhao and Wang (1990), it was proposed that the lower member of the Hongguleleng Formation at the Bulongguoer section is correlated with the *Palmatolepis crepida* Zone to *Pa. marginifera* Zone, which indicates an early to middle Famennian age. However, Xia (1996) disagrees with Zhao and Wang (1990), arguing that the lower member of the Hongguleleng Formation contains very few typical Frasnian conodont specimens, and its age belongs to the conodont Late *rhenana* Zone assigned to the late Frasnian and possibly into the Famennian *crepida* Zone. Chen et al. (2009) identified several important conodont zones, and they believed that the interval at 2.7 m of the lower member of the Hongguleleng Formation in the Bulongguoer section belongs to the Frasnian age. These authors also discovered a conodont assemblage of the *trachytera* Zone at 113.9 m, which belongs to the middle member of the Hongguleleng Formation. Similarly, Suttner et al. (2014) suggested that the Hongguleleng Formation (only the lower member) and the "Hebukehe" Formation (which is roughly equivalent to the middle member of the Hongguleleng Formation) are well constrained biostratigraphically by microfossils from the latest Frasnian *linguiformis* to mid-Famennian *trachytera* conodont biozones.

Ma et al. (2011, 2017) studied brachiopod assemblages and found that the brachiopod fauna assigned to the lower member of the Hongguleleng Formation in the Bulongguoer section, is characterized by productids, rhynchonellids, and cyrtospiriferid spiriferids, which are typical of post F/F extinction fauna. The authors also noted that no pre-Famennian brachiopod forms and Frasnian rugose corals were found in any level of the lower member of the Hongguleleng Formation (Ma et al., 2011, 2017). Recently, Zhang et al. (2021) re-examined the conodont assemblages in the Bulongguoer section and concluded that the lower member of the Hongguleleng Formation belongs to the *Pa. rhomboidea* Zone to the *Pa. marginifera* Zone of the

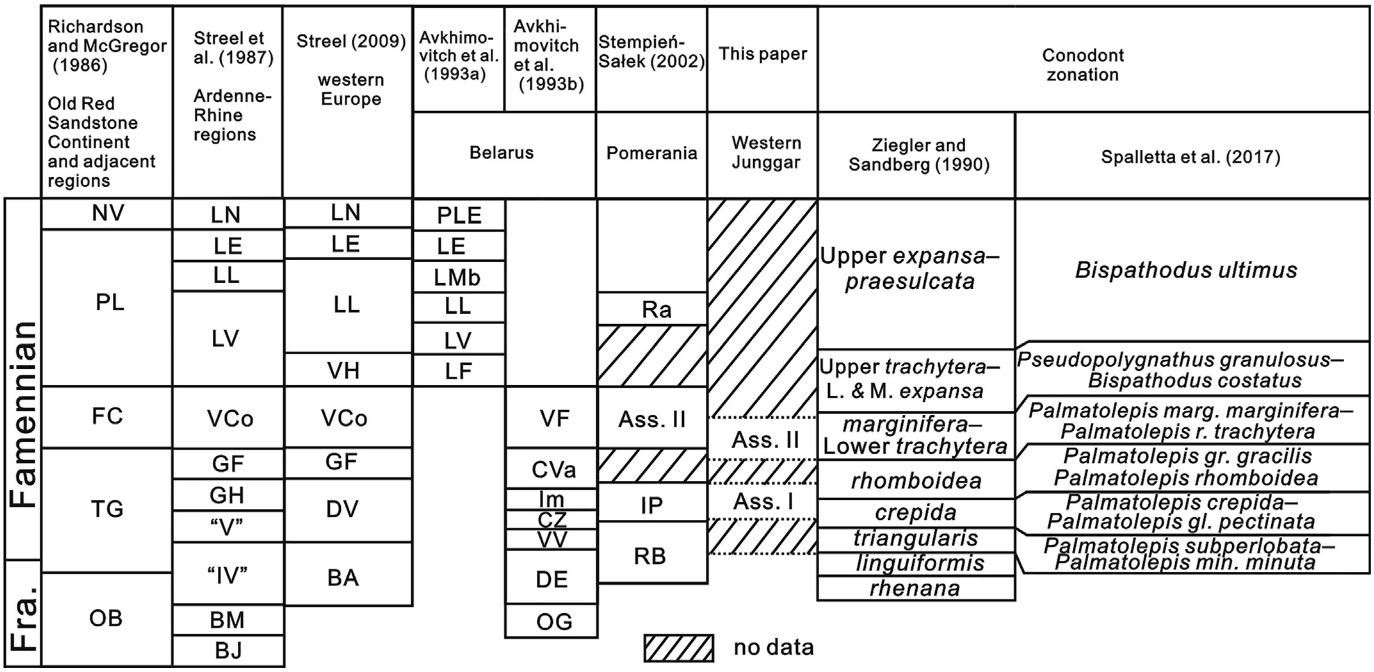

Fig. 4. Correlation of the spore and conodont zonal schemes for the Famennian in Western Junggar, with reference to the miospore zonal schemes of Western Europe (Streel et al., 1987; Streel, 2009), Eastern Europe (Avkhimovitch et al., 1993a, 1993b), ORSC and adjacent regions (Richardson and McGregor, 1986), and Pomerania (Stempień-Sałek, 2002), and the conodont zonal schemes of Ziegler and Sandberg (1990) and Spalletta et al. (2017). Abbreviation: Fra. = Frasnian; Ass. I = Assemblage I; Ass. II = Assemblage II.

early Famennian, without including the F/F boundary. Detrital zircon U-Pb ages of the upper part of the Zhulumute Formation belong to the earliest Famennian (Zheng et al., 2020), which confirms that there is no F/F boundary within the lower member of the Hongguleleng Formation.

When discussing the sedimentological context of the Hongguleleng Formation, Stachacz et al. (2021) stated that “the base is composed of siltstones with rare intercalations of greywacke, calcareous-silty heteroliths and mudstone, with isolated beds of greywacke and detrital limestones.” According to these authors, the lowermost 8 m-thick interval of the unit contains siltstones or silty greywacke, which occasionally include brachiopods, trilobites, and crinoid ossicles. However, we have noticed that the lower part of the lower member (Saerba Member from Ma et al., 2013) is composed of gray to gray-yellow bioclastic limestones, calcareous conglomerates, siliceous mudstones, mudstone-shales, or marlstones. This interval is rich in fossils and does not contain any greywacke. Many authors consider the disappearance of terrestrial conglomerate/-greywacke and the appearance of marine calcareous clastic sediments with limestone as the bottom of the Hongguleleng Formation (Zong et al., 2020, and references therein). Consequently, the lowermost part of the Hongguleleng Formation in the Bulongguoer section described by Stachacz et al. (2021) may include some intervals of the Zhulumute Formation. The characteristics of *Cristatisporites deliquescens–Verrucosisporites evlanensis* (DE) Zone mentioned by Avkhimovitch et al. (1993a) were primarily found in Stachacz et al. (2021)’s sample 9 and the samples below it, suggesting that the DE Zone is assigned to the uppermost Zhulumute Formation. Interestingly, the spore taxa identified by Shen et al. (2021) in the lowermost part of the lower member of the Hongguleleng Formation, are distinct from the miospore assemblages described by Stachacz et al. (2021) in samples 4, 9, and 11. These data indicate that the miospore assemblages from the two separate papers were collected from two different intervals, which suggests that the horizons reported from samples 4, 9, and 11 by Stachacz et al. (2021) may be slightly lower.

5.1.1. Assemblage I

At the Bulongguoer section, Shen et al. (2021) reported the presence of the key miospore taxa *Corbulispora viminea*, *Converrucosisporites curvatus* var. *medius*, and *Grandispora gracilis*, together with *Dictyotriletes famennensis*, *Geminospora vasjamica*, *Lophozonotriletes* cf. *furssenkoi*, and *Lophozonotriletes lebedianensis*, at the bottom of the Hongguleleng Formation. Shen et al. (2021) found that the spore characteristics at the bottom of the Hongguleleng Formation in the Bulongguoer section are comparable to those of the Eastern European CZ Zone, as described by Avkhimovitch et al. (1993a). Further analysis revealed that important taxa, such as *D. famennensis* and *L. lebedianensis*, were found in a lower part of the Bulongguoer section (sample BL-L-20), stratigraphically below sample GNR8 from the Gennaren section. This suggests that sample GNR8 possibly corresponds to the CZ Zone.

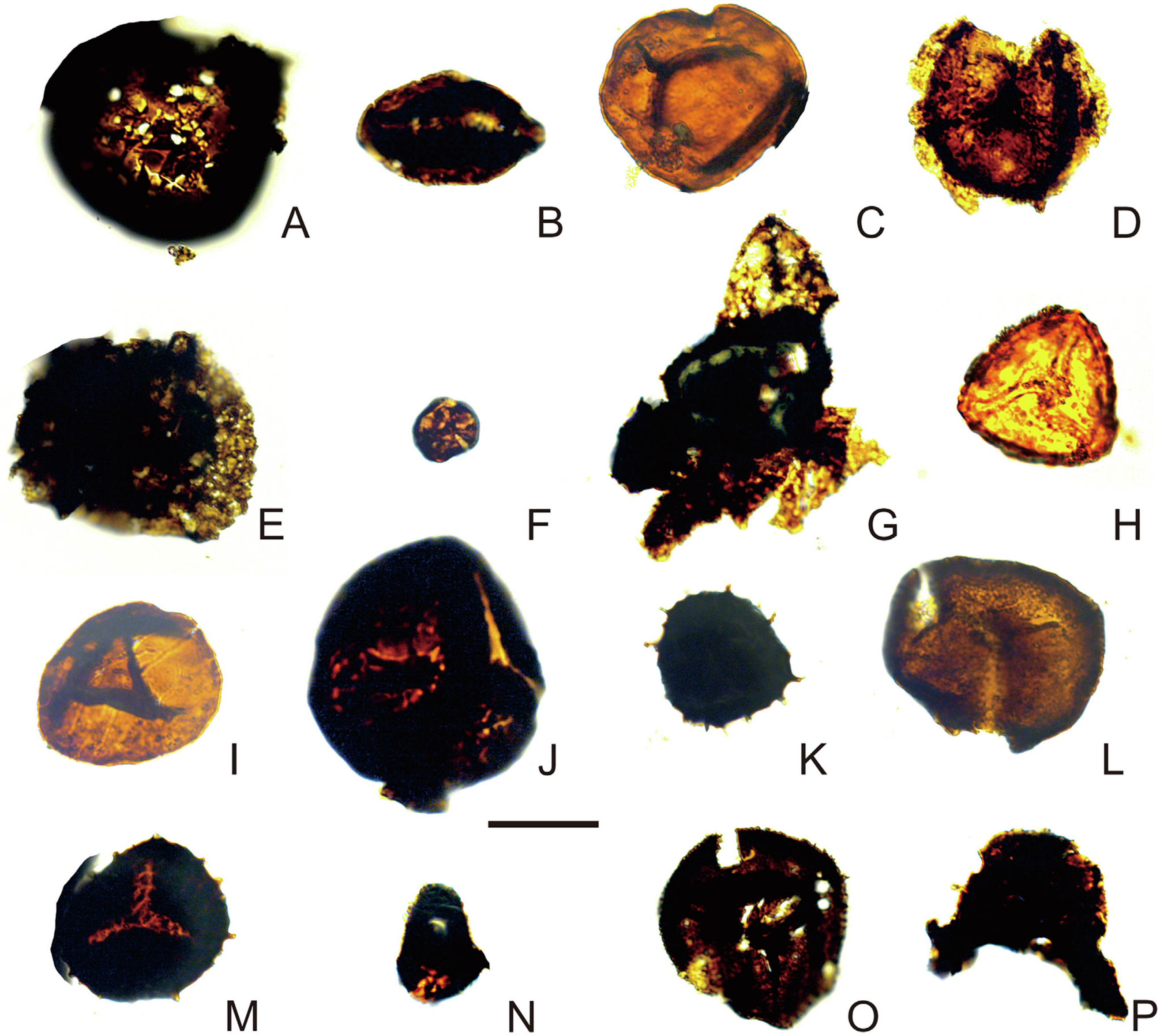

Fig. 5. Famennian miospores from the Hongguleleng Formation at the Gennaren section. Scale bar = 20 μm. (A) cf. *Densosporites* sp. 1, sample GNR8-141. (B) *Archaeoperisaccus* sp., sample GNR8-432. (C) *Punctatisporites* sp. 2, sample GNR62-7. (D) *Teichertospora* sp. 2, sample GNR54-3. (E) cf. *Cristatisporites* sp. 1, sample GNR8-9. (F) *Emphanisporites* sp., sample GNR8-423. (G) cf. *Auroraspora pseudocrista* Ahmed, sample GNR8-420. (H) cf. *Punctatisporites famennensis* (Naumova) Obukhovskaya*, sample GNR54-66. (I) *Punctatisporites* sp. 3, samples GNR61-1. (J) *Leotriletes* cf. *ornatus* Ishchenko, sample GNR8-424. (K) *Grandispora* sp., sample GNR8-9. (L) *Aneurospora greggsii* (McGregor) Streel in Becker et al., 1974, sample GNR55-1. (M) *Grandispora* cf. *famennensis* (Naumova) Streel var. *minutus* Nekriata, sample GNR49-8. (N) *Cyrtospora cristifera* (Luber) Van Der Zwan, sample GNR8-430. (O) *Cyclogranisporites isostictus* Balme, sample GNR8-268. (P) *Cornispora varicornata* Staplin and Jansonius in Staplin, sample GNR8-421.

In Western Europe and eastern North America, miospores are poorly represented in the early to middle Famennian age transition (Streel et al., 2000; Streel, 2007, 2009). This is consistent with the stratigraphically long-ranged *Knoxisporites dedaleus–Diducites versabilis* (DV) Oppel Zone defined in Western Europe and TG Zone established in eastern North America.

The CZ Zone is the second Eastern European Famennian miospore zone (Avkhimovitch et al., 1993a), which is comparable to the TG Zone of the Old Red Sandstone Continent and the DV Oppel Zone of Western Europe. In Western Europe, the miospore DV Oppel Zone correlates well with the conodont *triangularis* to *rhomboidea* Zone (Streel, 2009; Higgs et al., 2013; Fig. 4). In northern North America, the TG Assemblage Zone (the latest Frasnian to early late Famennian) roughly corresponds to the Lower *triangularis* Zone to the Middle *Scaphignathus velifer* Zone (possibly Lower *trachytera* Zone) in terms of the conodont succession (Richardson and McGregor, 1986). Filipiak and Krawczyński (2018) investigated the miospore assemblages from the Upper Devonian of the Central Devonian Field, Russia, the presence of the CZ and the

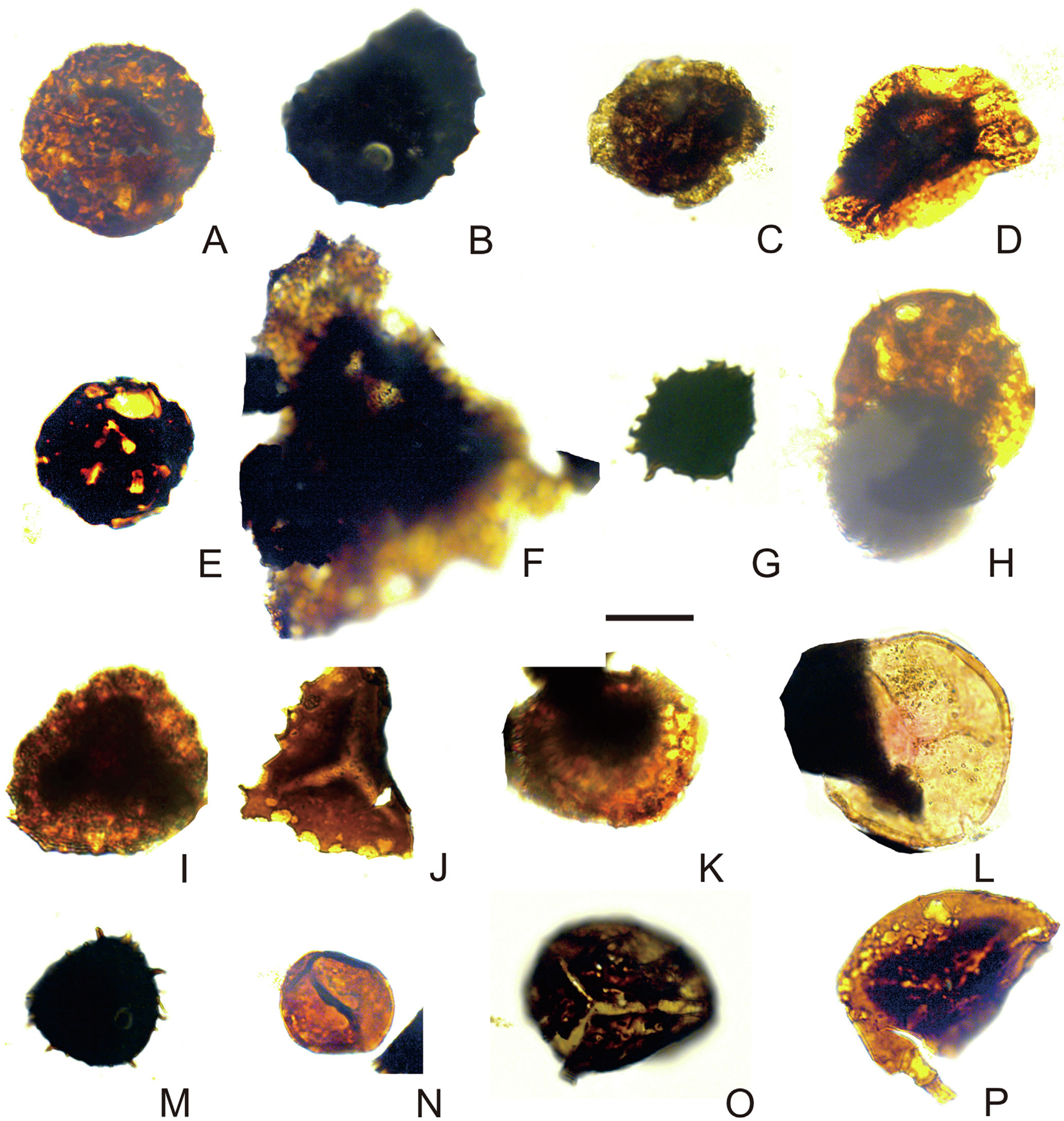

Fig. 6. Miospores from the Hongguleleng Formation at the Gennaren section. Scale bar = 20 μm. (A) *Lophotriletes linguaeformis* Bertelsen, sample GNR62-105. (B) *Grandispora famennensis* var. *famennensis* Higgs et al., 2000, sample GNR62-6. (C) *Auroraspora macra* Sullivan, sample GNR50-53. (D) *Diducites* sp. 2, sample GNR50-95. (E) *Convolutispora* sp., sample GNR62-107. (F) *Hymenozonotriletes argutus* Naumova (in Avkhimovitch et al., 1993a), sample GNR2-10. (G) cf. *Raistrickia* sp., sample GNR62-113. (H) cf. *Tergobulasporites immensus* (Nazarenko and Nekryata) Turnau, sample GNR56-1. (I) *Diducites* cf. *mucronatus* (Kedo) Van Veen, sample GNR51-2. (J) *Punctatisporites* sp. 5, sample GNR54-65. (K) cf. *Retispora* sp., sample GNR 83-2. (L) *Punctatisporites* sp. 4, sample GNR62-110. (M) *Grandispora cornuta* Higgs, sample GNR49-10. (N) *Latosporites* sp., sample GNR62-112. (O) *Punctatisporites* sp. 1, sample GNR8-191. (P) *Retusotriletes planus* Dolby and Neves, sample GNR2-2.

Za (*Convolutispora zadonica*) miospore zones indicates the existence of the lower Famennian (*crepida* conodont Zone). The assemblages of miospore and conodont reported from the Hongguleleng Formation probably indicate that the depositional environment in Western Junggar was very similar to that of Filipiak and Krawczyński (2018)'s Eastern Europe, with the earliest Famennian records missing.

Due to the poor preservation, few miospore specimens in Assemblage I can be identified at the species level with stratigraphic value. *Cornispora varicornata*, *C. monocor-*

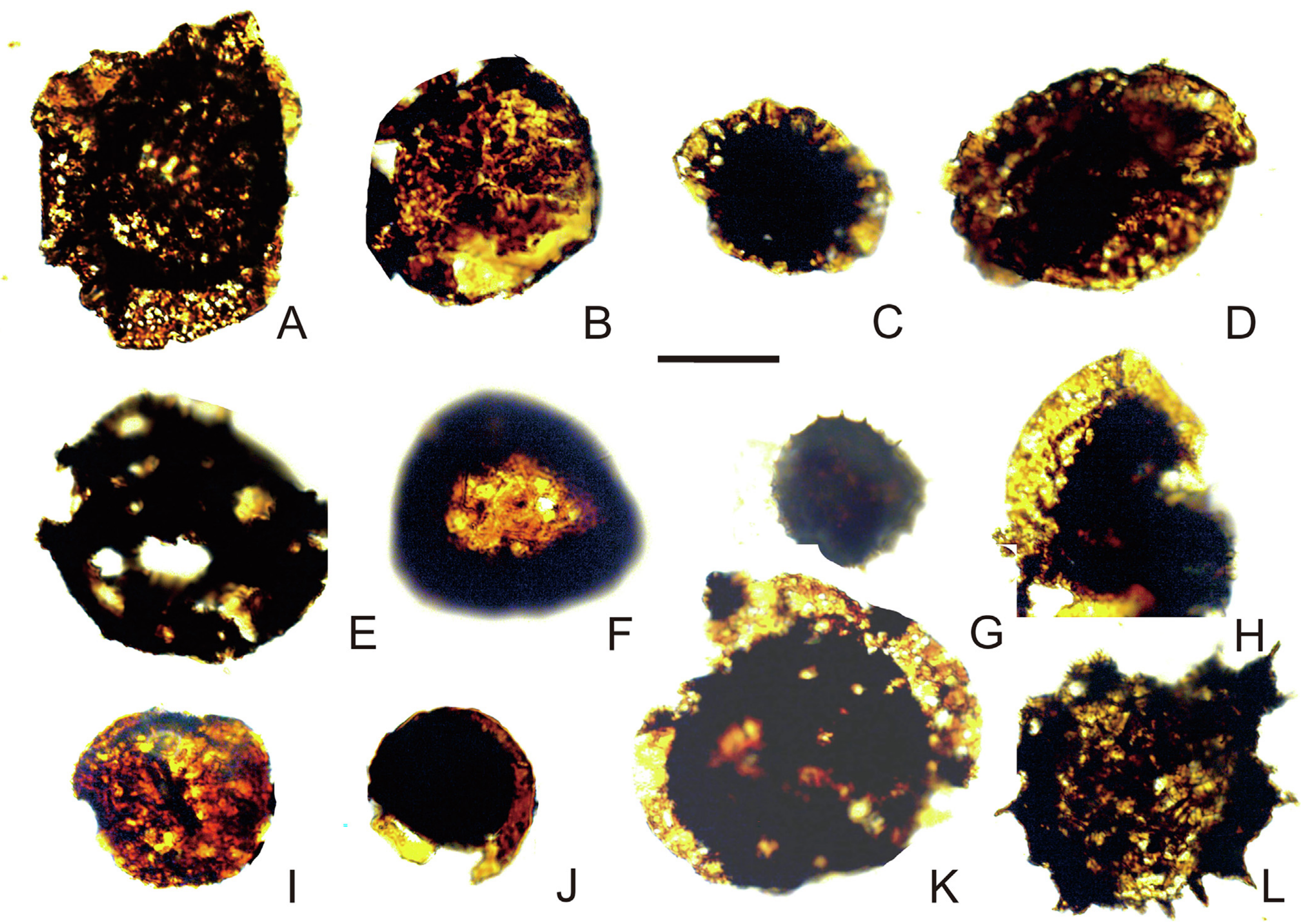

Fig. 7. Famennian miospores from the Hongguleleng Formation at the Gennaren section. Scale bar = 20 μm. (A) cf. *Teichertospora* sp. 1, sample GNR8-15. (B) *Verrucosisporites* sp., sample GNR8-411. (C) *Diducites* sp. 1, sample GNR8-30. (D) cf. *Auroraspora* sp. 1, sample GNR8-422. (E) *Knoxisporites* sp., sample GNR8-427. (F) cf. *Densosporites* sp. 2, samples GNR2-5. (G) *Grandispora microseta* (Kedo) Streel in Becker et al., 1974, sample GNR49-3. (H) *Discernisporites* sp., sample GNR8-13. (I) cf. *Rugospora radiata* (Juschko) Byvsheva, sample GNR62-115. (J) *Auroraspora macra* Sullivan, sample GNR62-13. (K) *Auroraspora* sp. 2, sample GNR8-329. (L) cf. *Cristatisporites* sp. 2, sample GNR8-3.

nata and *Cyrtospora cristifer* are often found in the early to middle Famennian miospore assemblages in northwestern Canada. *C. varicornata* was considered by McGregor (1979) to be widespread in the early to middle Famennian, while *C. cristifer* extends from the Famennian to the Tournaisian (Lower Carboniferous) (Van der Zwan and Walton, 1981). In Eastern Europe, *C. cristifer* is first observed in the CZ Zone and the biostratigraphic distribution can extend to the late Famennian, while *Cornispora bicornate* (a junior synonym of *C. varicornata*) is a typical taxon only observed in the Mid-Famennian *Cornispora varicornata* (CVa) Zone (Avkhimovitch et al., 1993a). The discovery of *Cornispora varicornata* and *Cyrtospora cristifer* in the Gennaren section, along with the index taxa recovered in the Bulongguoer section, suggests that the Assemblage I is not older than CVa Zone, and probably corresponds to the Famennian miospore zones ranging from the CZ Zone to the lower or middle part of the CVa Zone in Eastern Europe, and to the DV Oppel Zone in Western Europe, which can also be compared with the TG zone reported by Richardson and McGregor (1986) from ORSC.

Based on the miospore assemblages, we suggest that the miospore Assemblage I found in the lower member of the Hongguleleng Formation can be compared with the DV Oppel Zone of Western Europe. Additionally, combined with the miospore assemblage retrieved from the nearby Bulongguoer section, we believe that the bottom of the lower member of the Hongguleleng Formation corresponds to part of the *crepida* Zone (Fig. 4).

5.1.2. Assemblage II

The palynoflora abundance increased rapidly at the bottom of the lower member of the Hongguleleng Formation from sample GNR2 to GNR10, while they appear to be decreasing dramatically in the middle part of the lower member of the formation from 38.5 to 192.8 m (Fig. 3), with only few scolecodonts and plant debris found. In the upper part of the lower member of the formation, i.e., from samples GNR49 to GNR62, palynoflora abundance grad-

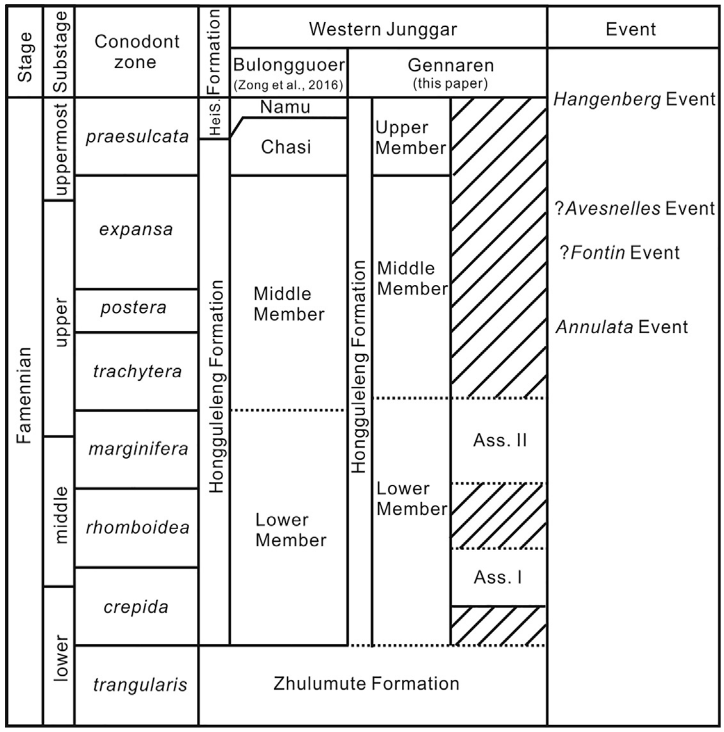

Fig. 8. Correlation of the Famennian miospore and conodont zonal schemes, with possible events in the Hongguleleng Formation in Western Junggar, Northwest China. Abbreviation: Heis. = Heishantou Formation; Ass. I = Assemblage I; Ass. II = Assemblage II.

ually increased again. Based on the proportion of terrestrial organic matter relative to phytoplankton, Marynowski et al. (2012) analyzed the upper Famennian Hangenberg Black Shale depositional environments and suggested that the increase of miospore abundance may be due to either the depositional basin being closer to land or a decrease in primary production in the ocean (or both). The horizon of the Assemblage II is consistent with this episode within the upper part of the lower member of the Hongguleleng Formation. In Western Europe, the Famennian miospore zonation scheme was described by Streel et al. (1987) based on well-studied strata in eastern Belgium. Subsequently, Maziane (1999) revised this scheme by erecting a new zone called *Apiculiretusispora verrucosa–Vallatisporites hystricosus* (VH) Zone by the first appearance of *Apiculiretusispora verrucosa* and *Vallatisporites hystricosus*. Additionally, Maziane (1999) replaced Streel et al. (1987)'s *Retispora lepidophyta–Apiculiretusispora verrucosa* (LV) Zone with the new *Retispora lepidophyta–Knoxisporites literatus* (LL) Zone. The *Grandispora gracilis–Grandispora famennensis* (GF) Oppel Zone in Western Europe is considered to span the middle and late Famennian boundary by Streel (2009). Higgs et al. (2013) revised the GF Oppel Zone and created two subzones: the *Grandispora famennensis* var. *minutus* Subzone in the lower, and the *Grandispora microseta* Subzone in the upper. According to Higgs et al. (2000), *Grandispora microseta* was initially identified in the middle and upper GF Oppel Zone and could extend into the LL Zone. In Western Europe, *Grandispora famennensis* var. *minutus* was first observed near the base of the middle Famennian, at the bottom of the GF Oppel Zone. It could extend into the LL Zone (Higgs et al., 2000). In Eastern Europe, *Grandispora famennensis* var. *minutus* first appears in the *Grandispora famennensis minutus* (GF) Subzone of the CVa Zone and extends to the *Discernisporites golubinicus* (DG) Subzone of *Diducites versabilis–Grandispora famennensis* (VF) Zone. In New York and Pennsylvania, USA, the palynozone of the middle Famennian sediments of the Upper Westfield and Lower Northeast Shale formations are characterized by the incoming of *Grandispora flavus*, *Vallatisporites anthoideus*, and *Convolutispora cancellothyris*. The subzone of *Grandispora flavus* (GF), i.e., *Grandispora famennensis* var. *minutus* (FM) Subzone can be compared to the Eastern European GF Subzone (Avkhimovitch et al., 2021). The *Grandispora famennensis* var. *minutus* found in the USA is shared with our species found in the Gennaren section (Fig. 5M). It was collected with *Grandispora microseta* from the lower part of this assemblage in sample GNR49.

Opinions differ on the age of the overlying GF Oppel Zone, which is believed to span the middle and late Famennian boundary. Some authors believe that the GF Oppel Zone is comparable to the *P. margnifera* to *P. rugosa trachytera* of Ziegler and Sandberg (1984) (Ogg et al., 2016; Lopes et al., 2021), while other authors argue that it should correspond to Early *marginifera* or Late *rhomboidea* (Higgs et al., 2000). In Belgium, the index species *Grandispora* *microseta* occurs at level 19 in the Bon-Mariage section, which was correlated with one of the *marginifera* conodont zones (Higgs et al., 2013).

According to Streel et al. (1987), the *Diducites versabilis–Grandispora cornuta* (VCo) Oppel Zone is equivalent to the *trachytera* to *expansa* conodont zones in Western Europe. Higgs et al. (2013) found that the base of the VCo Oppel Zone is marked by the first occurrence of *Rugospora radiata*, which corresponds with the transition from *trachytera* and *postera* conodont zones. The entire VCo Oppel Zone is consistent with the *trachytera* through Lower *expansa* conodont zones (Higgs et al., 2013). In Eastern Europe, the upper Famennian VF Zone is correlated with the VCo Oppel Zone in eastern Belgium. According to Avkhimovitch et al. (1993a), the VF Zone in Eastern Europe corresponds to the Uppermost *marginifera* through Middle *expansa* conodont zones.

Additional diagnostic species *Grandispora famennensis* var. *famennensis*, found in the upper part of this assemblage in sample GNR62, first appeared in the middle of the GF Oppel Zone in Belgium and last appeared in the middle of the LL Zone (Higgs et al., 2000).

The VCo Oppel Zone was initially defined by Streel et al. (1987) in Western Europe, and is marked by the co-occurrence of *Grandispora cornuta*, *Rugospora flexuosa* and *Retusotriletes philipsii*, which can be compared with the VF Zone in Eastern Europe. Higgs et al. (2013) proposed that the occurrence of *Rugospora radiata* and *Grandispora cornuta* defines the VCo Oppel Zone. Furthermore, the two taxa within the VCo Oppel Zone allow the definition of two new interval zones: the *Rugospora radiata* Interval Zone, succeeded by the *Grandispora cornuta* Interval Zone. *Rugospora radiata* (= *Rugospora flexuosa*) has been widely reported in South China (Gao, 2015), Tibet (Gao, 1988), Iran (Taherian et al., 2022), Western Europe (Becker et al., 1974), and the USA (Molyneux et al., 1984), and appears in sample GNR62 at the top of lower member of the Hongguleleng Formation (237.7 m) in the Gennaren section (Fig. 7I). Based on the available information, it is recommended that the Assemblage II at the upper part of the lower member of the Hongguleleng Formation should be considered as part of the VCo Oppel Zone and correlate with part of the *trachytera* conodont Zone.

The miospore Assemblage II, located in the upper part of the lower member of the Hongguleleng Formation, recovered from sample GNR49 to GNR62 indicates a middle to late Famennian age and can be compared with the GF through VCo Oppel Zone in Western Europe, the VCa through VF Zone in Eastern Europe and the *Rugospora flexuosa–Grandispora cornuta* (FC) in the ORSC.

5.2. The age of the middle member of the Hongguleleng Formation

The middle member of the Hongguleleng Formation has limited coverage and its palynological assemblage is not well-known.

It is widely accepted that two short transgressive events, known as the Annulata and Fontin Events, interrupted the late Famennian age regressive cycle globally (Higgs et al., 2013). The Annulata Event was known because of the sudden proliferation of the ribbed ammonoid *Platyclymenia annulate* (Walliser, 1984; House, 1985), which corresponds biostratigraphically to the conodont Upper *trachytera* Zone through ?Lower *expansa* Zone (Hartenfels, 2011; Higgs et al., 2013). In Southern Poland, the Annulata Black Shale levels date to the upper part of the Upper *Palmatolepis trachytera* conodont Zone, palynologically corresponding to the VF Zone (Racka et al., 2010). The age of the middle member of the Hongguleleng Formation can be supported by the emergence of ammonoid assemblages (Ma et al., 2011; Zong et al., 2014, 2015, 2016). Zong et al. (2014) reported the discovery of several ammonoids, including *Platyclymenia subnautilina*, *Sporadoceras* sp., and *Prionoceras frechi*. These ammonoids are similar to the standard Devonian ammonoid IV Zone in Western Europe, which is equivalent to the conodont Upper *trachytera* to Lower *expansa* Zone interval in Western Europe. The discovery of *Platyclymenia subnautilina* in Bed 5-2 (middle member of the Hongguleleng Formation) in Bulongguoer section provides evidence of the existence of the Annulata Event in the middle member of the Hongguleleng Formation (Zong et al., 2014, 2015).

Chen et al. (2009) discovered the conodonts of the *trachytera* Zone at 113.9 m in the Bulongguoer section (*sensu* the Bed 5-1 from Ma et al., 2011). Conodont species of the *trachytera* Zone were also reported by Suttner et al. (2014) from approximately 16 m above the base of the "Hebukehe" Formation, which is likely the same assemblage as Bed 5-1 in Ma et al. (2011). Thus, the middle member of the Hongguleleng Formation contains at least a portion of the *trachytera* Zone.

In Western Junggar, Xia (1997) reported the *expansa* to *praesulcata* conodont zones in the Hebukehe Formation; this "Hebukehe" Formation includes the Upper Devonian Zhulumute and Hongguleleng Formations, as well as the Lower Carboniferous (Mississippian) Heishantou Formation in most areas. Unfortunately, the exact location of these two zones is unknown. Zong et al. (2020) considered the controversial and commonly used term "Hebukehe" Formation invalid.

Streel and Hartkopf-Fröder (2005) demonstrated that in Belgium, the lower part of the LL Zone is correlated with the Middle *expansa* conodont Zone. Due to the deep-water depositional environment of the middle member of the Hongguleleng Formation, only one possible specimen of *Retispora lepidophyta* (referred to as cf. *Retispora* sp.) has been discovered, which could be a pyritized sample that indicate the presence of *Retispora* sp. However, further studies are needed to confirm this. If *R. lepidophyta* appears at the top of the middle member of the Hongguleleng Formation, it may correspond to the LL Zone. As a result, we could classify the middle member of the Hongguleleng Formation as belonging to the partial *trachytera* through the *expansa* conodont Zone.

The important index taxa of VH Oppel Zone from Western Europe just above the VCo Oppel Zone were not identified in the middle member of the Hongguleleng Formation.

6. Conclusions

We present an age proposal based on two miospore assemblages recovered in the lower member of Hongguleleng Formation. In this study, we recognize two palynological assemblages, one in the lower part of the lower member, correlated with the miospore DV Oppel Zone and corresponding to the *crepida* to *rhomboidea* conodont zones of early-middle Famennian age, and the other in the upper part of the lower member, which can be correlated with the miospore GF to VCo Oppel zones, corresponding to the conodont *marginifera* to Lower *trachytera* zones of middle-late Famennian age.

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Supplementary data

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