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Earth-Science Reviews 52 (2000) 121–173

EARTH-SCIENCE REVIEWS

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Late Frasnian–Famennian climates based on palynomorph analyses and the question of the Late Devonian glaciations

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Received 9 February 2000; accepted 27 July 2000

Abstract

Palynomorph distribution in Euramerica and western Gondwana, from the Latest Givetian to the Latest Famennian, may be explained, to some extent, by climatic changes. Detailed miospore stratigraphy dates accurately the successive steps of these changes. Interpretation is built on three postulates which are discussed: Euramerica at slightly lower latitudes than generally accepted by most paleomagnetic reconstructions; a conodont time-scale accepted as the most used available subdivision of time; and Late Devonian sea-level fluctuations mainly governed by glacio-eustasy. The Frasnian–Famennian timescale is also evaluated.

The comparison, based on conodont correlations, between Givetian and most of the Frasnian miospore assemblages from, respectively, northern and southern Euramerica demonstrates a high taxonomic diversity in the equatorial belt and much difference between supposed equatorial and (sub) tropical vegetations. On the contrary, a similar vegetation pattern and therefore probably compatible climatic conditions were present from tropical to subpolar areas. A rather hot climate culminated during the Latest Frasnian when equatorial miospore assemblages reached their maximum width. The miospore diversity shows also a rather clear global Late Frasnian minimum which is also recorded during the Early and Middle Famennian but only in low latitude regions while, in high latitude, very cold climates without perennial snow may explain the scarcity of miospores and so, of vegetation.

The Early and Middle Famennian conspicuous latitudinal gradient of the vegetation seems to attenuate towards the Late and Latest Famennian but this might be above all the result of the development, of cosmopolitan coastal lowland vegetations (downstream swamps) depending more on the moisture and equable local microclimates than on the probably adverse climates of distant hinterland areas. During that time, periods of cold climate without perennial snow cover and with rare vegetation may have alternated with less cold but wetter climates, thus giving rise to the development of mountain glaciers in high latitudes and explaining the jerking character of the global major marine regression. In high latitude regions, the development of an ice cap reaching sea level is only recorded by the end of the Latest Famennian, immediately below the DCB but, even if glacial evidences are not known at near the FFB, a short (0.1 Ma?) glaciation seems the best reasonable explanation of the major eustatic fall following the Kellwasser Event. The sudden growth and decay of a hypothetical

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PII: S0012-8252(00)00026-X

Earliest Famennian ice sheet can be explained by the reduction and, later, increase in greenhouse capacity of the atmosphere. These changes in the atmospheric CO_2 might have provoked changes in the mode of ocean-atmosphere operation. It may also be partly controlled by a volcanic paroxysm and/or bolide impacts. The Hony microtektites represent the best known evidence of the impact of extraterrestrial bodies on Earth corresponding to the UKW, and they are immediately followed by a regression, suggested by the quantitative analysis of acritarch assemblages.

In the paleo-tropical Late Famennian, a peat-forming vascular plant community occurs for the first time and makes possible quantitative palynology of autochthonous sediments allowing the recognition of different swamp and near-swamp characteristic miospores. The early Latest Famennian starts with a widespread transgression which could correspond to the melting phases of the hypothetical Late Famennian mountain glaciers. During the end-Famennian, the coastal lowland vegetation has a worldwide distribution from sub-polar to equatorial regions. The climate has become less cold in high latitudes but wetter than before probably because the midlatitude cyclonic activity allows sufficient polar transportation of moisture to form large snow cover. Extensive coastal glaciers developed in different Bolivian and Brazilian basins, well dated by miospores. Rapid climatic changes characterize the onset of glaciation. The cyclic nature of climate allowed even intertropical marine faunas to reach occasionally the subpolar regions.

For the plant kingdom, the crisis which follows the Hangenberg Event was more severe than the Late Frasnian Crisis.

Keywords: Late Frasnian–Famennian climates; palynomorph analyses; Late Devonian glaciations

1. Introduction

The Famennian Stage is bracketed by two main crises and two events in the biosphere: the Late Frasnian Crisis and the Kellwasser Event near the Frasnian/Famennian Boundary (FFB), the end-Famennian Crisis and the Hangenberg Event near the Devonian/Carboniferous Boundary (DCB). We consider a crisis in the biosphere to represent a rather long time interval, during which the biodiversity deteriorates, often resulting in a stepwise loss of taxa. On the contrary, an event is considered to be a geological short-term perturbation compared to preceding and succeeding time intervals (Walliser, 1990; Schindler, 1993). Of course, the abruptness of a short-term perturbation is difficult to establish in the geological past (Van Loon, 1999) and one can consider that crises and events might be only two facets of the same phenomenon.

The proposed causes of crises and events are very diverse, and climate change is only one of them which we intend to focus on (other proposed causes are bolide impacts, tectonism, oceanic overturn, eustatic fluctuations, etc). The Famennian climate itself is often reduced to the question: glaciation or no glaciation? According to Dickins (1993, p. 90), Becker (1993) and House (1996), there was no glaciation during the Famennian and the Earliest Carboniferous. After Boucot (1988, p. 223), the glaciation might be of Early Carboniferous age; after Isaacson et al. (1999), of Late Famennian and Tournaisian ages; after Loboziak et al. (1993), of late Latest Famennian age; after Caputo (1985), of mid-Famennian age. According to Veevers and Powell (1987) and Smith (1997, p. 167), a glaciation might have occurred during the entire Famennian. Too often also, glaciation is confused with global cooling ignoring the fact that, if glaciation requires cold climate, it also does require heavy snowfall.

Few contributions to the understanding of Devonian climates rely on terrestrial vegetation data despite the fact that its impact on the biosphere was very important during that period (Tappan, 1982, 1986; Algeo and Scheckler, 1998). Indeed a massive increase of land plant biomass from Middle Devonian to Early Carboniferous times (Berner, 1990) and the increased rate of organic matter burial during major transgression pulses (Caputo, 1994) is believed to explain the long-term shortage of atmospheric CO_2 at this time. The reason of this scarcity of information has to be found in the scattered and poorly dated occurrences of plant megafossils in the geological record at this time. It is also the result of the continued misconception that even miospores, produced by these land plants, are poorly correlated with marine faunas (see for instance McGhee, 1996, p. 187).

We believe that land plant miospores, which are much more abundant and widespread than land plant megafossils, can supply reliable quantitative data

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Review of Palaeobotany and Palynology 112 (2000) 229–246

Review of Palaeobotany & Palynology

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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)

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Received 25 February 1999; received in revised form 22 February 2000; accepted for publication 26 May 2000

Abstract

A zonal subdivision of the Frasnian–Famennian transitional deposits in the Pripyat Depression and Timan–Pechora Province, based on a detailed palynological study, has been completed. The data obtained on miospores and conodonts from the Timan–Pechora Province enable a correlation to be made with the Standard Conodont Zonation. The lateral extent of the palynozones in Eastern Europe and the correlation with Western Europe are discussed. The following previously published new combinations are validated: *Auroraspora speciosa* (Naumova) Obukhovskaya, comb. nov., *Corbulispora viminea* (Nekriata) Obukhovskaya and Nekriata, comb. nov., *Cristatisporites imperpetuus* (Sennova) Obukhovskaya, comb. nov., *Cymbosporites acanthaceus* (Kedo) Obukhovskaya, comb. nov., *Grandispora subsuta* (Nazarenko) Obukhovskaya, comb. nov., and *Verrucosisporites evlanensis* (Naumova) Obukhovskaya, comb. nov. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: conodonts; Frasnian–Famennian transition.; miospores; Pripyat Depression; Timan–Pechora Province

1. Introduction

The boundary deposits of the Frasnian and Famennian Stages are widespread on the territory of the Pripyat Depression in SE Belarus and the Timan–Pechora Province in Russia (Fig. 1). The present paper compares the biostratigraphic data known from many deep boreholes in the Pripyat Depression with a single borehole drilled in the Belgop site (left bank of the River Izhma) in the Timan–Pechora Province. The biostratigraphy of these deposits is based mainly on miospores in the Pripyat Depression, on both miospores and conodonts in the Timan–Pechora. This enables a correlation between the regional horizons and the zonal miospore and conodont scales (Fig. 2). Ultimately, a comparison between miospore zonations in Eastern and in Western Europe is proposed.

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PII: S0034-6667(00)00045-2

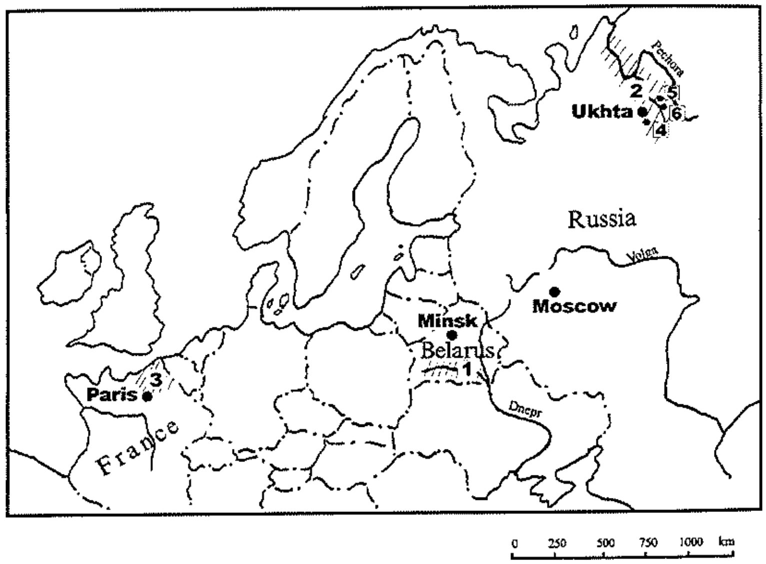


Fig. 1. Location of (1) the Pripyat Depression (Belarus), (2) the Timan–Pechora Province (Russia) and (3) the Boulonnais (France), (4) borehole Belgop 4; (5) borehole Vis 909; (6) borehole Tebuk 881.

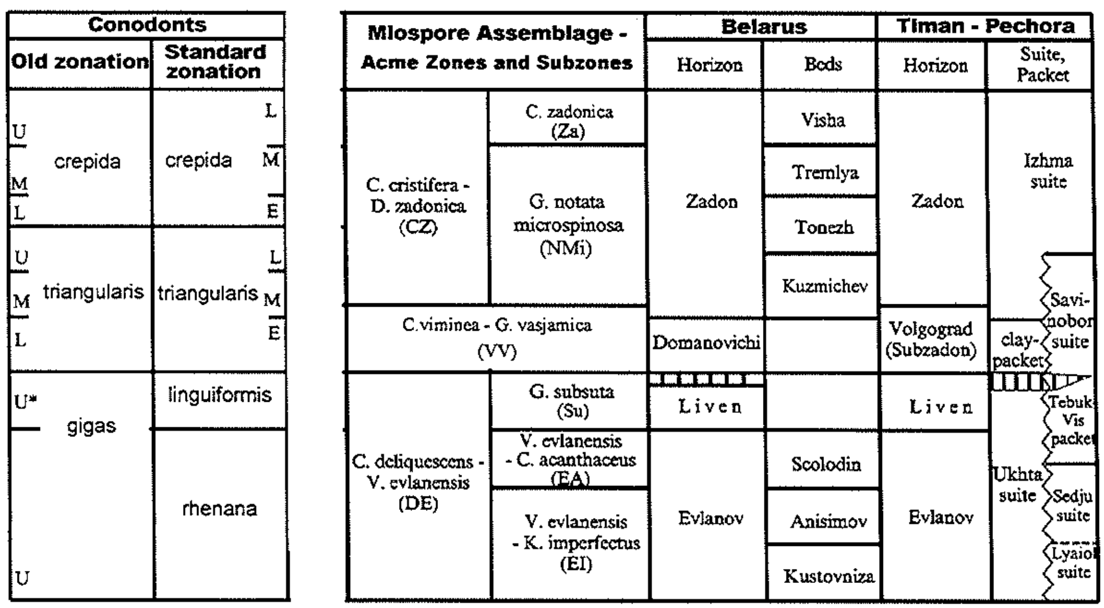


Fig. 2. Stratigraphic schemes of Upper Frasnian and Famennian of the Pripyat Depression and Timan–Pechora Province.

2. Lithology

In the Pripyat Depression, the boundary deposits of the Frasnian and Famennian Stages are stratigraphically composed of the Evlanov, Liven, Domanovichi and Zadon Horizons and include various facies. The lower part of the Evlanov Horizon is composed of carbonate facies. Its upper

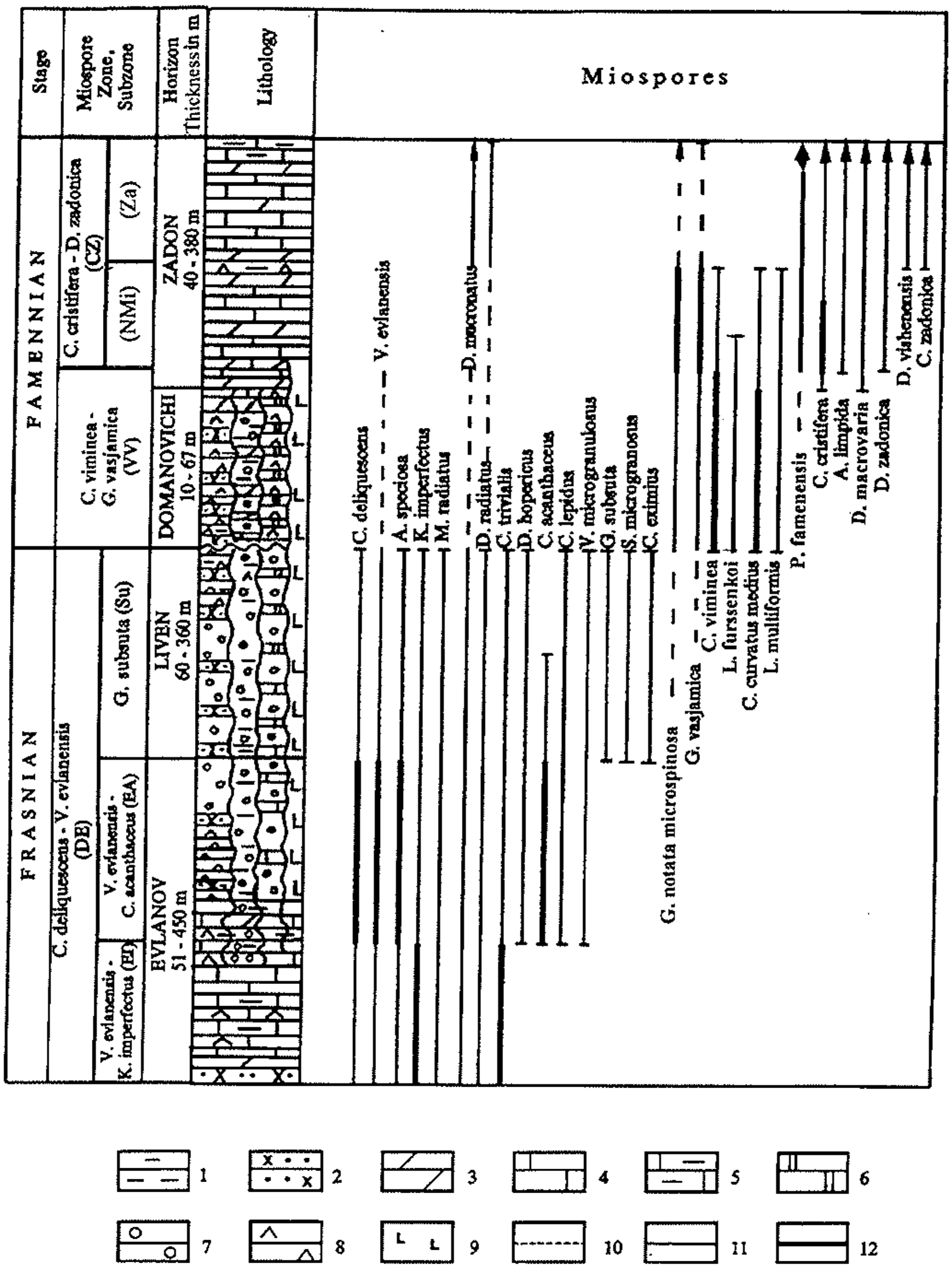
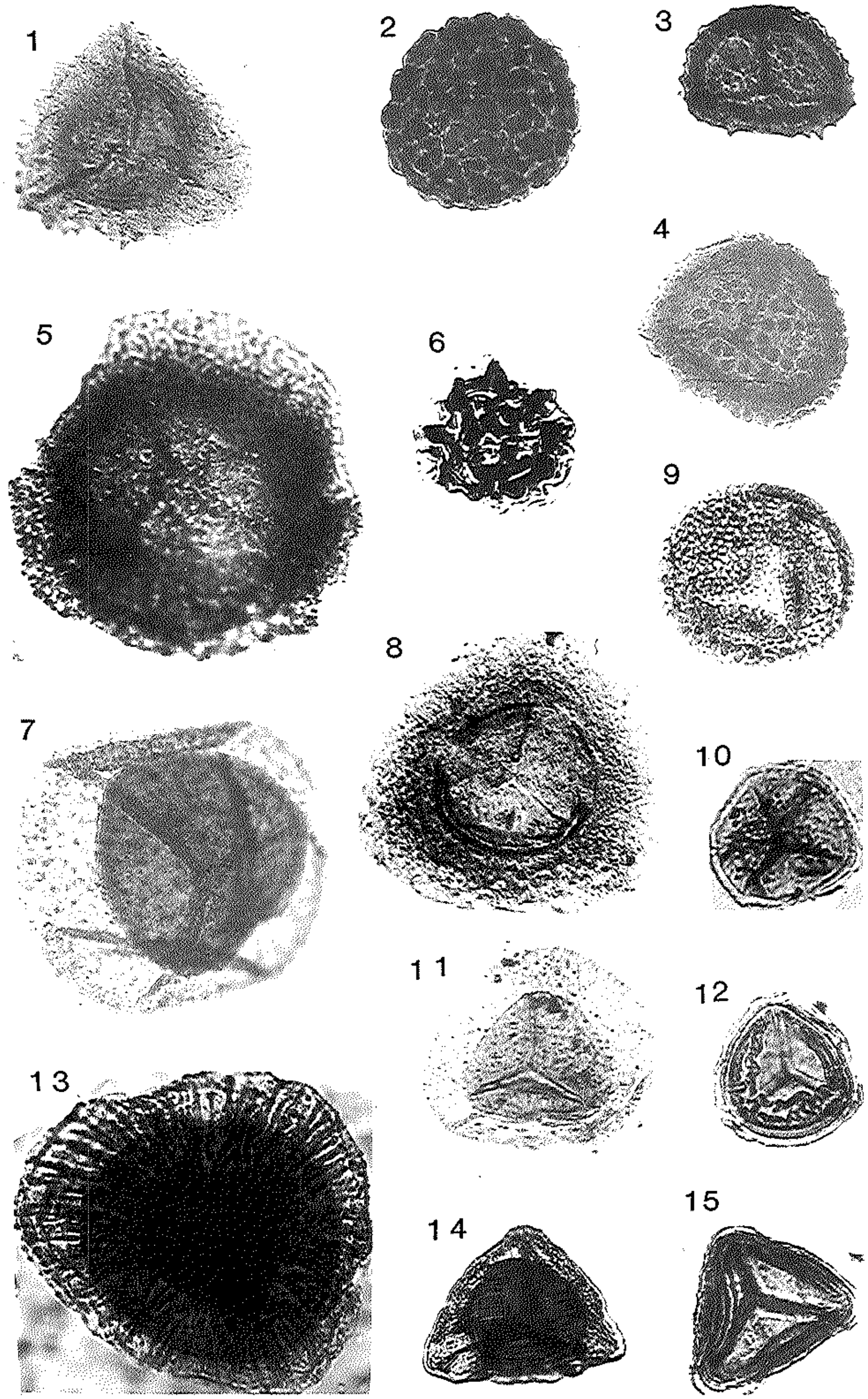


Fig. 3. General summary of the miospore stratigraphy of the Pripyat Depression. 1: claystone; 2: sandstone; 3: marl; 4: limestone; 5: clayey limestone; 6: dolomite; 7: salt; 8: sulphate; 9: volcanic rocks; 10: interrupted line: rare miospores; 11: full thin line: moderate presence of miospores; 12: thick line: abundant miospores.

PLATE I



part and the Liven and Domanovichi Horizons are represented by volcanogenic rocks in the east of the Pripyat Depression, by saliferous rocks in the central regions and in the south, and by sulphate–carbonate and sulphate terrigenous rocks in the north and west (Fig. 3). The Evlanov Horizon is subdivided into the Kustovniza, Anisimov and Scolodin Beds (Fig. 2).

The overlying Zadon Horizon is composed of carbonate facies, its lower part is represented by interbedded limestones, marls and dolomites, sometimes nodular or wavy-laminated limestones, while its upper part includes interbedded marls and muddy limestones (Pushkin, 1990; Pushkin et al., 1995). The Zadon Horizon is subdivided into the Kusmichev, Tonezh, Tremlya and Visha Beds (Fig. 2)

In the Timan–Pechora Province, the upper part of the Frasnian Stage is represented by shallow marine as well as by depression deposits (Kushnareva, 1977). The lower part of the Evlanov Horizon is composed of limestones, marls and clays. In shallow marine sulphate-bearing sequence, the upper part of the Evlanov Horizon and the whole Liven Horizon are composed of interbedded anhydrites, clays and marls, and rare limestones, with a dominance of clay-layers at the base. In the uppermost Liven Horizon, a multicolor packet of clays and marls without miospores is found. In the depression deposits, the upper part of the Evlanov Horizon and the Liven Horizon are composed of limestones with interbedded marls and shales. The Famennian Volgograd (Subzadon) Horizon is composed of clays with dolomite and rare limestone beds, while in the overlying Zadon Horizon, the limestone beds are dominant.

3. Palynostratigraphy

The detailed miospore zonation and correlation of the transitional Frasnian–Famennian deposits in Pripyat Depression and Timan–Pechora Province are mainly based on the Avkhimovitch et al. (1993) synthesis.

3.1. *Cristatisporites deliquescens–Verrucosisporites evlanensis (DE) Zone*

This miospore zone corresponds to the Evlanov and Liven Horizons. It is characterized by the appearance of *Verrucosisporites evlanensis* and by the acme of *Cristatisporites deliquescens*. The latter species disappears at the top of this zone in the Pripyat depression but is still, but rarely, present above this zone in Timan–Pechora Province.

Typical species of the miospore assemblages of this zone are illustrated on Plates I and IV.

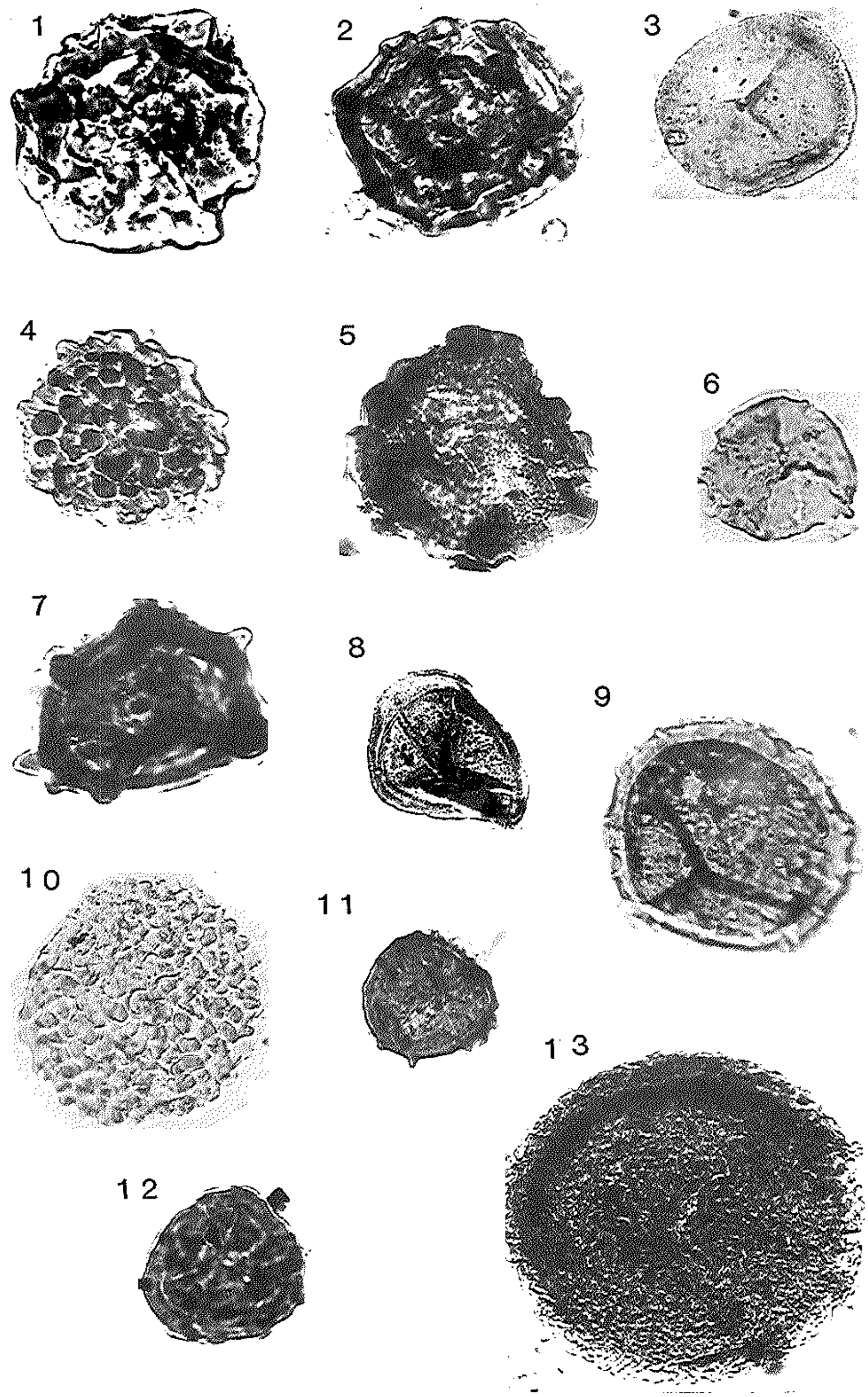
The Zone DE is subdivided into three subzones.

PLATE I

Cristatisporites deliquescens–Verrucosisporites evlanensis (DE) Zone (from the Pripyat Depression). Illustrated specimens magnification × 500, except where otherwise stated.

1. *Cristatisporites deliquescens* (Naumova) Arkhangelskaya; W—Kamenskaja, 3335 m.
2. *Verrucosisporites evlanensis* (Naumova) Obukhovskaya, comb. nov.; Petrikovskaja, 469, 962–968 m.
3, 4. *Cymbosporites acanthaceus* (Kedo) Obukhovskaya, comb. nov.; 3, Grebenevskaja, 1, 4774;
4. Grebenevskaja, 2, 4779.3, 4 m (× 1000).
5. *Spelaeotriletes microgranosus* (Kedo) Obukhovskaya; Marmovitchi, 1, 2890–2905 m.
6. *Chelinospora lepida* (Obukhovskaya) Obukhovskaya; Kasimirovskaja, 1, 2622.8–2654.0 m.
7. *Grandispora subsuta* (Nazarenko) Obukhovskaya, comb. nov.; Petrikovskaja, 469, 962–968 m.
8. *Auroraspora speciosa* (Naumova) Obukhovskaya, comb. nov.; Borovskaja, 1, 1791.7–1798.05 m.
9. *Verrucosisporites microgranulosus* (Kedo) Obukhovskaya; Radomlyanskaja, 16, 1630–1633.5 m.
10. *Kedoesporis evlanensis* (Naumova) Obukhovskaya; Grebenevskaya, 1, 4889.1–4897.4 m.
11. *Diducites hopericus* (Nazarenko) Obukhovskaya; Petrikovskaja, 469, 962–968 m.
12. *Kedoesporis imperfectus* (Naumova) Obukhovskaya; Mstislavskaja, 1, 70–75 m.
13. *Membrabaculisporis radiatus* (Naumova) Arkhangelskaya; Mstislavskaja, 1, 70–75 m.
14. *Cristatisporites trivialis* (Naumova) Obukhovskaya; Tulgovitchskaja, 1, 2132.5 m.
15. *Kedoesporis imperfectus* (Naumova) Obukhovskaya; Grebenevskaja, 1, 4889.1–4897.4 m.

PLATE II



3.1.1. Verrucosisporites evlanensis–Kedoesporis imperfectus (EI) Subzone

This subzone corresponds to the Kustovniza and Anisimov Beds of the Evlanov Horizon in the Pripyat Depression (Avkhimovitch et al., 1988), and the lower part of the Evlanov Horizon in Timan–Pechora Province. It is characterized by the appearance of *Verrucosisporites evlanensis* and by the acme of *Kedoesporis evlanensis*, *K. imperfectus*, *Cristatisporites trivialis*, *Membrabaculisporis radiatus*, rare *Diducites hopericus*, and by many representatives of the genera *Hystricosporites* and *Stenozonotriletes*.

The brachiopods *Theodossia anossofi* Verneuilli, and *T. evlanensis* Nalivkin are found within the subzone EI interval of the Pripyat Depression.

In the Timan–Pechora Province, the equivalent deposits are characterized by conodonts of the Upper *gigas* (=Late *rhenana*) Zone (Obukhovskaya and Kuzmin, 1993).

3.1.2. Verrucosisporites evlanensis–Cymbosporites acanthaceus (EA) Subzone

This subzone corresponds to the Skolodin Beds in the Pripyat Depression and to the upper part of Evlanov Horizon in Timan–Pechora. It is characterized by the appearance of *Cymbosporites acanthaceus* and *Chelinospora lepidus* and the wide distribution of *Verrucosisporites microgranulosus*. In addition, *Cristatisporites deliquescens*, *Auroraspora speciosa* and *Diducites radiatus* are abundant.

In Timan–Pechora, the deposits corresponding to this subzone interval are characterized by conodonts (Obukhovskaya and Kuzmin, 1993; Kuzmin et al., 1998). The conodont assemblage in the shallow marine sequence in the borehole Belgop 4 (Fig. 4) contains many species of *Polygnathus dentimarginatus* Kuzmin and occasional *P. politus* Ovnatanova, *P. unicornis* Mull. and Mull., belonging to the Upper *gigas* (=Late *rhenana*) Zone. The conodonts found in the depression deposits (borehole Wis 909, 1817.5–1823.5 m) such as *Palmatolepis rhenana* Bisch., *P. praetriangularis* Ziegl. and Sandb., *P. juntianensis* Han, *P. subrecta* Mill. and Young., *P. ederi* Ziegl. and Sandb., *P. rotunda* Ziegl. and Sandb., *Polygnathus macilentus* Kuzmin, are also typical of the Upper *gigas* (= Late *rhenana*) Zone.

3.1.3. Grandispora subsuta (Su) Subzone

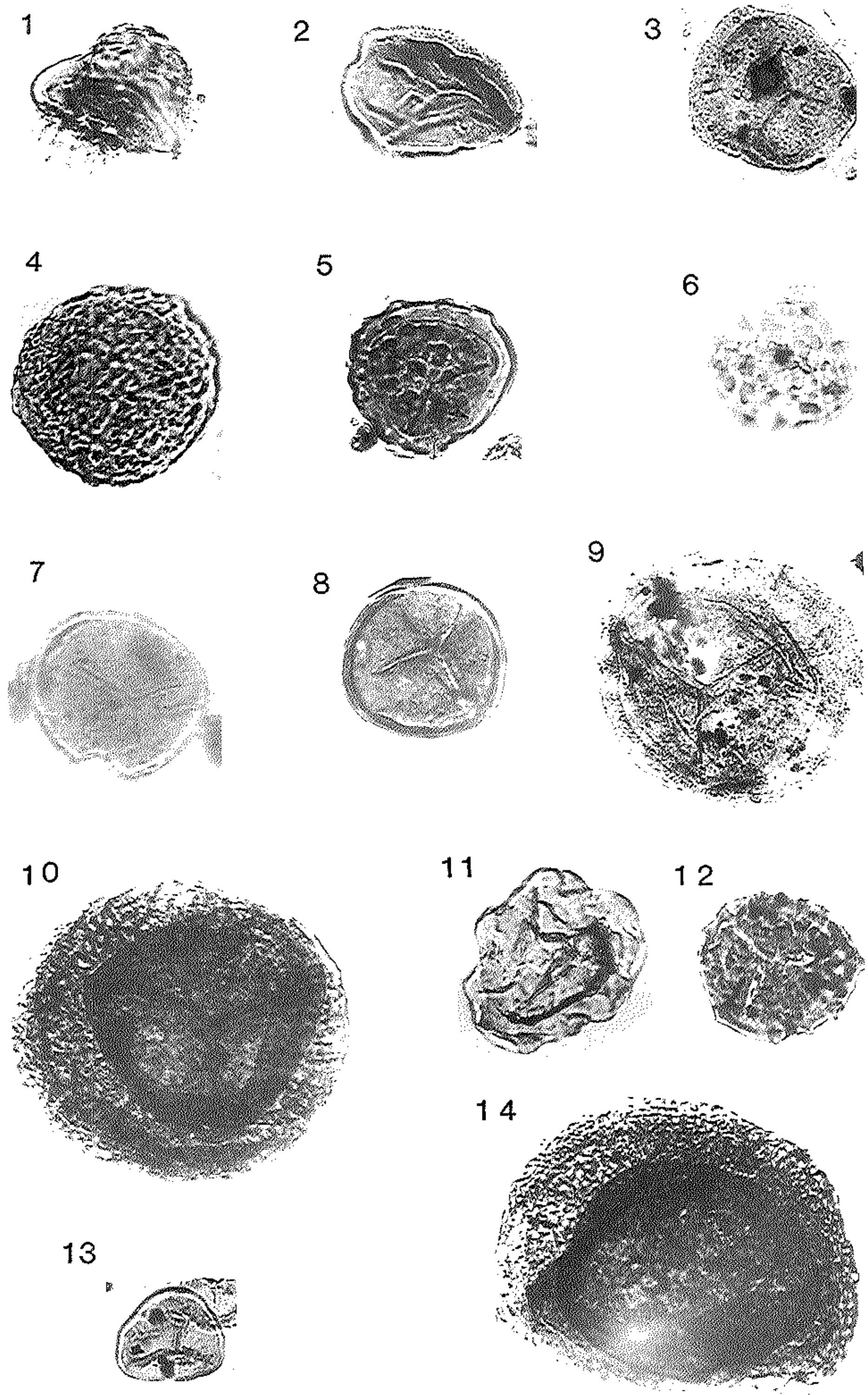
This subzone corresponds to the Liven Horizon. In the Pripyat Depression, *Grandispora subsuta*, *Cymbosporites eximius* and *Spelaeotriletes microgranosus* appear at its base. *Membrabaculisporis radiatus*, *Cristatisporites trivialis*, *Auroraspora speciosa*, *Chelinospora lepidus* and several other common Frasnian species gradually disappear towards its top. In the Timan–Pechora Province,

PLATE II

Corbulispora viminea–Geminospora vasjamica (VV) Zone (from the Pripyat Depression). Illustrated specimens magnification ×500.

1, 2. *Corbulispora viminea* (Nekriata) Obukhovskaya and Nekriata, comb. nov.
1. Svobodka, 2, 3983–3984 m.
2. Petrikovskaja, 469, 947–952 m.
3. *Geminospora vasjamica* (Tchibrikova) Obukhovskaya and Nekriata; Svobodka, 2, 3983–3984 m.
4, 5. *Lophozonotriletes furssenkoi* Nekriata.
4. Petrikovskaja, 469, 929–935 m, distal.
5. Petrikovskaja, 469, 947–952 m, proximal
6. *Pustulatisporites pullus* (Naumova) Obukhovskaya; Petrikovskaja, 468, 947–952 m.
7. *Lophotriletes multiformis* Tchibrikova; Petrikovskaja, 469, 929–935 m.
8. *Geminospora notata* (Naumova) Obukhovskaya var. *microspinosa* Tchibrikova; W.—Bobrovitchi, 4, 2621–2634 m.
9. *Lophozonotriletes grandis* (Naumova) Archangelskaya; Petrikovskaja, 469, 947–952 m.
10. *Verrucosisporites evlanensis* (Naumova) Obukhovskaya, comb.nov.; W.—Bobrovitchi, 4, 2621–2634 m.
11. *Converrucosisporites curvatus* (Naumova) Turnau; W.—Bobrovitchi, 4, 2610–2621 m.
12. *Converrucosisporites curvatus* (Naumova) Turnau var. *medius* Kedo; W.—Bobrovitchi, 4, 2621–2634 m.
13. *Bulbosisporites volgogradicus* (Nazarenko and Tchibrikova) Obukhovskaya; Petrikovskaja, 469, 947–952 m.

PLATE III



the miospore assemblages of this subzone are characterized by the acme of *Auroraspora speciosa*, *Diducites hopericus*, *D. radiatus*, *Cristatisporites deliquescens* and by rare specimens of *Grandispora* cf. *subsuta*, *Spelaeotriletes microgranosus*, *Auroraspora pseudocrista* and *Cymbosporites eximius*.

Conodonts such as *Ancyrodella ioides* Ziegl., *Palmatolepis juntianensis* Han, *P. linguiformis* Mull., *P. rhenana* Bisch., *P. subrecta* Mill. and Young., *Polygnathus decorosus* Stauff and *P. macilentus* Kuzmin, are found in the depression deposits within the subzone Su interval of the Timan–Pechora Province (boreholes Tebuk 881, 1711–1722 m and Wis 908, 1797–1799.5 m). They are typical of the Uppermost *gigas* (=*linguiformis*) Zone.

3.2. *Corbulispora viminea–Geminospora vasjamica* (VV) Zone

This miospore zone corresponds to the Domanovichi Horizon and the lowermost part of the Kuzmichev Beds of the Pripyat Depression and to the Volgograd (Subzadon) Horizon of the Timan–Pechora Province. Its base coincides with a short break in sedimentation and present a sharp palynological turnover. This zone is characterized by the appearance of *Corbulispora viminea*, *Lophozonotriletes furssenkoi* and *Pustulatisporites pullus*. Abundant *Geminospora vasjamica* and *G. notata* var. *microspinosus* are also present. In the Pripyat Depression, the miospore assemblages of this zone are characterized by the abundance of *Corbulispora viminea*, while in the Timan–Pechora Province, they include numerous *Cristatisporites imperpetuus* and *Cymbosporites boafeticus*.

The typical miospore species of this zone are illustrated on Plates II and V.

The deposits corresponding to the VV Zone interval in Timan–Pechora Province contain the following conodonts: *Icriodus cornutus* Sann., *I.* ex gr. *iowaensis* Young. and Pet., *I. iowaensis* Young. and Pet., and *Polygnathus brevilamminus* Branson and Mehl (Obukhovskaya and Kuzmin, 1993). These correspond to the *triangularis* Zone (or *crepida* Zone according to R. Dreesen, personnal communication).

3.3. *Cyrtospora cristifera–Diaphanospora zadonica* (CZ) Zone

This zone corresponds to the Zadon Horizon, with the exception of the lowest part of the Kuzmichev Beds. It is characterized, close to its base, by the abundance of *Cyrtospora cristifera* and *Pustulatisporites famenensis* and, higher, by the presence of *Diducites vishenensis* and *Convolutispora zadonica*. The CZ Zone is subdivided into two subzones in the Pripyat Depression.

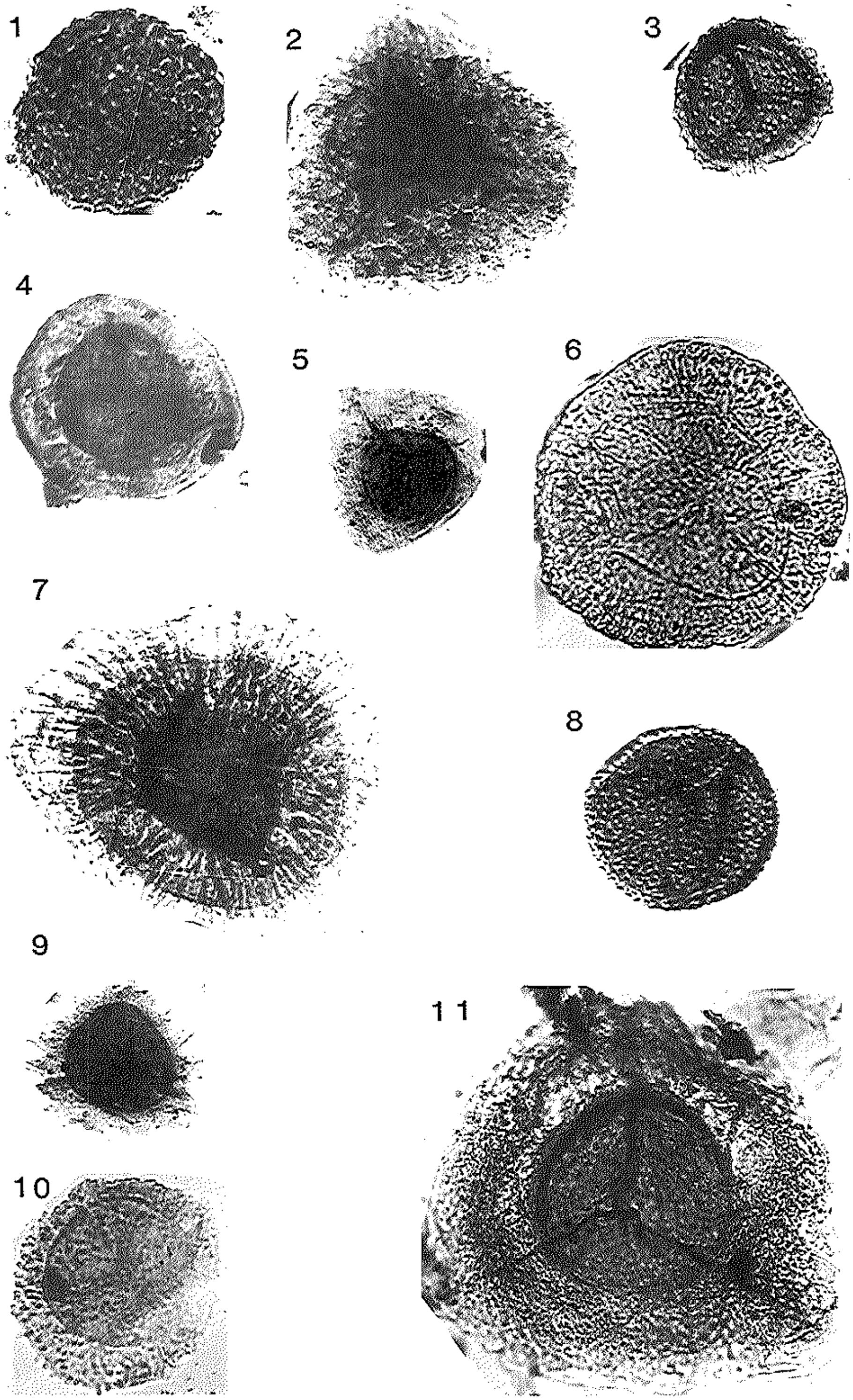
The typical miospore species of the CZ Zone are illustrated on Plate III.

PLATE III

Cyrtospora cristifera–Diaphanospora zadonica (CZ) Zone (from the Pripyat Depression). Illustrated specimens magnification ×500.

1. *Cyrtospora cristifera* (Luber) Van der Zwan; W.—Bobrovitchi, 4, 2565 m.
2. *Geminospora notata* (Naumova) Obukhovskaya var. *microspinosa* Tchibrikova; W.—Bobrovitchi, 4, 2545 m.
3. *Geminospora vasjamica* (Tchibrikova) Obukhovskaya and Nekriata; W.—Bobrovitchi, 4, 2577 m.
4. *Convolutispora zadonica* (Nekriata) Obukhovskaya and Nekriata; W.—Kamenskaja, 1, 3313–3327 m.
5. *Converrucosisporites curvatus* (Naumova) Turnau var. *medius* Kedo; W.—Bobrovichi, 4, 2577 m.
6. *Pustulatisporites famenensis* (Naumova) Obukhovskaya; W.—Bobrovitchi, 4, 2610–2620 m.
7. *Auroraspora limpida* (Naumova) Avkhimovitch ; W.—Bobrovitchi, 4, 2604–2610 m.
8. *Stenozonotriletes definitus* Naumova ; Petrikovskaja, 469, 923–928 m.
9. *Diducites mucronatus* (Kedo) Van Veen; Savitchi, 1, 2652–2660 m.
10. *Diducites vishenensis* Obukhovskaya and Avkhimovitch; Savitchi, 1, 2652–2660 m.
11. *Corbulispora viminea* (Nekriata) Obukhovskaya and Nekriata; Chobno, 1, 2547 m.
12. *Converrucosisporites curvatus* (Naumova) Turnau; Petrikovskaja, 469, 923–928 m.
13. *Punctatisporites famenensis* (Naumova) Obukhovskaya; W.—Bobrovichi, 4, 2610 m.
14. *Diducites radiatus* (Kedo) Obukhovskaya; Savitchi, 1, 2652–2660 m.

PLATE IV



3.3.1. Geminospora notata microspinosus (NMi) Subzone

This subzone corresponds to most of the Kuzmichev Beds and to the Tonezh and Tremlya Beds in the Pripyat Depression. It is characterized by the abundance of *Geminospora notata* var. *microspinosus* and the constant presence of *Cyrtospora cristifera*, *Pustulatisporites famenensis*, *Diaphanospora macrovaria*, *Geminospora vasjamica*, and *Converrucosisporites curvatus*. *Corbulispora viminea* has its last occurrence at this level. In the Timan–Pechora Province, the NMi Subzone corresponds to the lower part of the Zadon Horizon.

The conodont *triangularis* or *crepida* Zones, including *Palmatolepis triangularis* Sann., *P.* aff. *crepida* Sann., *P. quadrantinodosalobata* Sann., *P. termini* Sann. and *Icriodus iowaensis* Young. and Pet., *I. cornutus* Sann. and *Polygnathus brevilaminus* Branson and Mehl. were identified in the Pripyat Depression (Pushkin et al., 1995) as well as in the Timan Pechora Province (Obukhovskaya and Kuzmin, 1993).

3.3.2. Convolutispora zadonica (Za) Subzone

This subzone corresponds to the Visha Beds in the Pripyat Depression (Nekriata, 1979) and the upper part of the Zadon Horizon in the Timan–Pechora Province. It is characterized by the appearance of the index species *Convolutispora zadonica* and of *Diducites vishenensis* and by the constant presence of *Diducites radiatus*, *D. mucronatus*, *Converrucosisporites curvatus* and *Pustulatisporites famenensis*. Some specimens of *Knoxisporites dedaleus* have occasionally been observed. This subzone is also characterized by the high content of the genera *Stenozonotriletes* and *Retusotriletes*.

The deposits corresponding to the Za Subzone in the Pripyat Depression contain conodonts of the *crepida* Zone: *Palmatolepis wolskae* Ovn., *Polylopodonta confluens* (Ulrich and Bassler), *Ancyrognathus sinelamina* Branson and Mehl. (Pushkin et al., 1995).

4. Discussion and conclusion

A comparison between the miospore and conodont zonations allows for the first time accurate dating of the miospore zones at the Frasnian–Famennian transition in Eastern Europe. It is now possible to compare these new data with those available from Western Europe and to obtain even more refined correlations than those provided by Streel and Loboziak (1996, fig. 4).

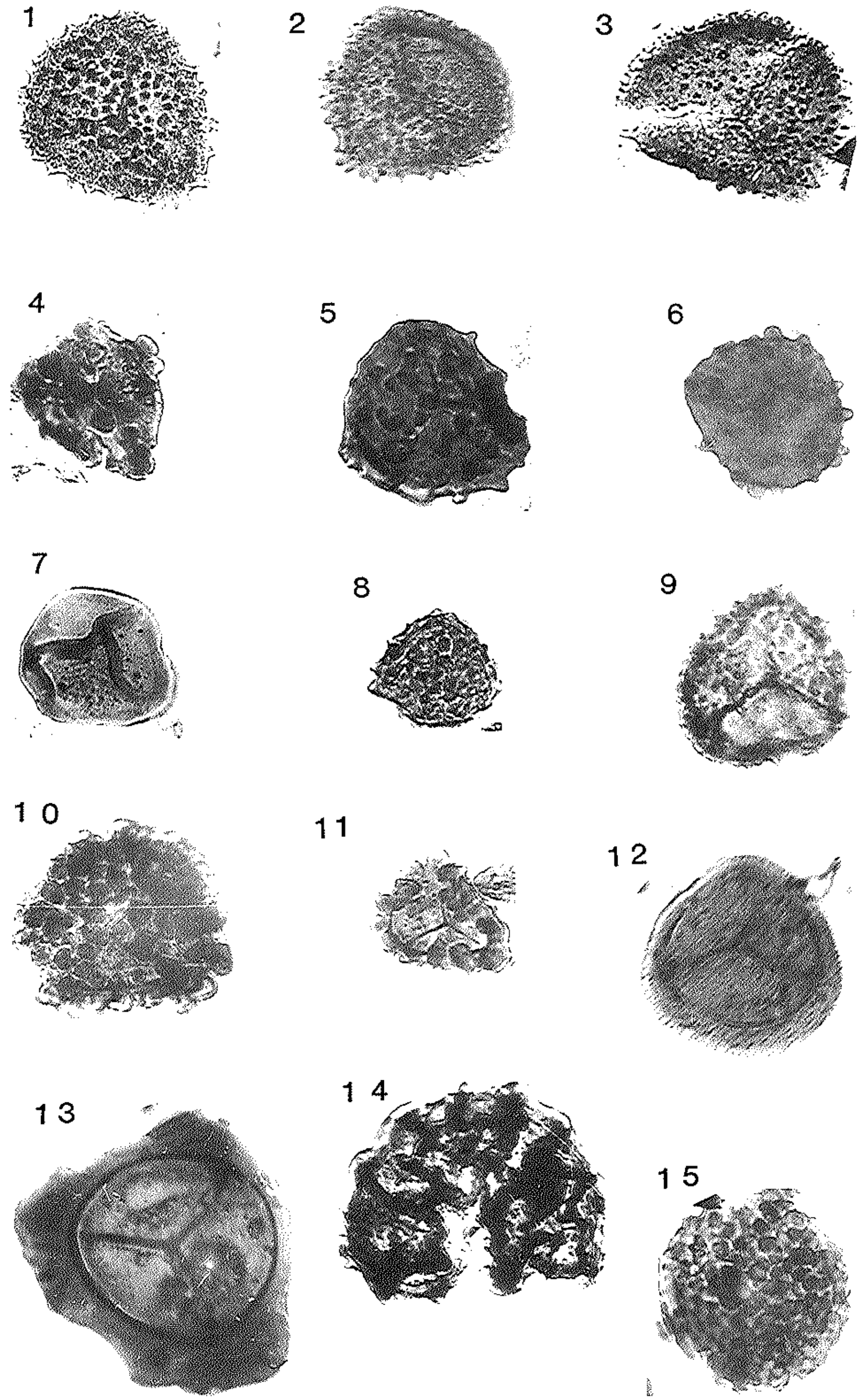
The first appearance of *Cymbosporites acanthaceus* and the acme zone of *Cristatisporites deliquescens* in the upper part of the Evlanov Horizon in the Pripyat Depression, and the presence and abundance of both species in the same Horizon in the Timan–Pechora may be correlated with the first occurrence of these species at or near the base of the Palynophase IV in the Frasnian Hydrequent Formation of Boulonnais in Northern France (Loboziak et al., 1983). As the last occurrence of

PLATE IV

Cristatisporites deliquescens–Verrucosisporites evlanensis (DE) Zone (from the Timan-Pechora Province). Illustrated specimens magnification ×500.

1. *Verrucosisporites evlanensis* (Naumova) Obukhovskaya; Belgop 4, 157–161 m.
2. *Cristatisporites deliquescens* (Naumova) Arkhangelskaya; Belgop 4, 157–161 m.
3. *Cymbosporites acanthaceus* (Kedo) Obukhovskaya; Belgop 4, 117–124 m.
4. *Diducites mucronatus* (Kedo) Van Veen; Belgop 4, 67–70 m.
5. *Auroraspora speciosa* (Naumova) Obukhovskaya var. *minor* Obukhovskaya, var. nov.; Belgop 4, 67–70 m.
6. *Diducites radiatus* (Kedo) Obukhovskaya; Belgop 4, 67–70 m.
7. *Membrabaculisporis radiatus* (Naumova) Arkhangelskaya; Belgop 4, 157–161 m.
8. *Verrucosisporites microgranulosus* (Kedo) Obukhovskaya; Belgop 4, 67–70 m.
9. *Cristatisporites* sp. A. Obukhovskaya; Belgop 4, 83–86 m.
10. *Diducites hopericus* (Nazarenko) Obukhovskaya; Belgop 4, 83–86 m.
11. *Auroraspora speciosa* (Naumova) Obukhovskaya; Belgop 4, 117–124 m.

PLATE V



both miospore taxa is found near the end of Palynophase IV (within subphase IVE), in the Boulonnais, and at the end of Zone DE in Eastern Europe, it is now possible to correlate this Palynophase IV with the DE Zone of Eastern Europe.

In Northern France, the base of Palynophase IV corresponds to the *Rugospora bricei* FOB (First Occurrence Biohorizon) and is dated between the conodont Late *hassi* and *linguiformis* Zones (Streel and Loboziak, 1996, fig. 3). As, in the Timan–Pechora, the conodonts of the Evlanov Horizon correspond to the Upper *gigas* Zone (or the Late *rhenana* Zone) and the conodonts of the Liven Horizon, to the Uppermost *gigas* Zone (or *linguiformis* Zone), they indirectly provide a much better dating of Palynophase IV than was possible previously, i.e. covering the interval of conodont Late *rhenana* and *linguiformis* Zones. Indirectly also, this correlation confirms the equivalence of Palynosubphase IVE with the *linguiformis* Zone, previously suggested by the occurrence of the acritarch species *Visbysphaera* (?) *occultata* at the critical levels of the Boulonnais (Streel and Loboziak, 1994).

In the Timan–Pechora Province, a sharp change in the vertical distribution of miospores below and near the Frasnian–Famennian Boundary is obviously the result of a large fossil gap in the upper part of the Liven Horizon (Fig. 4). In the Pripyat Depression, the range chart of species (Fig. 3) demonstrates a sharp miospore change near the same level but without a fossil gap. However, the first Famennian miospore VV Zone is poorly dated (*triangularis* or *crepida* Zones, see Section 3.2). It is possible, therefore, that the sharp turnover in the miospore distribution may be the result of a large sedimentary gap.

The equivalence in age between the *C. deliquescens–V. evlanensis* Zone and the Palynophase IV allows an accurate comparison of the composition of the miospore assemblages in different provinces. Indeed, according to Heckel and Witzke's (1979) Middle Devonian paleogeographic reconstruction, the equatorial belt was centered on North-western Canada and Western USA, as well as on Eastern Europe, in a province called Northern Euramerica and the tropical belt, on Eastern Canada and USA and on Western Europe, in a province called Southern Euramerica (Streel et al., 1990). Most of the Frasnian assemblages of Eastern Europe are easier to correlate with North-western Canada (Braman and Hills, 1992) than with Western Europe. For instance the co-occurrence of *Archaeoperisaccus* div. sp. and of *Cristatisporites deliquescens* is a common characteristic within Northern Euramerica. However, *Archaeoperisaccus* becomes less abundant in Eastern Europe (Avkhimovitch et al., 1993) at the same time as the correlation becomes easier with Western Europe (introduction of *C. deliquescens* and *C. acanthaceus*), i.e. during the DE Zone time-

PLATE V

Corbulispora viminea–Geminospora vasjarnica (VV) Zone (from the Timan–Pechora Province). Illustrated specimens magnification ×500.

1–3. *Cristatisporites imperpetuus* (Sennova) Obukhovskaya; 1, Izhma river, near Sosnogorsk, 50/30; 2–3, Belgop. 4, 36–38 m.
4. *Lophotriletes multiformis* Tchibrikova; Belgop. 4, 36–38 m.
5. *Converrucosisporites curvatus* (Naumova) Turnau var. *medius* Kedo; Belgop. 4, 36–38 m.
6. *Pustulatisporites pullus* (Naumova) Obukhovskaya; Belgop. 4, 33–36 m.
7. *Geminospora notata* (Naumova) Obukhovskaya var. *microspinosa* Tchibrikova; Belgop. 4, 33–36 m.
8. *Converrucosisporites curvatus* (Naumova) Turnau; 8, Tebukskaja, 881, 1645–1651 m.
9. *Cymbosporites boafeticus* (Tchibrikova) Obukhovskaya; Belgop. 4, 33–36 m.
10. *Lophozonotriletes furssenkei* Nekriata; Belgop. 4, 36–38 m.
11. *Converrucosisporites curvatus* (Naumova) Turnau; Belgop. 4, 33–36 m.
12. *Geminospora vasjamica* (Tchibrikova) Obukhovskaya and Nekriata; Belgop. 4, 33–36 m.
13. *Archaeozonotriletes variabilis* Naumova var. *zilairicus* Tchibrikova; Belgop. 4, 36–38 m.
14. *Corbulispora viminea* (Nekriata) Obukhovskaya and Nekriata; Belgop. 4, 33–36 m.
15. *Verrucosisporites evlanensis* (Naumova) Obukhovskaya; Belgop. 4, 36–38 m.

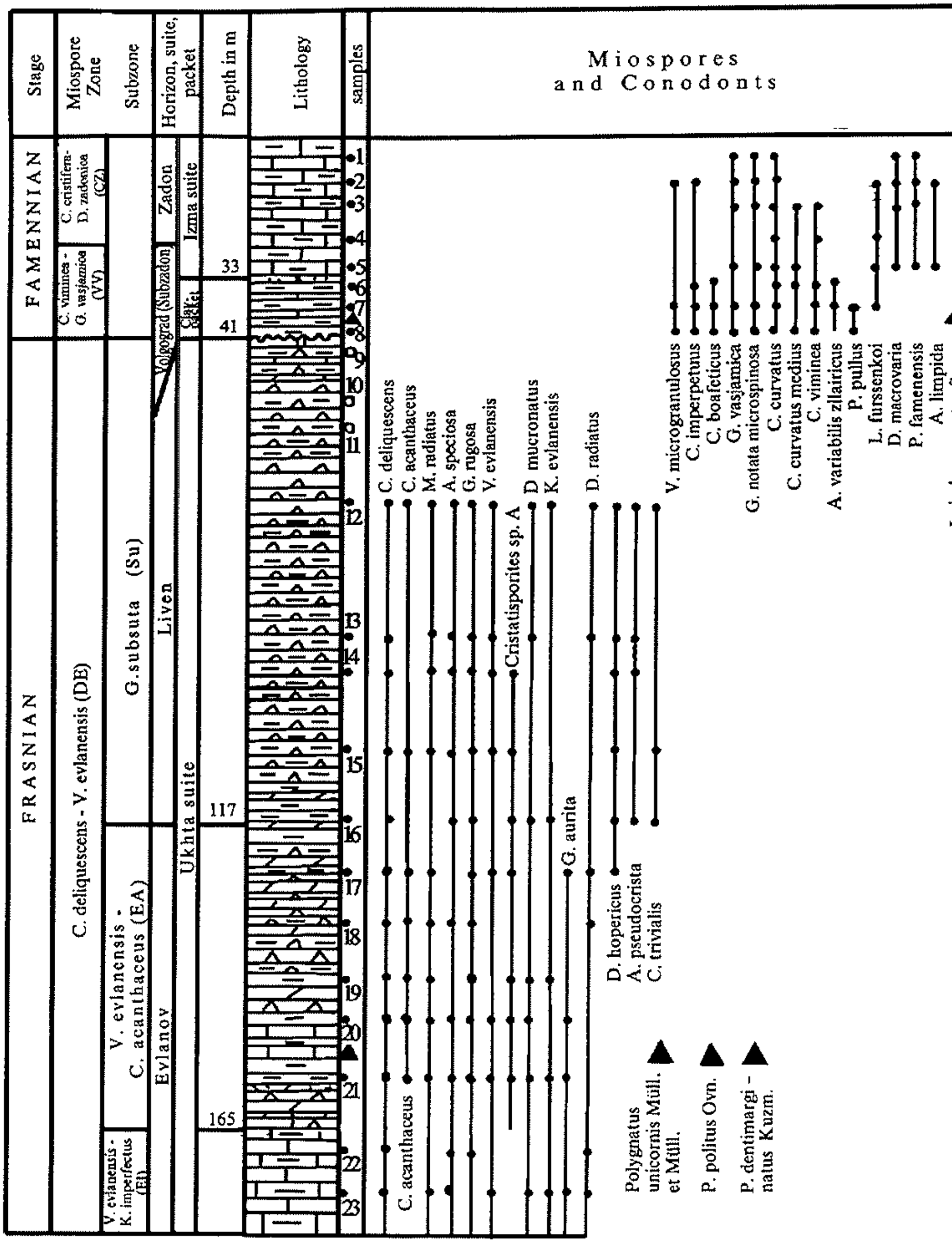


Fig. 4. Vertical distribution of miospores in borehole Belgop 4 (Timan–Pechora Province). ●: sample containing miospores; ○: sample without miospores; ▲: sample containing conodonts.

equivalent. Although there are few species in common between these Frasnian provinces, confirming a strong gradient of climate between Northern (equatorial) and Southern (tropical) areas (Streel and Loboziak, 1996), these differences seem to attenuate at the end of the Frasnian..

5. Systematic notes

The publication on Middle and Upper Devonian miospore zonation of Eastern Europe by Avkhimovitch et al. (1993) cited and illustrated, but did not describe, many characteristic taxa. Some are invalid combinations according to ICBN art. 33. Six of these taxa are validated below. When the original definition is unclear, a few synonyms and short description and comparison are given. Some of these taxa were also illustrated and described in Kuzmin et al. (1998). Their descriptions are not repeated below.

Genus *Auroraspora* Hoffmeister, Staplin and Malloy emend. Richardson, 1960
Auroraspora speciosa (Naumova) Obukhovskaya, comb. nov. (Plate I, 8; Plate IV, 11).

Basionym: Hymenozonotriletes speciosus Naumova in Naumova, 1953, Spore and pollen assemblages in Upper Devonian of the Russian Platform and their stratigraphic significance. Moscow, IGN, ser. Geol. 60, 143, p. 65, pl. 9, fig. 1 (in russian).
Illustrated specimens: Auroraspora speciosa (Naumova) Obukhovskaya in Avkhimovitch et al., 1993 (Combination invalid, ICBN Art. 33.2): pl. 16, fig. 12; pl. 17, fig. 11.
Description: Trilete camerate spore, amb triangular with rounded to subangular apices and convex sides. Suture distinct, simple, straight, accompanied by labra, length equal to the spore radius. Intexine distinct, outline comformable with amb, laevigate radius approximately 1/2–1/3 of the size of the exoexine radius. Exoexine thinner than the intexine. Distal surface and equatorial region of proximal surface infragranulate and ornamented with small wrinkles. Spore margin wavy.
Size range: 60–110 μm.

Comparison: Grandispora spuma Braman and Hills, 1992 has very small coni along the spore margin..
Occurrence: Miospore Subzone *C. vetlasjanicus* (CVe, in Avkhimovitch et al. 1993) to Zone *C. deliquescens–V. evlanensis* (DE) (late Frasnian).

Genus *Corbulispora* Bharadwaj and Venkatachala, 1961
Corbulispora viminea (Nekriata) Obukhovskaya and Nekriata, comb. nov. (Plate II, 1, 2).

Basionym: Dictyotriletes vimineus Nekriata in Nekriata, 1974, Spore assemblages from Lower Famennian (intersaliferous) strata of the Pripyat Depression and their stratigraphic significance. In: Paleozoic spores of Belorussia. Minsk, BelNIGRI, p. 85, pl. 24, fig. 4 (in russian).
Illustrated specimens: Corbulispora viminea (Nekriata) Obukhovskaya and Nekriata in Avkhimovitch et al., 1993 (Combination invalid, ICBN Art. 33.2), pl. 18, fig. 1–3; *Corbulispora viminea* (Nekriata) Obukhovskaya and Nekriata in Kuzmin et al., 1998 (Combination invalid, ICBN Art. 33.2), pl. 5, figs. 5, 6.
Description: in Kuzmin et al. (1998)..
Occurrence: Miospore Zones *C. viminea–G. vasjamica* (VV) and *C. cristifer–D. zadonica* (CZ) (early Famennian).

Genus *Cristatisporites* Potonié and Kremp emend. Butterworth, Jansonius, Smith and Staplin, 1964
Cristatisporites imperpetuus (Sennova) Obukhovskaya, comb. nov. (Plate V, 1–3).

Basionym: Hymenozonotriletes imperpetuus Sennova in Nazarenko, A.M. et al., 1971, New spore species from the Frasnian of the Russian Platform and the Altaï. The palynology research in Belorussia and other regions of the USSR. Minsk, pp. 162–163, pl. 6, figs. 7, 8.
Illustrated specimens: Cristatisporites imperpetuus (Sennova) Obukhovskaya in Avkhimovitch et al., 1993 (Combination invalid, ICBN Art. 33.2)., pl. 18, figs. 16, 17.; *Cristatisporites imperpetuus* (Sennova) Obukhovskaya in Kuzmin et al. (1998), (Combination invalid, ICBN Art. 33.2), pl. 5, fig. 4.
Description: in Kuzmin et al. (1998).
Comparison: Cristatisporites lupinovitchii

(Avkhimovitch) Avkhimovitch 1993 from the Middle Famennian has smaller size and more elaborate sculpture.
Occurrence: Miospore Zones *C. viminea–G. vasjamica* (VV) and *C. cristifera–D. zadonica* (CZ) (early Famennian).

Genus *Cymbosporites* Allen, 1965
Cymbosporites acanthaceus (Kedo) Obukhovskaya, comb. nov. (Plate I, 3, 4; Plate IV, 3).

Basionym: Archaeozonotriletes acanthaceus Kedo in Kedo, 1957, Spores from Suprasalt Devonian deposits of the Pripyat Depression and their stratigraphic significance. In Paleontology and Stratigraphy of Belorussia. Akad. Nauk BSSR, 2, p. 28, pl. 3, figs. 19, 20.
Illustrated specimens: Cymbosporites acanthaceus (Kedo) Obukhovskaya in Avkhimovitch et al., 1993 (Combination invalid, ICBN Art. 33.2), figs. 3, 4; *Cymbosporites acanthaceus* (Kedo) Obukhovskaya in Kuzmin et al., 1998 (Combination invalid, ICBN Art. 33.2), pl. 5, figs. 2, 3.
Synonyms: 1981 *Cymbosporites* sp. B in Loboziak and Streel, 1981 pl. 1, figs. 15, 16.
1983 *Cymbosporites* sp. B in Loboziak et al., plate 1, figs. 4–5.
Description: In Kuzmin et al. (1998).
Comparison: Archaeozonotriletes famenensis Naum. var. *minutus* Nekriata, 1974 has separate exine layers.
Occurrence: Miospore Subzones *V. evlanensis–C. acanthaceus* (EA) and *G. subsuta* (Su) (late Frasnian).

Genus *Grandispora* Hoffmeister, Staplin et Malloy emend. Neves and Owens, 1966
Grandispora subsuta (Nazarenko) Obukhovskaya, comb. mov. (Plate I, 7)

Basionym: Hymenozonotriletes subsutus Nazarenko in Nazarenko, 1978, Miospore assemblage from Famennian Stage of the Volgograd-Volga region and their stratigraphic importance, Volgograd, 139, p. 123, pl. 38, figs. 8,11.
Illustrated specimens: Grandispora subsuta (Nazarenko) Obukhovskaya in Avkhimovitch et al., 1993, pl. 17, figs. 1, 2. (Combination invalid ICBN Art. 33.2).
Description: Trilete camerate spore, amb rounded triangular to subcircular. Suture distinct, slightly sinuous and often accompanied by labra up to 1.5 μm width. Intexine distinct, laevigate, outline circular, comprising approximately 1/2–2/3 of the overall spore diameter. Exoexine thin, laevigate, sometimes infragranulate, bearing distal and equatorial ornament of coni and spinae 2–4 μm in height, 2 μm in basal diameter. Ornament discrete.
Size range: 58–90 mm.
Comparison: Hymenozonotriletes spinulosus Naumova 1953 lacks labra and has thinner intexine and exoexine. *Grandispora sola* Braman and Hills 1992 differs by smaller sculptural elements.
Occurrence: Miospore Subzone *G. subsuta* (Su) (late Frasnian).

Genus *Verrucosisporites* Ibrahim emend. Smith, 1971
Verrucosisporites evlanensis (Naumova) Obukhovskaya, comb. nov., Plate I, 2; Plate II, 10.

Basionym: 1953 *Lophozonotriletes evlanensis* Naumova, in Naumova, 1953, Spore and pollen assemblages in Upper Devonian of the Russian Platform and their stratigraphic significance. Moscow, IGN, ser. Geol. 60, 143, p. 77, pl. 11, fig. 16.
Illustrated specimens: Verrucosisporites evlanensis (Naumova) Obukhovskaya in Avkhimovitch et al., 1993, plate 16, fig. 1. (Combination invalid, ICBN Art. 33.2); *Verrucosisporites evlanensis* (Naumova) Obukhovskaya in Kuzmin et al., 1998 (Combination invalid, ICBN Art. 33.2), pl. 5, fig. 1.
Description: In Kuzmin et al. (1998).
Comparison: Verrucosisporites confertus Owens, 1971 from the Upper Frasnian of Canada is larger (73–108 μm). *Verrucosisporites grumosus* Naumova, 1953 from Frasnian deposits has more rounded and regular disposed verrucae. *Verrucosisporites bulliferus* Richardson and McGregor, 1986 has triangular-rounded amb.
Occurrence: Miospore Zones *C. deliquescens-V.evlanensis* (DE) and *C. viminea-G. vasjamica* (VV) (late Frasnian–early Famennian).

6. List of miospore taxa cited in text and pl. explanations

Archaeozonotriletes variabilis Naumova var. *zilairicus* Tchibrikova (pl. 5, fig. 13)
Auroraspora limpida (Naumova) Avkhimovitch (pl. 3, fig. 7).
Auroraspora pseudocrista Ahmed
Auroraspora speciosa (Naumova) Obukhovskaya, comb. nov. (pl. 1, fig. 8; pl. 5, fig. 11)
Auroraspora speciosa (Naumova) var. *minor* Obukhovskaya var. nov. (pl. 4, fig. 5)
Bulbosisporites volgogradicus (Nazarenko and Tchibrikova) Obukhovskaya (pl. 2, fig. 13)
Chelinospora lepida (Obukhovskaya) Obukhovskaya (pl. 1, fig. 6)
Converrucosisporites curvatus (Naumova) Turnau (pl. 2, fig.11; pl. 3, fig. 12; pl. 5, figs. 8, 11)
Converrucosisporites curvatus (Naumova) Turnau var. *medius* Kedo (pl. 2, fig. 12; pl. 3, fig. 5; pl. 5, fig. 5)
Convolutispora zadonica (Nekriata) Obukhovskaya and Nekriata (pl. 3, fig. 4)
Corbulispora viminea (Nekriata) Obukhovskaya and Nekriata, comb. nov. (pl. 2, figs.1, 2; pl. 3, fig. 11; pl. 5, fig. 14)
Cristatisporites sp. A Obukhovskaya (pl. 4, fig. 9)
Cristatisporites deliquescens (Naumova) Arkhangelskaya (pl. 1, fig.1; pl. 4, fig. 2)
Cristatisporites imperpetuus (Sennova) Obukhovskaya, comb. nov. (pl. 5, figs. 1–3)
Cristatisporites trivialis (Naumova) Obukhovskaya (pl. 1, fig. 14)
Cymbosporites acanthaceus (Kedo) Obukhovskaya comb. nov. (pl. 1, figs. 3, 4; pl. 4, fig. 3)
Cymbosporites boafeticus (Tchibrikova) Obukhovskaya (pl. 5, fig. 9)
Cymbosporites eximius (Obukhovskaya) Obukhovskaya
Cyrtospora cristifera (Luber) Van der Zwan (pl. 3, fig. 1)
Diaphanospora macrovaria (Nazarenko) Nekriata and Avkhimovitch
Diaphanospora zadonica (Naumova) Avkhimovitch
Diducites hopericus (Nazarenko) Obukhovskaya (pl. 1, fig. 11; pl. 4, fig. 10)
Diducites mucronatus (Kedo) Van Veen (pl. 3, fig. 9; pl. 4, fig. 4)
Diducites radiatus (Kedo) Obukhovskaya (pl. 3, fig. 14; pl. 4, fig. 6)
Diducites vishenensis Obukhovskaya and Avkhimovitch (pl. 3, fig.10)
Geminospora aurita Arkhangelskaya
Geminospora notata (Naumova) Obukhovskaya var. *microspinosa* Tchibrikova (pl. 2, fig. 8; pl. 3, fig. 2; pl. 5, fig. 7)
Geminospora rugosa (Naumova) Obukhovskaya
Geminospora vasjamica (Tchibrikova) Obukhovskaya and Nekriata (pl. 2, fig. 3; pl. 3, fig. 3; pl. 5, fig. 12)
Grandispora subsuta (Nazarenko) Obukhovskaya comb. nov. (pl. 1, fig. 7)
Kedoesporis evlanensis (Naumova) Obukhovskaya (pl. 1, fig. 10)
Kedoesporis imperfectus (Naumova) Obukhovskaya (pl. 1, figs. 12, 15)
Kedoesporis rugilobus (Naumova) Obukhovskaya and Avkhimovitch
Knoxisporites dedaleus (Naumova) Moreau-Benoit
Lophotriletes multiformis Tchibrikova (pl. 2, fig. 7; pl. 5, fig. 4)
Lophozonotriletes furssenkoi Nekriata (pl. 2, figs. 4, 5; pl. 5, fig. 10)
Lophozonotriletes grandis (Naumova) Arkhangelskaya (pl. 2, fig. 9)
Membrabaculisporis radiatus (Naumova) Arkhangelskaya (pl. 1, fig. 13; pl. 4, fig.7)
Punctatisporites famenensis (Naumova) Obukhovskaya (pl. 3, fig. 13)
Pustulatisporites famenensis (Naumova) Obukhovskaya (pl. 3, fig. 6)
Pustulatisporites pullus (Naumova) Obukhovskaya (pl. 2, fig. 6; pl. 5, fig. 6)
Spelaeotriletes microgranosus (Kedo) Obukhovskaya (pl. 1, fig. 5)
Stenozonotriletes definitus Naumova (pl. 3, fig. 8)
Verrucosisporites evlanensis (Naumova) Obukhovskaya comb. nov. (pl. 1, fig. 2; pl. 2, fig. 10; pl. 4, fig. 1; pl. 5, fig. 15)
Verrucosisporites microgranulosus (Kedo) Obukhovskaya (pl. 1, fig. 9; pl.pl. 4, fig. 8)

Acknowledgements

The authors thank R. Dreesen (Mol, Belgium) for comments on the conodont data provided in the paper. They also thank E. Turnau (Krakow, Poland) and J. Utting (Calgary, Canada) for their detailed review of a former version of the manuscript.

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