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CONODONTS FROM THE SEDIMENTS OF THE TREMLIA AND VISHA HORIZONS (LOWER FAMENNIAN) OF THE PRIPYAT TROUGH (BELARUS)

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The present study reports data on conodont assemblages recovered from Lower Famennian sediments of the Tremlia and Visha Horizons within the Pripyat Trough. Conodont associations comprising taxa diagnostic of biozones of the Standard Conodont Scale have been recognised. The conodont assemblage recorded from the Tremlia Horizon is assigned to the Palmatolepis termini and Pa. glabra prima zones, whereas the assemblage identified in the Visha Horizon corresponds to the Pa. glabra prima and Pa. glabra pectinata zones. The stratigraphic ranges of the species Polygnathus inaequilateralis Strel'chenko 2013, P. barskovi Strel'chenko 2013, and P. polesicus Strel'chenko 2000 have been refined. Regional stratigraphic correlations have been established between this interval of the Pripyat Trough succession and coeval sections in Volyn–Podolia, the central regions of the East European Platform, the Volgograd–Volga region, the western slope of the Southern Urals, Lithuania, Pomerania, and the Świętokrzyskie Mountains of Poland. Furthermore, palaeogeographic reconstructions were undertaken and spatial patterns in Conodont Alteration Index (CAI) values were evaluated.

Keywords*:* conodonts, Upper Devonian, Lower Famennian, Belarus, Pripyat Trough, biostratigraphy, biozonation.

INTRODUCTION

The Pripyat Trough is located within the Russian Plate of the East European Platform and forms part of the Pripyat–Dnieper Aulacogen**,** which belongs to the broader tectonic framework of the Sarmatian–Turanian lineament system. Structurally, the trough represents a sub-latitudinally oriented, deeply subsided, and structurally complex graben [46].

According to the Stratigraphic Charts of the Devonian sediments of Belarus (2010), the Lower Famennian succession comprises (from base to top): the Domanovichi Horizon; the Zadonsk Superhorizon including the Kuzmichi, Tonezh, Tremlia and Visha Horizons; the Yelets Superhorizon including the Turov and Drozdov Horizons; and the Petrikov Horizon [30].

Lower Famennian sediments occur across almost the entire area of the Pripyat Trough, with the exception of narrow sub-latitudinal zones associated with major fault systems. These strata attain considerable thicknesses, reaching up to 800–1000 m within the most subsided parts of the basin [28]. The structural complexity of the trough combined with pronounced facies variability creates favourable conditions for the development of numerous genetically diverse hydrocarbon traps, and consequently these deposits constitute the principal petroleum-bearing complex of the basin [42].

The principal fossil groups used for detailed stratigraphic subdivision of the Lower Famennian succession in the Pripyat Trough include miospores, brachiopods, ostracods, and conodonts [42].

Lower Famennian conodonts from the sediments of the Pripyat Trough were first reported by S.A. Kruchek in the mid-1960s [34–36]. Subsequent investigations of conodont assemblages from this part of the section carried out by T.V. Strel'chenko [19; 44; 45] significantly expanded their systematic diversity and refined their stratigraphic distribution**.** A re-examination of the conodont collection together with analysis of newly obtained material enabled the author to revise the taxonomic composition, correlate the recognised conodont assemblages with zones of the Standard Conodont Scale (2017) [8], undertake stratigraphic correlations with geographically distant sections, and perform palaeogeographic reconstructions based on biofacies analysis.

MATERIAL AND RESEARCH METHODS

Conodonts from sediments of the Tremlia Horizon have been identified in eight borehole sections, whereas those from the Visha Horizon were recovered from ten boreholes located within the northern, central, eastern, and southern lithofacies zones of the Pripyat

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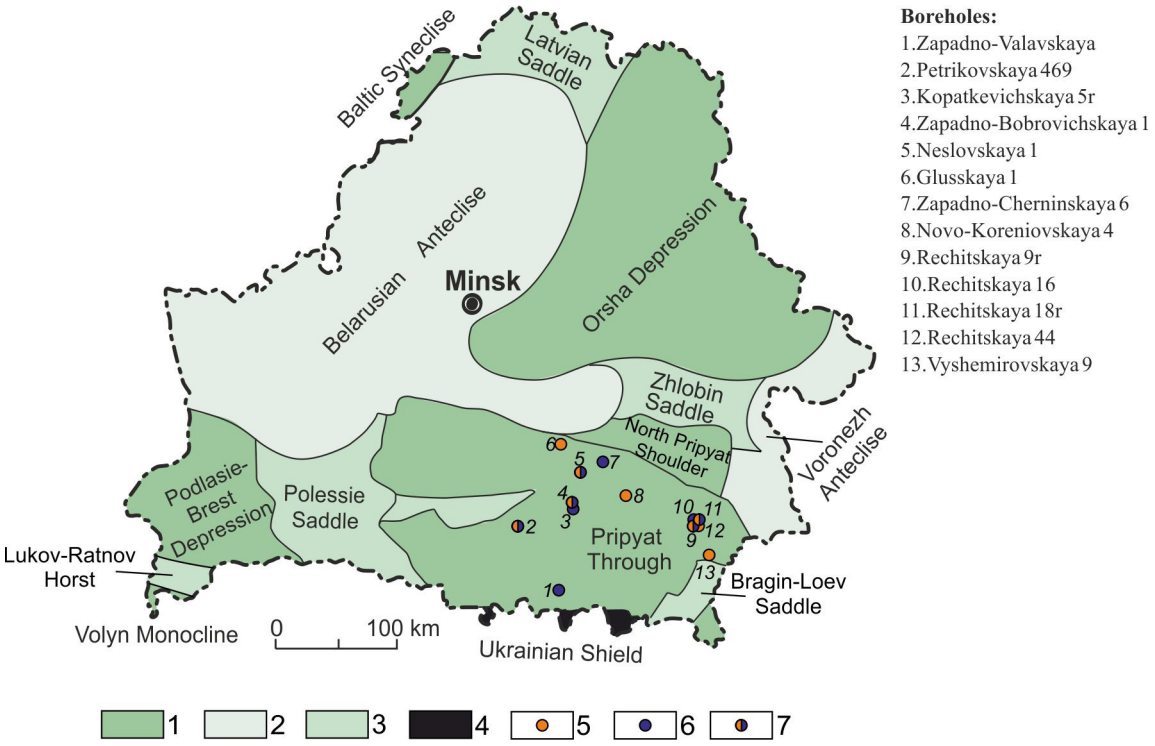


Figure 1 — Location of boreholes within the Pripyat Trough, characterized by conodonts from the sediments of the Tremlia and Visha Horizons:
1 — troughs, depressions, syneclises; 2 — anteclises; 3 — saddles, uplifts, horsts; 4 — crystalline shield; 5 — boreholes yielding conodont elements from the Tremlia Horizon sediments; 6 — boreholes yielding conodont elements from the Visha Horizon sediments; 7 — boreholes yielding conodont elements from sediments of both the Tremlia and Visha Horizons

Trough (Figure 1). Samples were collected primarily from carbonate and clay-carbonate lithologies, including limestones, argillaceous limestones, marls, and dolomites, and were processed using standard conodont extraction techniques involving dissolution in 10% acetic acid. The studied collection is curated in the Institute of Geology, a branch of the State Enterprise "Research and Production Center for Geology". Photographic documentation of the elements was produced using a Chongqing Optec SZ780 stereoscopic microscope.

RESULTS AND DISCUSSION
CONODONT ASSEMBLAGES

The sedimentary succession of the Tremlia Horizon (Zadonsk Superhorizon, Lower Famennian) conformably overlies deposits of the Tonezh Horizon and is in turn overlain by strata assigned to the Visha Horizon. These deposits are developed across almost the entire territory of the Pripyat Trough, with the exception of the Svetlogorsk structural region, that is most probably related to short-lived pre-Visha erosional truncation. The stratotype of the Tremlia Horizon is established in the Petrikovskaya 469 borehole section, depth 676–770 m. The age of these deposits has been determined on the basis of brachiopod assemblages of the *Sinotectirostrum furssenkoi — Iloerhynchus tichomirovi* Regional Zones, together with miospore assemblages of the *Geminospora notata microspinosus* Regional Zone [42].

The thickness of the Tremlia deposits displays considerable lateral variability. Across most parts of the Pripyat Trough it ranges from 40 to 60 m, whereas maximum thicknesses are recorded in the eastern sector of the Rechitsa structural region and to the south of the Petrikov buried massif, where they reach 100–127 m. The sediments of the Tremlia Horizon are readily recognisable in stratigraphic sections and record a major palaeogeographic reorganisation of the basin, during which predominantly carbonate sedimentation was replaced by a dominantly clay-rich depositional regime. In addition, the Tremlia deposits exhibit pronounced lithological heterogeneity and well-expressed facies differentiation [42].

Within this Horizon, several formations are recognised. In the western regions of the Pripyat Trough, the Tremlia Formation is developed and is composed of interbedded limestones, sandstones, marls and clays. In the northern zone of the trough, the Ozemlia Formation occurs and is represented by dark-grey, fine-nodular, banded marls and limestones. In the central zone of the Pripyat Trough, the Tremlia

and overlying Visha Horizons correspond to the Noviki Formation, which is characterised by thick sequences of dark-grey marls and clays containing thin, lens-shaped interbeds of grey clayey limestones. At the top of the horizon an anhydrite bed ranging from 0.5 to 15 m in thickness is present, which constitutes the regional marker "A" [28; 30].

The sediments of the Visha Horizon complete the stratigraphic succession of the Zadonsk Superhorizon, and their upper boundary is defined by the transition from clay-dominated Visha deposits to the massive limestones of the Turov Horizon belonging to the Yelets Superhorizon [30]. The stratotype of the Visha Horizon is considered to be the section of the Petrikovskaya 469 borehole, depth 642–676 m. The thickness of the horizon ranges from 15 to 140 m and is comparatively small relative to other stratigraphic units of equivalent rank. Across the greater part of the Pripyat Trough the thickness typically varies between 14 and 30 m, whereas maximum values are observed along the northern flank of the trough (Sudovitskaya, Olanskaya, Berezinskaya, Pervomayskaya and Vostochno-Pervomayskaya areas) and in areas south and east of the Mikashevichi Uplift. The age of these deposits has been established on the basis of the *Verrucosisporites zadonicus* miospore assemblage [39].

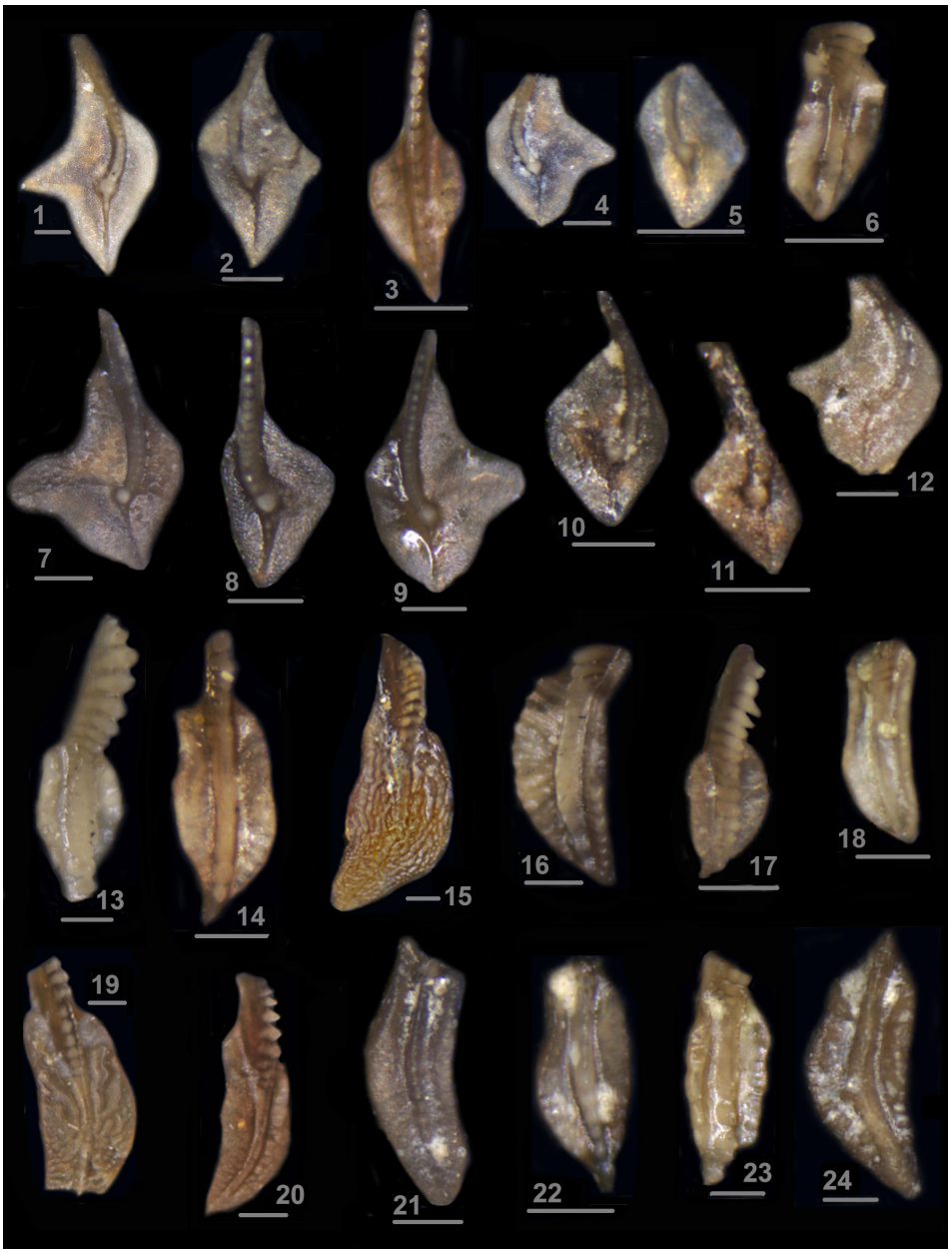
In the local stratigraphical scheme, several formations correspond to the Visha Horizon. In the western and north-western sectors of the Pripyat Trough, the Visha Formation is developed and consists of alternating marls, limestones and sandstones interlayered with clays and anhydrites. In the northern zone of the depression, the section of this formation is composed predominantly of thin-bedded dark and brownish-grey limestones grading upward into dense marls. Within the central zone, the Visha and underlying Tremlia Horizons are jointly represented by the Noviki Formation, which comprises dark-grey marls containing lens-shaped limestone interbeds. In the eastern part of the trough, the sediments of the horizon correspond to the upper subdivision of the Vyshemirovskaya Formation, which is composed mainly of carbonate–clayey lithologies [41]. No direct stratigraphic analogues of this segment of the Pripyat Trough succession have been identified in the stratotype of the Zadonsk Horizon within the Central Devonian Field [42].

Conodont elements from the Tremlia Horizon sediments were found within eight boreholes (Figure 1) located within the northern, central and eastern lithofacies zones of the Pripyat Trough. The elements display variable states of preservation with CAI values ranging from 1 to 4, and belong to three genera: *Polygnathus*, *Icriodus* and *Palmatolepis* (Plate 1). The conodont assemblage of this unit, despite the relatively limited thickness of the sediments, demonstrates considerable taxonomic diversity: 32 taxa have been identified based on 99 platform elements. Several species are recorded for the first time within this stratigraphic interval, including: *Palmatolepis klapperi* Sandberg et Ziegler, 1973; *Pa. minuta elegantula* Wang et Ziegler, 1983; *Polygnathus angustidiscus* Youngquist; *P. deplanatus* Chalymbadza, Shinkaryov et Gatovsky 1991; *P. glaber glaber* Ulrich et Bassler, 1926; *P. nodocostatus ovatus,* Helms, 1961; *P. pomeranicus* Matyja, 1993; *P. semeni* Streľchenko 2013 (Plate 1). Species previously documented in the underlying Tonezh Horizon continue to occur within this unit**,** including *Icriodus alternatus alternatus* Branson et Mehl, 1934; *I. cornutus* Sannemann, 1955; *I. deformatus* Han, 1987; *Polygnathus barskovi* Streľchenko 2013]; *P. brevilaminus* Branson et Mehl, 1934; *P. chegodaevi* Streľchenko 2013; *P. communis communis* Branson et Mehl, 1934; *P. communis larysazimae* Drygant 2010; *P. communis solididentatus* Drygant 2010; *P. izhmensis* Kuzmin, 1998; *P. lennarti* Drygant 2010; *P. subapertus* Drygant, 1986; *P. subinornatus* Strelchenko; *Palmatolepis delicatula* Branson et Mehl, 1934; *Pa. minuta loba* Helms, 1963; *Pa. minuta minuta* Branson et Mehl, 1934; *Pa. minuta wolskae* Szulczewski, 1971; *Pa. subperlobata subperlobata* Branson et Mehl, 1934; *Pa. quadrantinodosalobata* Sannemann, 1955; *Pa. werneri* Ji et Ziegler, 1993; *Pa. wolskae* Ovnatanova, 1969 [16]. At the same time, the assemblage is devoid of numerous taxa that are characteristic of the underlying sediments**,** including: *Icriodus alternatus hemialternatus* Drygant 2010; *I. iowaensis iowaensis* Youngquist et Peterson, 1947; *I. subterminus uyenoi* Savage, 1992; *I. iowaensis ancylus* Sandberg et Dreesen, 1984; *Polygnathus admirandus* Strlchenko, 2000; *P. brevillaminus* Branson et Mehl, 1934; *P. communis communis* Branson et Mehl, 1934; *P. communis solididentatus* Drygant 2010; *P. communis vorontzovae* (Kuzmin, 1998); *P. delicatulus* Ulrich et Bassler, 1926; *P. delenitor* Drygant 1986; *P. lagoviensis* Helms et Wolska, 1967; *P. lanceolus* Vorontsova, 1993; *Palmatolepis circularis* Szulczewski, 1971; *Pa. crepida* Sannemann, 1955; *Pa. perlobata perlobata* Ulrich et Bassler, 1926; *Pa. tenuipunctata* Sannemann, 1955; *Pa. triangularis* Sannemann 1955; *Ancyrognathus sinelaminus* (Branson et Mehl, 1934).

Besides conodont elements, the rocks of the Tremlia Horizon yield abundant and taxonomically diverse remains of foraminifera, ostracods, bivalves, brachiopods, algae, and miospores [24; 25; 28; 30; 41].

The presence of index species together with characteristic taxa belonging to the zones of the Standard Conodont Scale [4; 8] within the sediments of the Tremlia Horizon of the Pripyat Trough allows the recognised conodont assemblage to be correlated with zones of this scale. Thus, *Polygnathus glaber glaber* serves as the index species of the *Palmatolepis termini* Zone, within which the latest occurrences of *P. angustidiscus, P. inaequilateralis, Palmatolepis*

Plate 1 — Conodonts from the Tremlia Horizon of the Pripyat Trough. Scale bar equals 0.2 mm



1 — *Palmatolepis minuta loba,* borehole Petrikovskaya 469, depth 769.2 m, specimen 2–23; 2 — *Palmatolepis minuta wolskae,* borehole Zpadno-Bobrovichskaya 4, depth 2508.7 m, specimen 3–33; 3 — *Polygnathus glaber glaber,* borehole Rechitskaya 44, depth 1996.0–2003.0 m, specimen 5–45; 4 — *Palmatolepis subperlobata subperlobata,* borehole Petrikovskaya 469, depth 769.2 m, specimen 2–24; 5 — *Palmatolepis werneri,* borehole Petrikovskaya 469, depth 769.2 m, specimen 2–25; 6 — *Polygnathus deplanatus,* borehole Rechitskaya 18, depth 2276.2––2279.5 m, specimen 6–46; 7– *Palmatolepis quadrantinodosalobata*, borehole Zapadno-Cherninskaya 6, depth 3276.3 m, specimen 10–100; 8 — *Palmatolepis minuta minuta*, borehole Zapadno-Cherninskaya 6, depth 3261.8 m, specimen 10–66; 9 — *Palmatolepis wolskajae,* borehole Zapadno-Cherninskaya 6, depth 3276.3 m, specimen 10–101; 10 — *Palmatolepis delicatula*, borehole Zapadno-Cherninskaya 6, depth 3275.0 m, specimen 10–83; 11, 12 — *Palmatolepis minuta elegantula*, borehole Zapadno-Cherninskaya 6, 11 — depth 3275.0 m, specimen 10–80; 12 depth 3276.3m, specimen 10–91; 13 — *Polygnathus inaequilateralis,* borehole Petrikovskaya 469, depth 766.5 m, specimen 2–20; 14 — *Polygnathus lennarti,* borehole Rechitskaya 44, depth 1996.0–2003,0 m, specimen 5–44; 15 — *Polynodosus ovatus,* borehole Vyshemirovskaya 9, depth 1930.0 m, specimen 1–4; 16–17 — *Polygnathus subinornatus,* 16 — borehole Zpadno-Bobrovichskaya 4, depth 2506.5 m, specimen 3–32; 17 — borehole Glusskaya 1, depth 1544.2–1548.2 m, specimen 9–2; 18 — *Polygnathus pomeranicus,* borehole Petrikovskaya 469, depth 766.5 m, specimen 2–19; 19–20 — *Polygnathus barskovi,* borehole Vyshemirovskaya 9, depth 1925.0–1940.0 m, specimen 1–1, 1–2; 21 — *Polygnathus semeni*, borehole Zapadno-Cherninskaya 6, depth 3282.5 m, specimen 10–114; 22 — *Polygnathus communis larysazimae,* borehole Zpadno-Bobrovichskaya 4, depth 2499.5 m, specimen 3–27; 23 — *Polygnathus subapertus,* borehole Petrikovskaya 469, depth 759.1 m, specimen 2–18; 24 — *Polygnathus chegodaevi*, borehole Zpadno-Bobrovichskaya 4, depth 2496.5 m, specimen 3–26

delicatula, and *Pa. werneri* are also documented [3; 9; 19]. Within the overlying *Palmatolepis glabra prima* Zone, *Palmatolepis klapperi, Polygnathus pomeranicus,* and *P. nodocostatus ovatus* make their first appearance, whereas *Pa. wolskae* disappears from the stratigraphic record [2; 8; 10; 18]. Accordingly, the Tremlia Horizon is correlated with two conodont zones: *Palmatolepis termini* and *Pa. glabra prima* (Figure 2).

Conodont elements recovered from the sediments of the Visha Horizon were identified in ten borehole sections (Fig. 1) located within the northern, central, eastern, and southern lithofacies zones of the Pripyat Trough. The specimens display variable states of preservation, with a colour alteration index of 1–4, and are assigned to the genera *Polygnathus*, *Icriodus*, and *Palmatolepis* (Plate 2). The assemblage demonstrates considerable taxonomic diversity: 28 taxa have been recognised on the basis of 132 platform elements. A number of species first appear within this interval, including: *Palmatolepis glabra lepta* Ziegler et Huddle; *Pa. circularis* Szulczewski 1971, 1969; *Pa. glabra prima* Ziegler et Huddle, 1969; *Pa. subperlobata helmsi* Ovnatanova 1976; *Polygnathus belorussicus* Strel'chenko 2000; *P. inconcinnus* Kuz'min et Mel'nikova, 1991; *P. polesicus* Strel'chenko, 2000; *P. porrectus* Vorontzova et Kuzmin, 1984; *P. rhomboideus* Helms, 1961; *P. semicostatus* Branson et Mehl, 1934; *P.* aff. *tinus* Pazuhin, 1988. Several species recorded in the underlying Tremlia Horizon persist into this stratigraphic unit, including: *Icriodus alternatus alternatus; I. deformatus; Polygnathus barskovi; P. brevilaminus; P. glaber glaber; P. inaequilateralis; P. lennarti; P. nodocostatus ovatus; P. semeni; P. subinornatus; Palmatolepis circularis; Pa. minuta loba; Pa. minuta wolskae; Pa. subperlobata subperlobata; Pa. quadrantinodosalobata; Pa. wolskae.* The assemblage lacks numerous taxa that are typical of the underlying deposits, including: *Icriodus cornutus; Palmatolepis delicatula; Pa. klapperi; Pa. minuta elegantula; Pa. werneri; Polygnathus chegodaevi;*

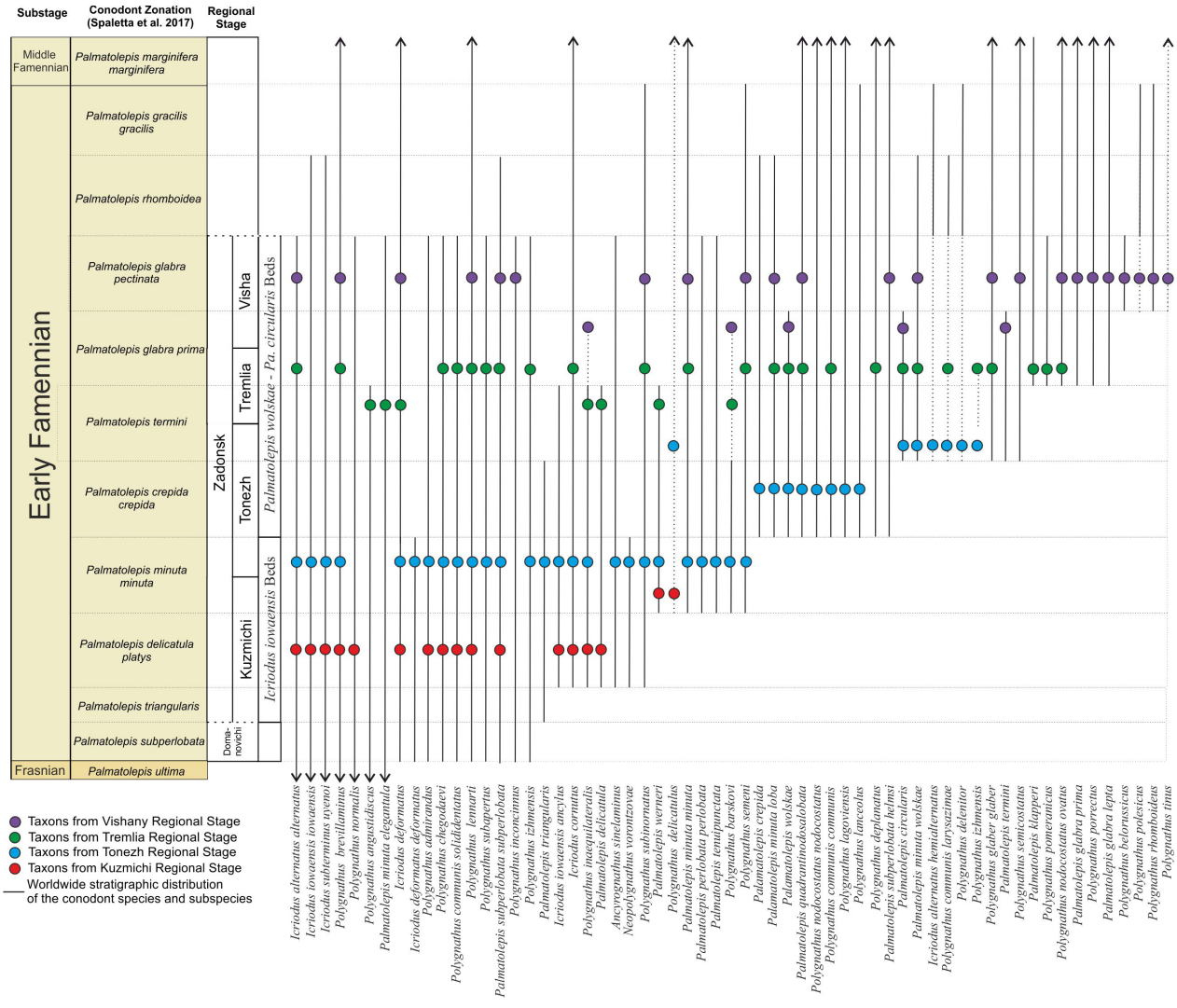
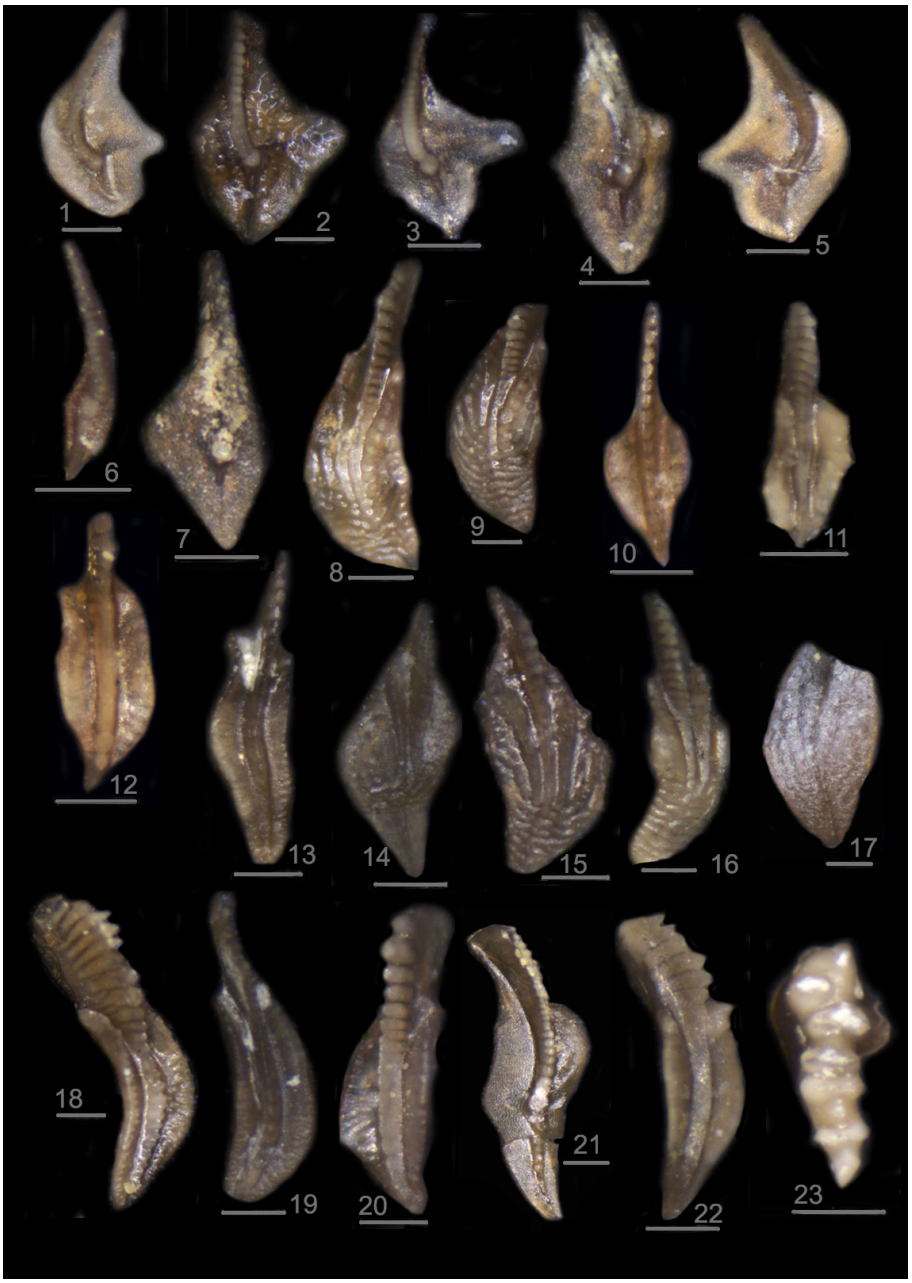


Figure 2 — Correlation of conodont assemblages from the Zadonsk Superhorizon sediments of the Pripyat Trough with Standard Conodont Scale

Plate 2 — Conodonts from the Visha Horizon of the Pripyat Trough. Scale bar **equals** 0.2 mm



1 — Palmatolepis circularis, borehole Zapadno-Valavskaya 1, depth 3641.0 m; specimen 4–25; 2 — *Palmatolepis quadrantinodosalobata,* borehole Zapadno-Valavskaya 1, depth 3641.0 m; specimen 4–46; 3 — *Palmatolepis subperlobata subperlobata,* borehole Zapadno-Valavskaya 1, depth 3665.7 m; specimen 4–45; 4 — *Palmatolepis termini,* borehole Neslovskaya 1, depth 2763.6 m; specimen 5–68; 5 — *Palmatolepis wolskajae,* borehole Neslovskaya 1, depth 2763.6 m; specimen 5–65; 6 — *Palmatolepis glabra lepta,* borehole Zapadno-Cherninskaya 6, depth 3259.0 m; specimen 6–90; 7 — *Palmatolepis minuta wolskae,* borehole Zapadno-Cherninskaya 6, depth 3259.0 m; specimen 6–83; 8, 9 — *Polygnathus rhomboideus,* borehole Zapadno-Valavskaya 1, depth 3641.0 m; specimen 4–32, 33; 10 — *Polygnathus glaber glaber,* borehole Rechitskaya 44, depth 1999.0 m; specimen 9–71; 11 — *Polygnathus inaequilateralis,* borehole Rechitskaya 18, depth 2255.0 m; specimen 8–73; 12 — *Polygnathus lennarti,* borehole Rechitskaya 44, depth 1999.0 m; specimen 9–70; 13 — *Polygnathus porrectus,* borehole Neslovskaya , depth 2763.6 m; specimen 5–67; 14–15 — *Polygnathus polesicus,* borehole Neslovskaya 1, 14 — depth 2753.0 m; specimen 5–61; 15 — depth 2760.0 m; specimen 5–62; 16 — *Polygnathus belorussicus,* borehole Zapadno-Valavskaya 1, depth 3641.0 m; specimen 4–14; 17 — *Polygnathus barskovi,* borehole Novo-Koreniovskaya 4, depth 2975.0 m, specimen 8–5; 18, 19 — *Polygnathus semeni,* 18 — borehole Zapadno-Valavskaya 1, depth 3634.4–3648.8 m; specimen 4–59; 19 — borehole Neslovskaya 1, depth 2763.6 m; specimen 5–66; 20 — *Polygnathus subinornatus,* borehole Zapadno-Valavskaya 1, depth 3641.0 m; specimen 4–37; 21 — *Palmatolepis glabra prima,* borehole Novo-Koreniovskaya 4, depth 2951.5 m, specimen 8–1; 22 — *Polygnathus tinus?,* borehole Rechitskaya 18, depth 2255.0 m; specimen 8–74; 23 — *Icriodus* aff. *deformatus,* borehole Zapadno-Valavskaya 1, depth 3665.7 m; specimen 4–60

P. communis communis; P. communis solididentatus; P. deplanatus; P. izhmensis; P. pomeranicus; P. subapertus.

In addition to conodonts, the rocks of the Visha Horizon contain rare and fragmentary remains of ostracods, gastropods, scolecodonts, bivalves, brachiopods, and miospores; furthermore, the lower part of the section is characterised by the presence of stromatolites and oncolites formed by blue-green algae [24; 25; 28; 30; 42].

The occurrence of characteristic taxa belonging to the zones of the Standard Conodont Scale [4; 8] within the sediments of the Visha Horizon of the Pripyat Trough enables correlation of the identified assemblage with the corresponding zones of this scale. The uppermost occurrences of *Palmatolepis circularis, Pa. termini*, and *Pa. wolskae* are recorded within the *Palmatolepis glabra prima* Zone, whereas the first appearance of *Polygnathus rhomboideus* is characteristic of the *Palmatolepis glabra pectinata* Zone [2; 14; 10; 18]. Consequently, the sediments of this horizon are correlated with the *Pa. glabra prima* and *Pa. glabra pectinata* zones (Fig. 2).

In the Zadonsk Superhorizon sediments of the Pripyat Trough, two subsidiary biostratigraphic units (conodont beds) are recognised: the *Icriodus iowaensis* Beds, corresponding the Kuzmichi Horizon and the lower part of the Tonezh Horizon; and the *Palmatolepis wolskae — Pa. circularis* Beds, established within the upper part of the Tonezh, Tremlia and Visha horizons [19] (Fig. 2).

The present study refines the stratigraphic ranges of three endemic species originally described by T.V. Streĺchenko. *Polygnathus inaequilateralis* was initially reported from deposits of the Kuzmichi and Tonezh Horizons [19], but is here additionally recorded from the younger Visha deposits (Rechitskaya-18 borehole, depth 2255.0 m; Plate 2). *Polygnathus barskovi* was originally identified within the Tonezh Horizon [19], but its occurrence is now also documented from the overlying Tremlia deposits (Novo-Koreniovskaya-4 borehole, depth 2975.0 m; Plate 1). *Polygnathus polesicus* was previously recorded from strata of the Yelets Superhorizon and the Petrikov Horizon [45], whereas the present investigation demonstrates its presence in the older Visha deposits of the Zadonsk Superhorizon (Neslovskaya-1 borehole, depths 2753.0 and 2760.0 m; Plate 2).

The conodont assemblage recovered from the Tremlia sediments shows close similarity to that described from the middle part of the Varezhanka Formation of the Sadov Horizon in Volyn–Podolia [43]. Shared taxa include: *Icriodus alternatus alternatus*, *I. cornutus, I. deformatus deformatus Polygnathus brevilaminus, P. communis communis, P. communis solididentatus, P. lennarti, Palmatolepis circularis* and *Pa. wolskae* [31]. Furthermore, this interval of the Pripyat Trough succession correlates with the middle part of the Zadonsk Horizon in the central regions of the East European Platform, where the following taxa occur in common: *Polygnathus glaber, P. nodocostatus, Palmatolepis circularis, Palmatolepis subperlobata* and *Pa. wolskae* [26]. More specifically, within the Voronezh Anteclise the assemblages share: *Polygnathus brevilaminus, P. nodocostatus, Pa. subperlobata subperlobata* and *Pa. wolskae* [33]. The same stratigraphic interval also correlates with deposits of the lower part of the Gruzdžiai Beds of the Ioniškis Horizon in Lithuania, where *Icriodus iowaensis*, *I. alternatus* and *I. deformatus* have been recorded [21]. Comparable assemblages occur in the middle part of the Makarovo Horizon on the western slope of the Southern Urals**,** where the following taxa are present: *Palamatolepis perlobata perlobata, Pa. subperlobata subperlobata, Pa. wolskae, Pa. circularis, Pa. delicatula, Pa. minuta loba* and *Pa. quadrantinodosalobata* were found [1].

The conodont assemblage of the Visha Horizon likewise shows close correspondence with assemblages from the upper part of the Varezhanka Formation of the Sadov Horizon in Volyn–Podolia [43]. Common taxa include *Polygnathus lennarti*, *P. inconcinnus*, *Palmatolepis circularis* and *Pa. wolskae* [31]. In addition, this part of the Pripyat Trough succession correlates with the upper part of the Zadonsk Horizon of the central East European Platform, where the following species occur in common: *Icriodus alternatus alternatus*, *Palmatolepis circularis*, *Pa. subperlobata* and *Polygnathus brevilaminus* [1]. Within the Voronezh Anteclise in particular, assemblages share *Polygnathus brevilaminus*, *P. nodocostatus*, *Palmatolepis subperlobata subperlobata* and *Pa. wolskae* [33]. The same interval correlates with deposits of the upper part of the Gruzdžiai Beds of the Ioniškis Horizon in Lithuania, where *Icriodus alternatus*, *I. deformatus,* and *Polygnathus brevilaminus* have been identified [21]. In the upper part of the Makarovo Horizon on the western slope of the Southern Urals the following taxa have been recorded: *Palmatolepis subperlobata subperlobata*, *Pa. circularis*, *Pa. minuta wolskae* and *Pa. quadrantinodosalobata* [1]. Conodont assemblages from the Tonezh, Tremlia and Visha horizons display a considerable number of taxa in common with assemblages characteristic of the *Palmatolepis crepida–Pa. glabra pectinata* zones of Pomerania, including *Icriodus alternatus alternatus*, *I. iowaensis iowaensis*, *Palmatolepis circularis*, *Pa. triangularis*, *Pa. wolskae*, *Pa. quadrantinodosalobata*, *Polygnathus communis communis* and *P. nodocostatus ovatus*; similar taxa are also recorded from the Świętokrzyskie Mountains of Poland, including *Pa. quadrantinodosalobata*, *Pa. circularis* and *Pa. tenuipunctata* [14; 22].

PALAEOGEOGRAPHIC RECONSTRUCTIONS

Palaeoecological reconstructions based on conodonts commonly rely on analogy with the ecological habits of extant chaetognaths. The distribution of present chaetognaths is distinctly stratified with respect to water depth [32]. Species inhabiting deeper water masses are unlikely to be preserved in shallow-water sediments, whereas taxa occupying higher levels of the pelagic realm may occur in both shallow- and deep-water depositional settings. Consequently, the relative dominance of particular conodont genera within stratigraphic sections may be used as a proxy for estimating palaeobasin depth, taking into account that conodont animals inhabited the photic zone [38; 40].

Numerous conodont biofacies models have been proposed, notably by M. Lindstrцm [13], G. Merril [15], E. Druce [6], J. Klapper and D. Barrick [11], J. Klapper and D. Johnson [12], R. Dreesen, C. Sandberg, and W. Zeigler [5], Kirilishina [33], V.M. Nazarova, E.M. Kirilishina, L.I. Kononova, E.V. Karpova, S.S. Demyankov [38], among others. These models generally employ two principal criteria for defining biofacies: palaeobasin depth and distance from the shoreline.

During the Early Famennian, the territory of the Pripyat Trough formed part of a shallow epicontinental marine basin characterised by normal or near-normal salinity. Biofacies analysis based on the distribution of conodont genera within the investigated sections was therefore undertaken. Only well-preserved platform elements were considered, whereas *Polygnathus brevilaminus* and *P. communis vorontzovae*, which occur both in shallow-water shelf sections of the central East European Platform and in deeper-water settings of the Rhenish Slate Mountains, were excluded from palaeobathymetric interpretation [23].

Sediments of the Zadonsk Superhorizon within the Pripyat Trough accumulated under open-marine conditions. Assemblages from the Kuzmichi, Tonezh, Tremlia and Visha horizons contain a substantial proportion of the cosmopolitan deep-water genus *Palmatolepis*, whose elements were widely dispersed by marine currents, while shallow-water representatives of *Polygnathus* constitute the bulk of most assemblages. It should also be emphasised that the Pripyat Trough basin extended over a large area and possessed a complex tectonic architecture; consequently, the depth of the Early Famennian sea was spatially heterogeneous and varied through time.

Four conodont biofacies are distinguished for the Early Famennian palaeobasin of the Pripyat Trough[1]:

– extremely shallow-water biofacies, characterised by the predominance of endemic representatives of *Icriodus*;

– shallow-water biofacies, dominated by species of *Polygnathus* (40–100%) with subordinate cosmopolitan icriodids;

– relatively deep-water biofacies, marked by the presence of species of *Palmatolepis* (15–100%), with minor occurrences of icriodids and polygnathids;

– reef-related biofacies, characterised by the occurrence of taxa of *Ancyrognathus*.

In the conodont assemblage of the Kuzmichi Horizon, shallow-water representatives of *Polygnathus* predominate, comprising approximately 67% of the total assemblage, whereas extremely shallow-water icriodids account for about 25% and deep-water palmatolepids for roughly 8% (Table; Figure 3 D_3kz). The Kopatkevichskaya area is characterised by assemblages dominated by extremely shallow-water icriodids, while the Zapadno-Bobrovichskaya, Ostashkovichskaya, Yuzhno-Savichskaya and Rechitskaya areas are typified by coastal shallow-water icriodid–polygnathid associations; the Komarovichskaya area yields assemblages dominated by relatively deep-water palmatolepids (Table; Figure 4 D_3kz).

During sedimentation of the Tonezh Horizon a general deepening of the palaeobasin is inferred. The proportion of deep-water *Palmatolepis* increases significantly (to c. 28%), whereas shallow-water *Icriodus* and *Polygnathus* decrease to approximately 21% and 51%, respectively (Table; Fig. 3 D_3ton). This interpretation is supported by lithological evidence, as the sediments become markedly more argillaceous (Fig. 4 D_3kz, D_3ton). The greatest palaeobathymetric depths are inferred for the central, northern and eastern sectors of the basin, including the Zapadno-Kamenskaya, Kopatkevichskaya, Zapadno-Bobrovichskaya, Komarovichskaya, Rechitskaya (Rechitskaya-15 borehole), Zapadno-Peretokskaya, Ostashkovichskaya and Yastrebovskaya areas, where assemblages are dominated by relatively deep-water *Palmatolepis* taxa. Within the central part of the depression (Yuzhno-Savichskaya area) the near-reef taxon *Ancyrognathus sinelaminus* has been recorded [16] (Fig. 4 D_3ton).

During deposition of the Tremlia Horizon the palaeobasin experienced further overall deepening. A pronounced palaeogeographical reorganisation is reflected both in lithological characteristics—carbonate-dominated sedimentation being replaced by a predominantly argillaceous regime [42]—and in the composition of the conodont biofacies. The proportion of extremely shallow-water *Icriodus* declines markedly (to about 6%), whereas deep-water *Palmatolepis* increases to approximately 37% (Table; Fig. 3 D_3trm). The taxonomic composition of the conodont

[1] The biofacies are defined on the basis of the complex model for the Upper Paleozoic – Triassic by E. Druce [6].

assemblages indicates progressive submergence of the Petrikovskaya and Zapadno-Cherninskaya areas (Fig. 4 D_3ton; D_3trm).

During the Visha time, further subsidence of the Pripyat Trough paleobasin occurred. The proportion of deep-water *Palmatolepis* increased to 53%, while shallow-water *Icriodus* accounted for only 2% (Table, Fig. 3 D_3vsh). Biofacies analysis of conodont assemblages indicates progressive subsidence within the Neslovskaya area (Fig. 4 D_3trm and D_3vsh).

Thus, analysis of the stratigraphic and palaeoecological distribution of conodont genera indicates that throughout the Zadonsk time interval the Pripyat Trough palaeobasin experienced persistent tectonic subsidence, reflected in the establishment of both shallow-water and relatively deeper-water depositional environments, with maximum bathymetric deepening attained during the Visha time. A single shallow-water, nearshore conodont biofacies dominated by representatives of the genus *Icriodus* characterise the Kopatkevichskaya area within the Kuzmichi interval; a distinct reef-related biofacies, diagnosed by the occurrence of *Ancyrognathus sinelaminus* is exhibited in the Yuzhno-Savichskaya area during the Tonezh time.

Table 1 — Distribution of conodont genera within the sediments of the Zadonsk Superhorizon of the Pripyat Trough

Borehole	Depth interval	*Palmatolepis*	*Polygnathus*	*Icriodus*	*Ancyrognathus*	*Pelekysgnathus*	Indeterminate elements	Total platform elements	Total
Kuzmichi Horizon									
Zapadno-Bobrovichskaya 4	2503–2613	1	32	10		17	41	43	101
Komarovichskaya 2	3031–3143	3	2	2		2	3	7	12
Kopatkevichskaya 5r	2300–2400			3			30	3	33
Кормянская 4	3480–3540		5					5	5
Ostashkovichskaya 1r	3098–3190		2					2	2
Rechitskaya 7r	2064–2085		2	1			16	3	19
Yuzhno-Savichskaya 7	2523–2610	3	18	7		3	19	28	50
Yastrebovskaya 3k	1683–1728						3	0	3
Total		7	61	23		22	112	91	225
Percent among platform elements		8	67	25					
Tonezh Horizon									
Borshchevskaya 1	2664–2795						1	0	1
Vyshemirovskaya 3r	2253–2384			1			26	1	27
Vyshemirovskaya 9	1928–2052		1				168	1	169
Zapadno-Bobrovichskaya 4	2460–2503	30	98	32			124	160	284
Zapadno-Domanovichskaya 43	2426,6–2498						3	0	3
Zapadno-Kamenskaya 1	3255–3285	37	3			2		40	42
Zapadno-Peretokskaya 1	3470–3515	3					3	3	6
Zapadno-Cherninskaya 6	2386–3397		7	4			43	11	54

Cont. of table 1

Borehole	Depth interval	*Palmatolepis*	*Polygnathus*	*Icriodus*	*Ancyrognathus*	*Pelekysgnathus*	Indeterminate elements	Total platform elements	Total
Kamenskaya 5	3422–3447		4					4	4
Komarovichskaya 2	2974–3031	23	22	11			4	56	60
Kopatkevichskaya 5r	2262–2300	6					5	6	11
Kormianskaya 4	3408–3480	1	12	7			7	20	27
Krasnoselskaya 215	3853–3906	2	16	6			14	24	38
Ostashkovichskaya 1r	2803–2891	1						1	1
Petrikovskaya 469	770–881		6	7			9	13	22
Rechitskaya 15r	2118–2133	10	7	9			221	26	247
Rechitskaya 18r	2283–2410	1	8	2			27	11	38
Rechitskaya 19	2188,1–2306,3						5	0	5
Rechitskaya 21	2478,6–2526,15						12	0	12
Rechitskaya 44	2042–2109,4						3	0	3
Rechitskaya 9r	2033–2100		4	4			58	8	66
Skolodinskaya 1p	2349–2393		1					1	1
Yuzhno-Savichskaya 7	2488–2523		11	5	2		41	18	59
Yastrebovskaya 3k	1533–1683	2	4				4	6	10
Total		116	204	88	2	2	778	410	1190
Percent among platform elements		28	50	21	0				
Tremlia Horizon									
Vyshemirovskaya 9	1910–1928		9				159	9	168
Zapadno-Bobrovichskaya 4	2430–2460	4	4	1			18	9	27
Zapadno-Cherninskaya 6	3260–3286	30	17	3			65	50	115
Neslovskaya 1	2772–2808		16				13	16	29
Petrikovskaya 469	752–770	3	5					8	8
Rechitskaya 18r	2256–2283		1				2	1	3
Rechitskaya 44	1998–2022		2					2	2
Rechitskaya 9r	2016–2033		9				159	4	168
Total		37	56	6			318	99	704
Percent among platform elements		37	57	6					

End of table 1

Borehole	Depth interval	*Palmatolepis*	*Polygnathus*	*Icriodus*	*Ancyrognathus*	*Pelekysgnathus*	Indeterminate elements	Total platform elements	Total
Visha Horizon									
Glusskaya 1	1487–1539		2				1	2	3
Zapadno-Valavskaya 1	3608–3732	10	38	1			108	49	157
Zapadno-Cherninskaya 6	3222–3260	13	1				5	14	19
Kopatkevichskaya 5r	2174–2230						35	0	35
Neslovskaya 1	2730–2772	46	8					54	54
Novo-Koreniovskaya 4	2910–2946	1	4	1			29	6	35
Petrikovskaya 469	642–752						2	0	2
Rechitskaya 16	1991–1994		2					2	2
Rechitskaya 18r	2248–2256		3					3	3
Rechitskaya 44	1996–1998		2					2	2
Total		70	60	2			180	132	312
Percent among platform elements		53	45	2					

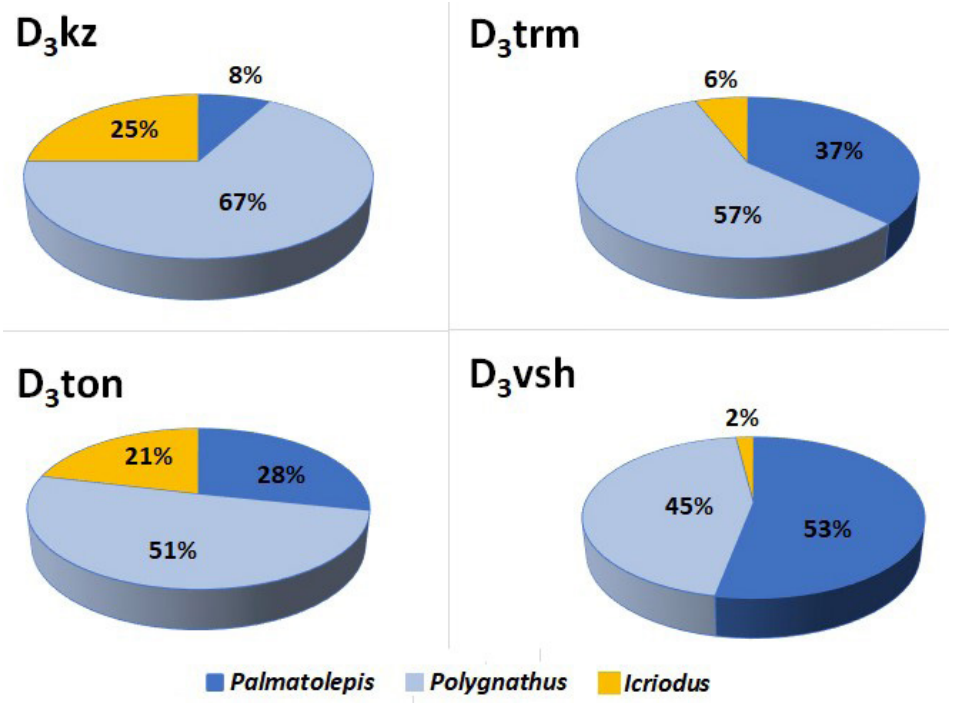


Figure 3 — The proportions of conodont genera within the sediments of the Zadonsk Superhorizon of the Pripyat Trough: D_3kz — Kuzmichi Horizon, D_3ton — Tonezh Horizon; D_3trm — Tremlia Horizon; D_3vsh — Visha Horizon

Several factors control the quantitative abundance of conodont elements within sedimentary rocks, including food availability, taphonomic conditions, temperature regime, and seawater salinity. Under conditions of high sedimentation rates the concentration of conodont elements in the host rock may be extremely low owing to

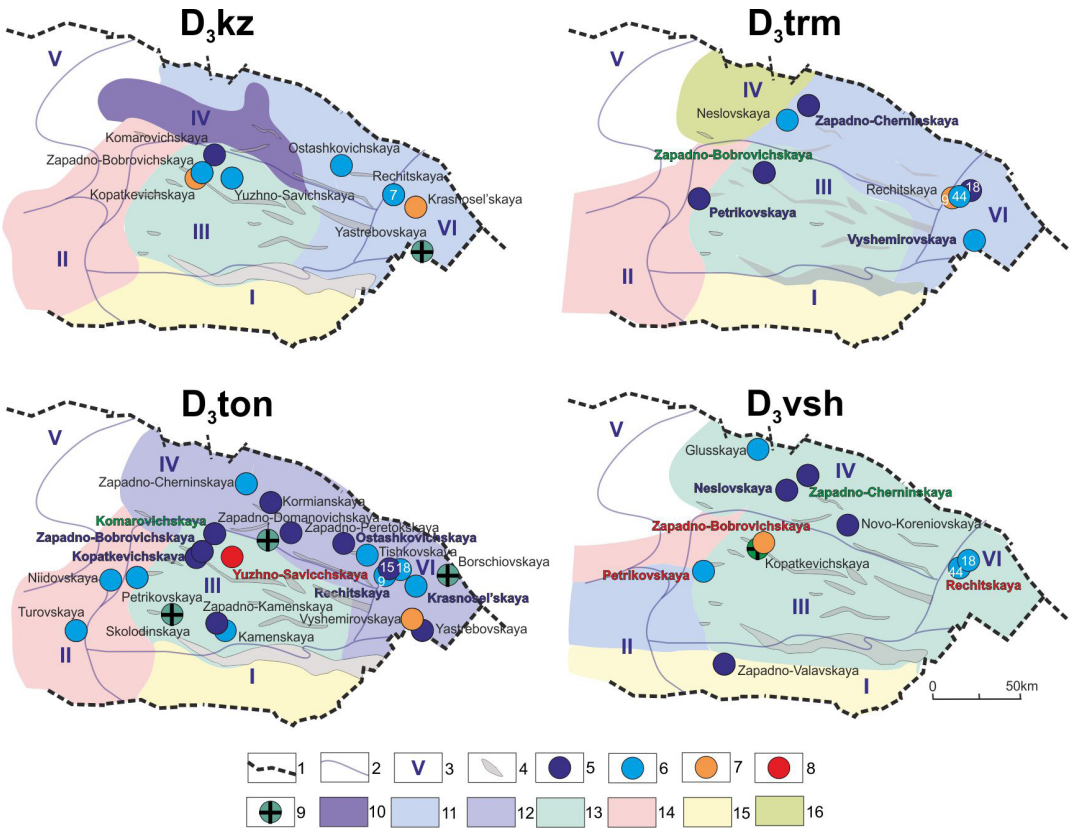


Figure 4 — Conodont biofacies of the Pripyat Trough paleobasin during Zadonsk time:
1 — deep-seated faults bounding the Pripyat Trough; *2* — boundaries of lithofacies zones; *3* — lithofacies zones: I — South; II — Southwest; III — Central; IV — North; V — Northwest; VI — East; *4* — areas lacking Lower Famennian deposits; *5* — relatively deep-water conodont biofacies characterised by the predominance of *Palmatolepis*; *6* — shallow-water biofacies dominated by *Polygnathus*; *7* — extremely shallow-water biofacies dominated by *Icriodus*; *8* — reef-related biofacies with the presence of *Ancyrognathus*; *9* — boreholes yielding indeterminate conodont elements; *10–16* — lithofacies distinguished by V.I. Pushkin and I.I. Uriev [42]: *10* — dolomites; *11* — limestones; *12* — interlayered dolomites and limestones; *13* — marls with limestone interbeds; *14* — interbedded limestones and sandstones; *15* — interlayered sandstones, marls and clays; *16* — interlayered marls, clays and limestones. Areas named in blue indicate subsiding sectors, whereas areas named in green represent tectonically stable regions. D_3kz — Kuzmichi Horizon, D_3ton — Tonezh Horizon; D_3trm — Tremlia Horizon; D_3vsh — Visha Horizon

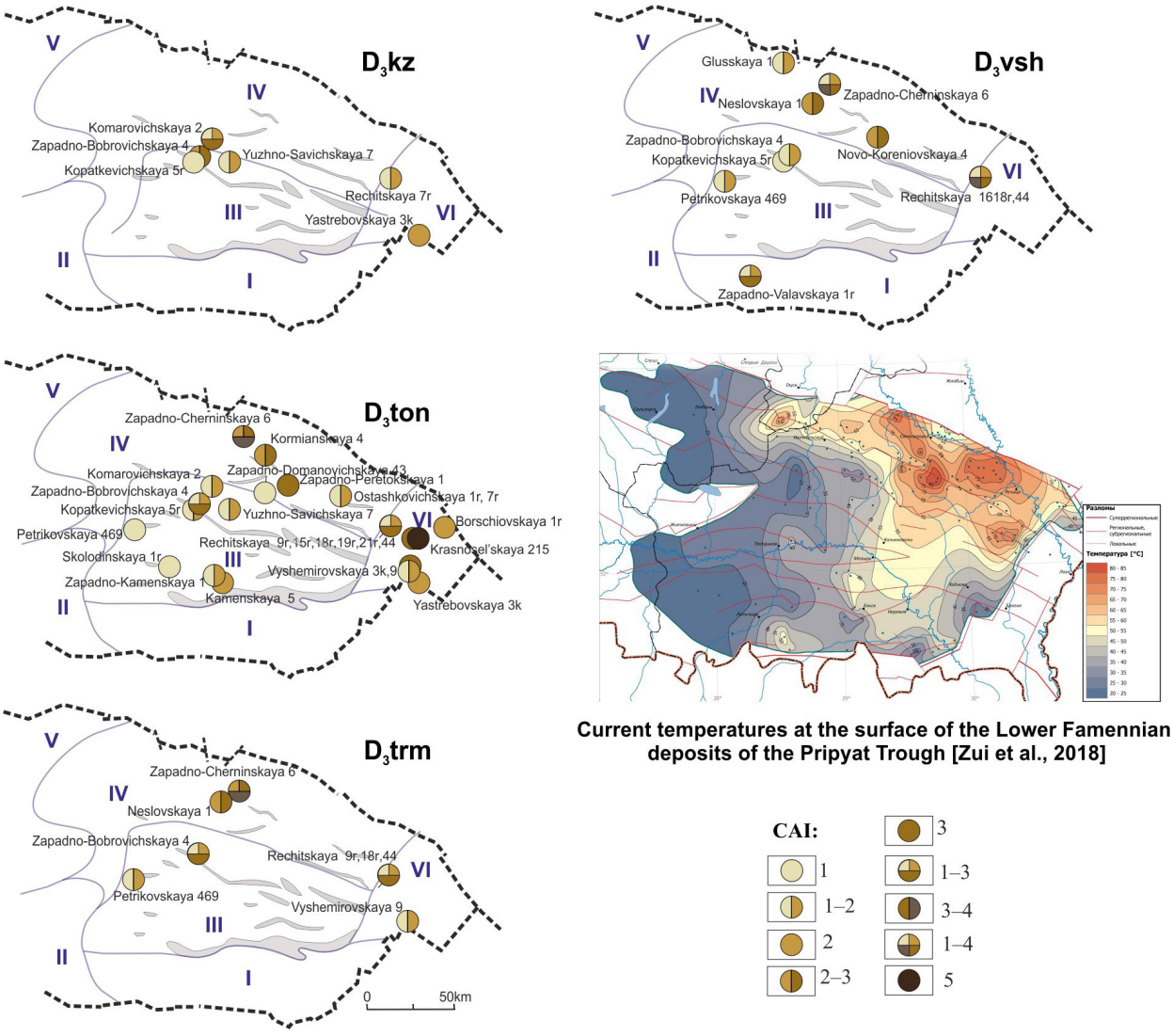
dilution effects. Devonian and Carboniferous conodont faunas are predominantly known from tropical marine deposits [12]. In addition, most conodont animals were normal-marine stenohaline organisms [20].

The highest number of boreholes yielding conodonts (29), together with the highest number of recovered elements (1190) and identified taxa (42), was recorded from the sediments of the Tonezh Horizon. These data indicate normal-marine depositional conditions in the Pripyat Trough palaeobasin at that time. The Tremlia and Visha sediments show a decrease in all of the aforementioned quantitative parameters. Furthermore, the presence of an anhydrite bed up to 15 m thick at the boundary between the Tremlia and Visha horizons suggests an increase in seawater salinity during this interval.

Conodont Alteration Indices

Numerous hydrocarbon accumulations have been discovered within the Lower Famennian deposits of the Pripyat Trough. The Conodont Alteration Index (CAI) method [7; 10] has been widely used in petroleum geology for more than four decades to assess the thermal maturity of sedimentary rocks, and obtained results show a high degree of correlation with those derived from other maturity indicators. The CAI method is based on the irreversible color change of conodont elements composed primarily of fluorapatite containing a minor proportion of organic matter during progressive heating. The index ranges from 1 (slightly altered, light brown) to 5 (strongly altered, dark brown). The degree of color alteration depends not only on the maximum temperature reached but also on the duration of heating, reflecting a cumulative thermal effect. CAI values are widely used to delineate the so-called “oil window”. Values of 1.5–2.5 indicate optimal conditions for oil generation, whereas CAI values exceeding 4 indicate thermal overmaturity of the rocks, resulting in the destruction of liquid hydrocarbons.

Within the sediments of the Zadonsk Superhorizon of the Pripyat Trough, CAI values range from 1 to 5 (Figure 5), reflecting asymmetric thermal heating of the enclosing strata. Higher palaeotemperatures were recorded in the eastern and north-eastern sectors of the structure compared with the western and south-western parts. The maximum conodont colour index (CAI = 5) was recorded from Tonezh-age elements recovered from the Krasnoselskaya area (borehole Krasnoselskaya-215, depth 3858.5–3904.0 m). Notably, the Krasnoselskoye oil and gas condensate field — the only accumulation of this type currently known in Belarus — occurs within productive strata of the Zadonsk Superhorizon. It is well established that the gas-generation phase succeeds the oil-generation stage and develops under higher temperature conditions and at greater burial depths. At depths exceeding approximately 4 km, temperatures become too high for oil preservation and favour gas generation [27]. Elevated CAI values (up to 4) are also characteristic of Tonezh-age conodonts from the Zapadno-Cherninskaya area and Visha-age conodonts from the Rechitskaya area (Fig. 5). Salt tectonics exerted a significant influence on the temperature distribution within the rocks of the Pripyat Trough, as indicated by the presence of well-developed salt diapirs and salt ramparts. The regional pattern of temperature distribution is still broadly preserved today, although expressed at lower absolute values, as illustrated by the temperature map of the Lower Famennian surface (Fig. 5) [29]. For example, maximum palaeotemperatures of the Zadonsk deposits in the Krasnoselskaya area reached approximately 200 °C [17; 37], whereas present-day temperatures are about 90 °C [29].



Current temperatures at the surface of the Lower Famennian deposits of the Pripyat Trough [Zui et al., 2018]

Figure 5 — Conodont Alteration Indices (CAI) from the sediments of the Kuzmichi, Tonezh, Tremlia and Visha Horizons of the Pripyat Trough:
1 — deep-seated faults bounding the Pripyat Trough; *2* — boundaries of lithofacies zones; *3* — lithofacies zones: I — South; II — Southwest; III — Central; IV — North; V — Northwest; VI — East; *4* — areas lacking Lower Famennian deposits. D_3kz — Kuzmichi Horizon, D_3ton — Tonezh Horizon; D_3trm — Tremlia Horizon; D_3vsh — Visha Horizon

CONCLUSIONS

Within the sediments of the Tremlia and Visha horizons of the Pripyat Trough, 44 conodont taxa were identified, allowing the recognition of two representative conodont assemblages. The occurrence of index species together with characteristic taxa of the standard conodont zonation enables correlation of these assemblages with the Standard Conodont Zonal Scale [8]. The assemblage from the Tremlia Horizon corresponds to the *Palmatolepis termini* and *Pa. glabra prima* zones, whereas the Visha assemblage corresponds to the *Pa. glabra prima* and *Pa. glabra pectinata* zones.

The stratigraphic ranges of three species have been refined. The latest occurrences of *Polygnathus inaequilateralis* Strel'chenko, 2013 and *Polygnathus barskovi* Strel'chenko, 2013 [19] are recorded in Visha deposits of the Zadonsk Superhorizon within the Pripyat Trough. The species *Polygnathus polesicus* Strel'chenko, 2000 [45] first appears during Visha time.

The conodont assemblages of the Tremlia and Visha horizons are broadly comparable with those recorded from the upper part of the Varezhanka Formation of the Sadov Horizon in Volyn–Podolia; the lower interval of the Gruzdžiai Beds assigned to the Ioniškis Horizon of Lithuania; the middle to upper parts of the Zadonsk Horizon in the central regions of the East European Platform and the Volgograd–Volga region; as well as from the Barmin Formation and the Makarovo Horizon on the western slope of the Southern Urals. These associations also correlate with conodont faunas characteristic of the *Palmatolepis crepida–Pa. glabra pectinata* zones recognised in Pomerania and the Świętokrzyskie Mountains of Poland.

Palaeogeographic reconstruction of conodont communities, supported by lithological evidence, indicates that during deposition of the Zadonsk Horizon the territory of the Pripyat Trough was occupied by a shallow epicontinental sea. Four conodont biofacies are recognised: (1) an extremely shallow-water biofacies dominated by species of *Icriodus* (identified only in the Kopatkevichskaya area during Kuzmichi time); (2) a shallow-water biofacies characterised by the predominance of *Polygnathus* species; (3) a relatively deeper-water biofacies marked by the occurrence of *Palmatolepis*; and (4) a reef-related biofacies characterised by the presence of *Ancyrognathus sinelaminus* (recognised only in the Yuzhno-Savichskaya area during Tonezh time). Throughout Zadonsk time the Pripyat Trough palaeobasin underwent progressive subsidence, attaining its maximum water depths during Visha time.

Quantitative characteristics of the conodont assemblages (including the number of boreholes yielding conodonts, the total number of recovered elements, and the diversity of identified taxa), in combination with lithological data, indicate that fully normal marine conditions became established in the Pripyat Trough palaeobasin during Tonezh time, whereas during Tremlia and Visha time intervals an increase in water salinity is inferred.

Conodont Alteration Index (CAI) values from sediments of the Zadonsk Superhorizon of the Pripyat Trough range from 1 to 5. Analysis of their spatial distribution indicates asymmetric thermal maturation of the host strata, with higher palaeotemperature estimates in the eastern and north-eastern parts of the structure compared with the western and south-western sectors. The maximum CAI value (5) was recorded in Tonezh-age elements from the Krasnoselskaya area, where the Krasnoselskoye oil-and-gas condensate field — the only known accumulation of this type in Belarus — was discovered. The regional pattern of temperature distribution persists at present, although expressed by lower absolute values.

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КАНАДОНТЫ З АДКЛАДАЎ ТРЭМЛЯНСКАГА І ВІШАНСКАГА ГАРЫЗОНТАЎ НІЖНЯГА ФАМЕНА ПРЫПЯЦКАГА ПРАГІНУ (БЕЛАРУСЬ)

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Прыведзены дадзеныя аб канадонтах з адкладаў трэмлянскага і вішанскага гарызонтаў ніжняга фамена Прыпяцкага прагіну. Вылучаны комплексы канадонтаў з таксонамі, характэрнымі для зон стандартнай канадонтавай шкалы: комплекс канадонтаў з адкладаў трэмлянскага гарызонту адпавядаюць зонам

Palmatolepis termini і Pa. glabra prima; вішанскага — зонам Pa. glabra prima і Pa. glabra pectinata. Удакладнены час існавання відаў Polygnathus inaequilateralis Strel'chenko 2013, P. barskovi Strel'chenko 2013, P. polesicus Strel'chenko 2000. Праведзены стратыграфічныя карэляцыі гэтай часткі разрэзу з Валына-Падоліяй, цэнтральнымі раёнамі Усходне-Еўрапейскай платформы і Валгаградскім Паволжам, заходнім схілам Паўднёвага Урала, Літвой, Памераніяй і Свентакшыскімі гарамі Польшчы. Выкананы палеагеаграфічныя рэканструкцыі, прааналізаваны характар размеркавання індэксаў афарбоўкі канадонтавых элементаў.

Ключавыя словы: канадонты, верхні дэвон, ніжні фамен, Беларусь, Прыпяцкі прагін, біястратыграфія, біязанаванне.

КОНОДОНТЫ ИЗ ОТЛОЖЕНИЙ ТРЕМЛЯНСКОГО И ВИШАНСКОГО ГОРИЗОНТОВ НИЖНЕГО ФАМЕНА ПРИПЯТСКОГО ПРОГИБА (БЕЛАРУСЬ)

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Приведены данные о конодонтах из отложений тремлянского и вишанского горизонтов нижнего фамена Припятского прогиба. Выделены комплексы конодонтов с таксонами, характерными для зон стандартной конодонтовой шкалы: комплекс конодонтов из отложений тремлянского горизонта соответствуют зонам Palmatolepis termini и Pa. glabra prima; вишанского — зонам Pa. glabra prima и Pa. glabra pectinata. Уточнено время существования видов Polygnathus inaequilateralis Strel'chenko 2013, P. barskovi Strel'chenko 2013, P. polesicus Strel'chenko 2000. Проведены стратиграфические корреляции данной части разреза с Волыно-Подолией, центральными районами Восточно-Европейской платформы и Волгоградским Поволжьем, западным склоном Южного Урала, Литвой, Померанией и Свентокшискими горами Польши. Выполнены палеогеографические реконструкции, проанализирован характер распределения индексов окраски конодонтовых элементов.

Ключевые слова: конодонты, верхний девон, нижний фамен, Беларусь, Припятский прогиб, биостратиграфия, биозонирование.