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Carbonate sedimentary environments in the epeiric Baltic Devonian Basin: Pļaviņas Formation, Lower Frasnian

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ABSTRACT

This study focuses on a detailed facies analysis of the Pļaviņas Formation (Upper Devonian, Lower Frasnian) and the interpretation of their sedimentary environments. The study area is located in the northwestern part of the Main Devonian Field, including the territory of Latvia and the southeastern part of Estonia. Facies analyses primarily rely on geological section documentation, macro-scale sample studies, and various methods, such as X-ray diffraction, X-ray fluorescence, total organic carbon analysis, biomarker analysis, and carbon and oxygen stable isotope analysis. Shallow-water sedimentation occurs across all studied areas of the Baltic Devonian Basin. The basin territory exhibits multiple areas with diverse hydrodynamic activities, leading to fluctuations in environmental energy levels during the study period. Notably, the lagoonal to tidal flat environment is particularly related to the northeastern part of the study area, especially within the Sēlija and Atzele members of the Pļaviņas Formation.

Introduction

The carbonate rocks of the Frasnian Stage, Pļaviņas Regional Stage and Pļaviņas Formation were mainly studied from the 1960s to 1990s (Gravītis 1967; Liepiņš 1963; Sorokin 1978; Stinkulis 1998). While these earlier studies covered extensive areas and provided detailed insights, they did not incorporate facies analysis based on stratigraphic methods, and precise analytical methods were unavailable at that time.

The Upper Devonian of the study area is represented by various siliciclastic deposits, dolomites, and their transitional varieties, with some parts of the section also containing gypsum deposits. The Pļaviņas Regional Stage deposits of the Upper Devonian occur in several dolomite quarries and on the banks of small rivers in south- and northwestern Latvia, as well as southeastern Estonia. Moreover, the Pļaviņas Regional Stage deposits are prominently exposed in the Venta and Gauja river basins.

While the sedimentary environments of Late Devonian siliciclastic deposits have been rather widely studied over the last decade (Pontén and Plink-Björklund 2009; Lukševičs et al. 2011; Stinkulis et al. 2020), there has been much less focus on carbonate rocks, with the exception of the study conducted by Kleesment et al. (2013). In that study, from the territory of Latvia only the Ape region in northeastern Latvia was included.

Based on correlations with the nearby boreholes, all 13 study objects represent the sedimentary rocks of the Pļaviņas Regional Stage, exhibiting various thicknesses and relevance, and encompassing one to four of its members: Koknese, Sēlija, Atzele and Ape (Fig. 1). Data from these boreholes were gathered from the Latvian State Geology Fund and the personal archives of Associate Professor Dr. Ģirts Stinkulis.

Geological setting and stratigraphy

All 13 cross-sectional studies were conducted in the central, north- and southeastern regions of Latvia, as well as in the southeastern part of Estonia. The carbonate rocks of the Pļaviņas Formation were accessible in various outcrops along the Venta, Amata, and Gauja rivers, as well as within several active and abandoned quarries that extract dolomite and limestone (Fig. 2). These sections vary in size, ranging from small sections, such as the 2-m high Riežupe cliffs, to larger ones, such as the 23-m high Randāti cliffs. The overall thickness of the Pļaviņas Formation can reach up to 50 m in northeastern Latvia and southeastern Estonia, and can be as low as about

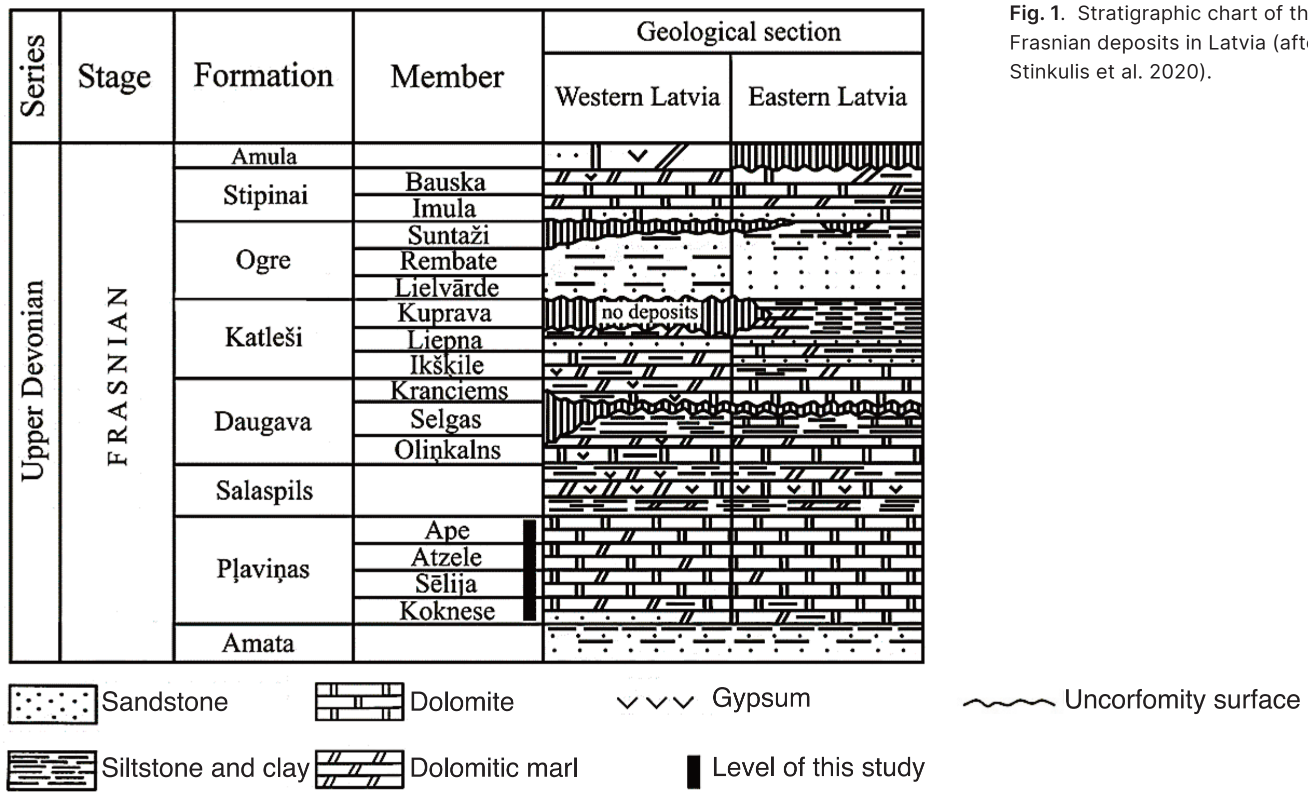

Fig. 1. Stratigraphic chart of the Frasnian deposits in Latvia (after Stinkulis et al. 2020).

11 to 15 m in southwestern Latvia, close to the border with Lithuania.

The Upper Devonian Pļaviņas Formation is divided into four members (listed from lower to higher parts): Koknese, Sēlija, Atzele and Ape. According to Sorokin (1978), the Koknese Member corresponds to the Snetnaya Gora Member, the Sēlija Member corresponds to the Lower Pskov Member, the Atzele Member corresponds to the Upper Pskov Member, and the Ape Member corresponds to both the Lower Chudovo and Upper Chudovo members.

All four members belong to the Frasnian, as correlated by nearby boreholes and previously published data (Stinkulis et al. 2020; Stinkulis and Lukševičs 2018).

The Koknese Member is characterized by dolomitic marls, clays, clayey dolomites, and dolomites. The Sēlija, Atzele and Ape members, on the other hand, are mainly composed of metasomatic dolomites, with dolomitized limestones also observed in the northeastern part of the study area (Stinkulis et al. 2020). While all four members were studied, in several study objects only one or two of them were present (see Fig. 8), probably as a result of glacial erosion. The most complete succession is that of the Randāti cliffs, where all four members are present.

Materials and methods

From autumn 2015 to summer 2022, detailed geological logging was performed for all 13 studied sections (Fig. 8). Dolomite texture, sedimentary structures, fossils, admixtures, and secondary formations were studied. A total of 140 macro-samples were collected from outcrops, which were sawn, grinded, and examined visually and under a reflected-light microscope. Additionally, 23 macro-samples prepared by Marianna Meire-Kārkle, Linda Vīksna, and Kristaps Seilis from the University of Latvia were used.

For the interpretation of various paleoenvironmental parameters, carbon and oxygen stable isotope analysis was conducted. Before proceeding with the isotope analysis, rock powder was prepared using Bosch GSB 13 RE electric drill. The carbon and oxygen stable isotope analysis was performed using GasBench II preparation line and Thermo Scientific Delta V Advantage mass spectrometer. The carbonate rock macro-sample was prepared by Edgars Danefelds at the University of Vienna, Austria. The carbon and oxygen stable isotope analysis was performed by Dr. Tõnu Martma from the Tallinn University of Technology.

Results and discussion

Facies

The following twelve facies were distinguished based on the field sedimentological logging and laboratory study of polished samples (slabs).

F1: carbonate rocks with wavy lamination and wave ripples. The layering suggests calm sedimentary environments, while wavy layering indicates wave processes (Fig. 3).

F2: carbonate rocks with both regular and irregular lamination. Changes in the layering suggest calm and changing environments (Immenhauser 2009).

F3: carbonate rocks with disrupted lamination (Fig. 7A). Marks of bioturbation indicate shallow sea environments, while tepee structures imply subaerial exposure episodes (Immenhauser 2009; Masse et al. 2003).

F4: carbonate rocks containing biodetritus (Fig. 3B). The presence of biodetritus suggests material overwashing, probably as a result of wave action.

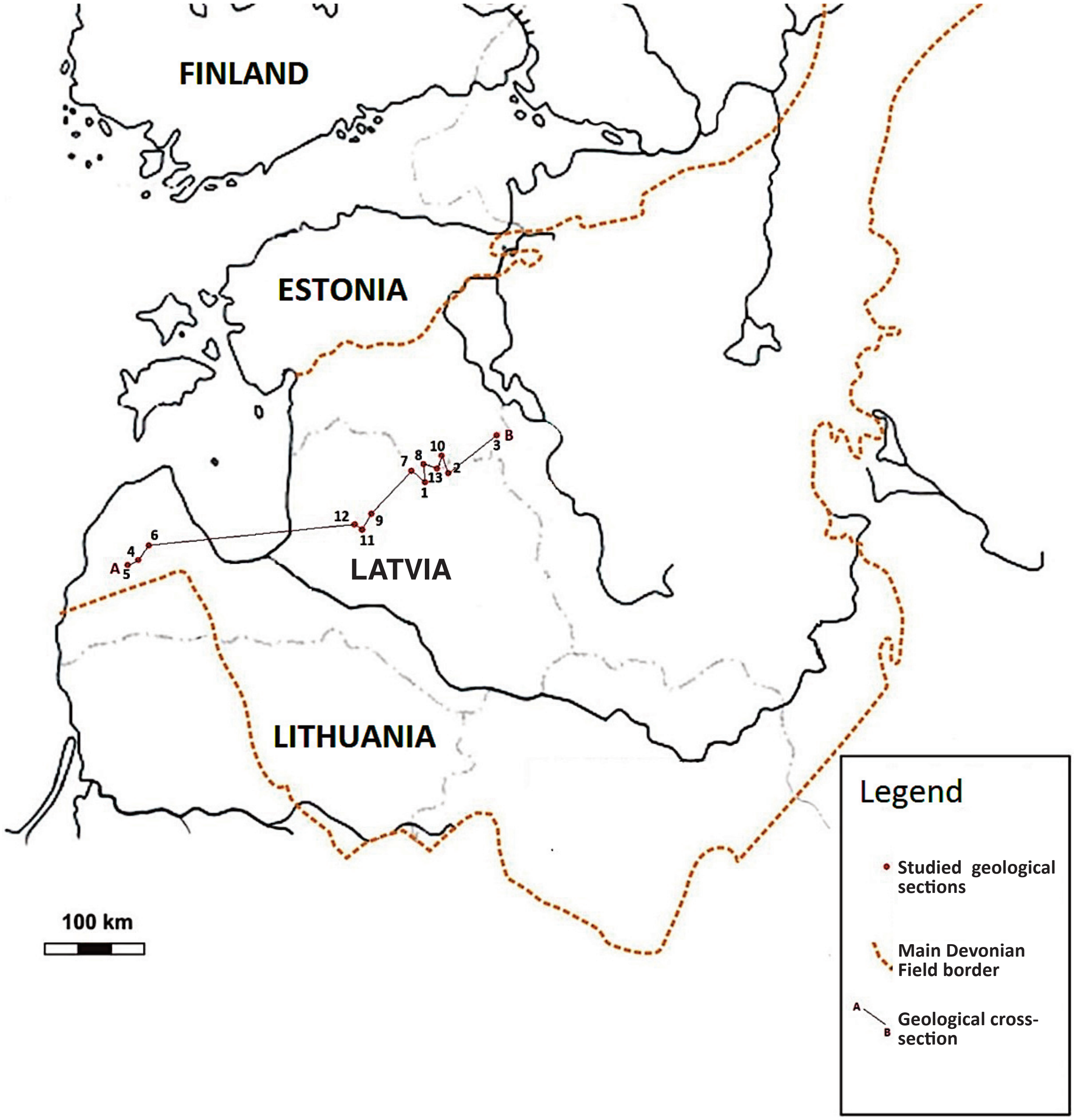

Fig. 2. Position of 13 studied geological sections (marked by red dots) and alignment of correlated geological cross-section (from point A to point B). 1 – Randāti cliffs (57°26′54.1″ N, 26°20′47.7″ E), 2 – Grūbe dolomite quarry (57°31′35.0″ N, 26°46′44.3″ E), 3 – Marinova dolomite quarry (57°44′26.0″ N, 27°31′21.6″ E), 4 – Riežupe cliffs (56°59′16.7″ N, 22°02′40.7″ E), 5 – Venta Falls (56°58′04.7" N, 21°58′40.2" E), 6 – Īvande Falls (57°04′05.0″ N, 22°17′43.0″ E), 7 – Dārzciems dolomite quarry (57°29′32.9″ N, 26°25′7.0″ E), 8 – Ape abandoned dolomite quarry (57°31′52.6″ N, 26°41′21.9″ E), 9 – Lauciņi (Cēsis) dolomite quarry (57°19′4.6″ N, 25°19′0.3″ E), 10 – Kalkahju (Peetri) section (57°32′48.9″ N, 26°34′49.7″ E), 11 – Īļaki cliffs (57°13′28.2″ N, 25°13′32.8″ E), 12 – Vizuļi cliffs (57°13′31.9″ N, 25°13′25.3″ E), 13 – Kalameci and Markuzi ravine (57°32′30.6″ N, 26°26′40.1″ E).

F5: stromatoporoid carbonate rocks. Stromatoporoids indicate normal salinity levels and shallow sea environments (Garland 1997; De Vleeschouwer et al. 2011). In almost all cases, the remains have been overwashed (Fig. 4).

F6: carbonate rocks containing various invertebrate fossils and bioturbation (Fig. 7C). Sedimentary environments may differ here. In some cases, bioturbation may suggest tidal influence (Mešķis 2013).

F7: ooidal carbonate rocks. Ooid factories are characteristic of shallow sea with normal salinity and indicate an active hydrodynamic regime (Tucker and Wright 1990).

F8: carbonate rocks with interlayers of sandy material (Fig. 7D). Interlayers of sandy (clastic) material suggest normal salinity environments with the influx of freshwater and material inflow from the continent (Guangquan and Lidong 2021; Reading and Collinson 1996).

F9: carbonate rocks composed of lithoclasts. These rocks can be entitled as storm layers, as proved by changes in lithoclast gradation.

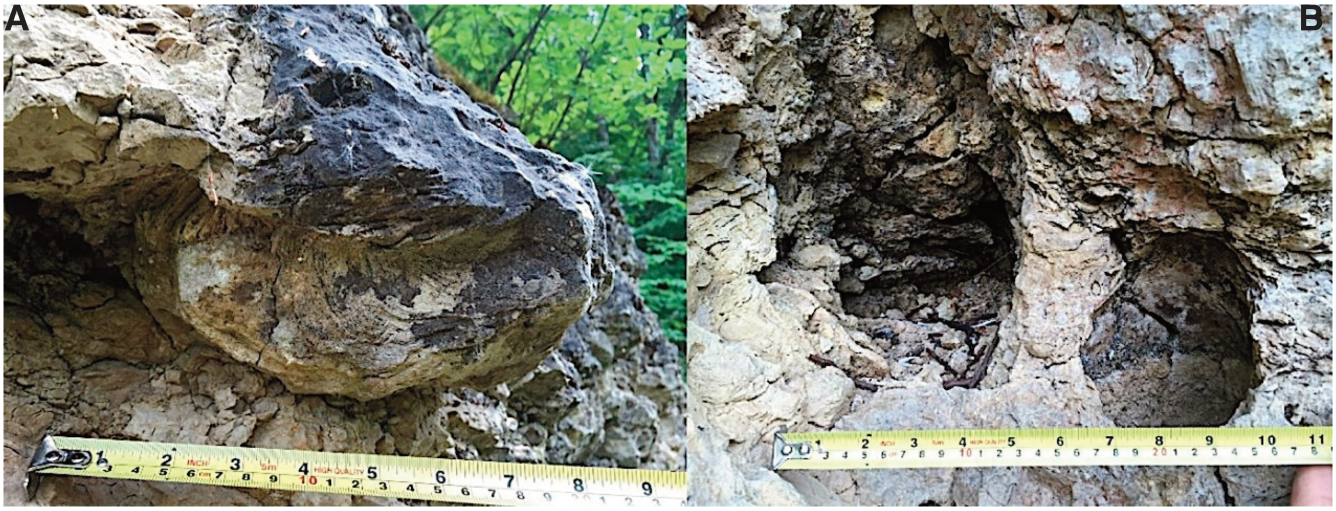

Fig. 4. **A** – approximately 18 cm long overturned stromatoporoid remain, found in the Ape abandoned dolomite quarry (layer 6, facie F5), **B** – two vugs with a diameter of about 10 to 14 cm, found in dissolved bulbous-type stromatoporoid remains (layer 6, facie F5).

Fig. 3. Irregularly laminated dolomite from the Dārzciems dolomite quarry (layer 1, facie F1).

Fig. 6. Dolomite with lithoclasts from the Īļaki cliffs (layer 7, facie F9).

F10: karstified carbonate rocks, which indicate paleokarst processes. Angular lithoclasts suggest minimal transport of materials (Chow and Wendte 2011).

F11: carbonate rocks with clayey interlayers, which suggest the conclusion of tidal processes at the time of deposition (Nichols 1999).

F12: clayey carbonate rocks, which suggest higher clay material input and calm sedimentary environments (Messadi et al. 2016).

Detailed facies information, including affiliation with facies associations, lithological characteristics, and interpretations, are presented in Table 1.

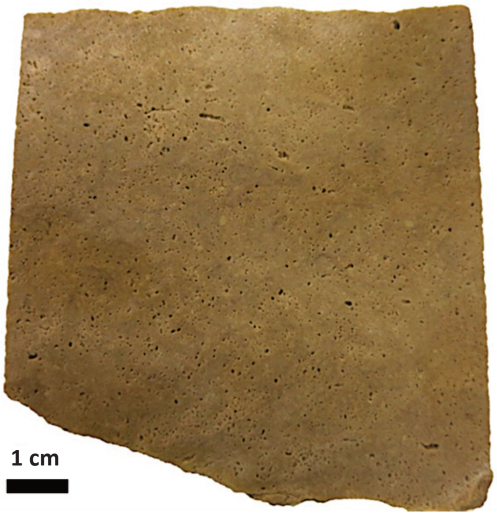

Fig. 5. Ooidal dolomite from the Īļaki cliffs (layer 2, facie F7).

Facies associations

Three distinct facies associations were identified through the utilization of the facies themselves, as well as the thicknesses of the various bedforms, structures, and textures encountered.

FA1: intertidal to supratidal zone with carbonate sedimentation – laminated carbonate rocks (facies F1, F2, F3, F11, F12).

FA2: shallow water, normal salinity, open basin carbonate sedimentation – fossiliferous and ooidal carbonate rocks (facies F2, F3, F4, F5, F6, F8, F11, F12).

FA3: high-energy environments (facies F8, F9, F10).

Figure 8 offers a visual representation of all logged geological sections, showcasing their correlations and providing data on facies and facies associations.

FA1: intertidal to supratidal zone with carbonate sedimentation – laminated carbonate rocks (facies F1, F2, F3, F11, F12)

This facies association was extensively examined in various sections. In several instances, carbonate rocks exhibit irregular or undulating laminations. The thickness of these units

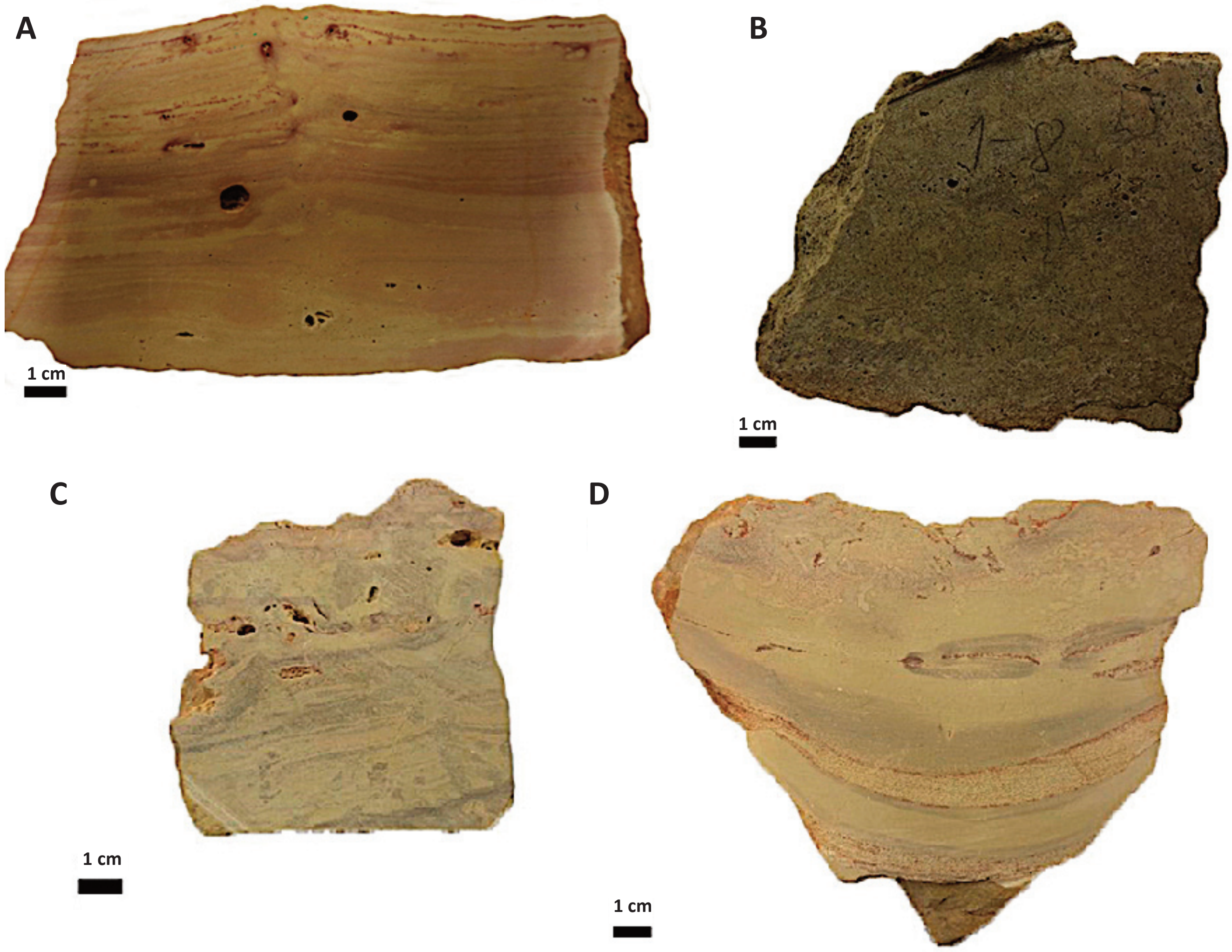

Fig. 7. **A** – irregular laminated dolomite from the Dārzciems dolomite quarry with bioturbation marks and tepee structures (layer 12, facie F3), **B** – dolomite with randomly distributed fossil debris, probably also containing ooids, from the Dārzciems dolomite quarry (layer 8, facie F4), **C** – dolomite with gastropod and brachiopod fossil remains and bioturbation marks from the Īļaki cliffs (layer 7, facie F6), **D** – clastic material and dolomite alternation from the Īļaki cliffs (layer 1, facie F8).

varies from approximately 0.25 to 3.5 m. Five different facies – F1, F2, F3, F11, and F12 – represent this facies association.

In the Ape abandoned dolomite quarry, FA1 is exclusively characterized by F2, which includes regularly and irregularly laminated dolomites, along with some remnants of brachiopods.

The Dārzciems dolomite quarry displays FA1 at the beginning and end of the section, with two units also present in the middle part. Layer 1 in this section exhibits desiccation cracks resembling those of tepees. Trace fossils are present in these units, although no specific taxa were identified.

In the Grūbe and Dārzciems dolomite quarries, FA1 occurs cyclically, with thickness gradually increasing upwards.

In the Īvande Falls, FA1 is present solely in the middle portion (layer 3), with a thickness of 0.35 m. No organism remains were identified, and only small voids were observed, possibly in locations where gastropod and brachiopod remains had dissolved.

Repeating cycles are also evident in the Kalameci and Markuzi ravine. The carbonate rocks primarily consist of laminated dolomites, occasionally transitioning to medium-layered dolomites. Wave ripples, wavy bedding, desiccation cracks, and trace fossils were observed.

The entire Kalkahju (Peetri) section is characterized by FA1. No residual organisms were detected. The upper part section consists of layered, laminated laminae, and massive limestone. Trace fossils and brachiopod and gastropod remains were discovered. *Chondrites* trace fossils (2–3 mm traces on the surfaces of smaller layers) were also present.

In the Marinova dolomite quarry, FA1 is present in the middle and uppermost parts of the section. Most of the units consist of laminated dolomites, with unidentified voids in the lower part of the section (ranging in size from 2 mm to 5 cm) in places of dissolved remains. Bird-eye structures were also identified, interpreted as coral remnants. Stromatoporoid remains were found higher up in the middle part of the section, along with large-sized dolomite crystals known as apites. The uppermost part of the section consists of laminated dolomite with saddle-type lenses filled with clayey material.

In the Randāti cliffs, FA1 is present in several intervals. These units comprise clayey layers at the bottom, followed by laminated dolomite layers featuring wave ripple marks, desiccation cracks, and tepee structures. In the uppermost unit, where FA1 is present, clayey marl predominates and transitions into medium- to thick-layered dolomite with disturbed wave ripple marks and wavy bedding.

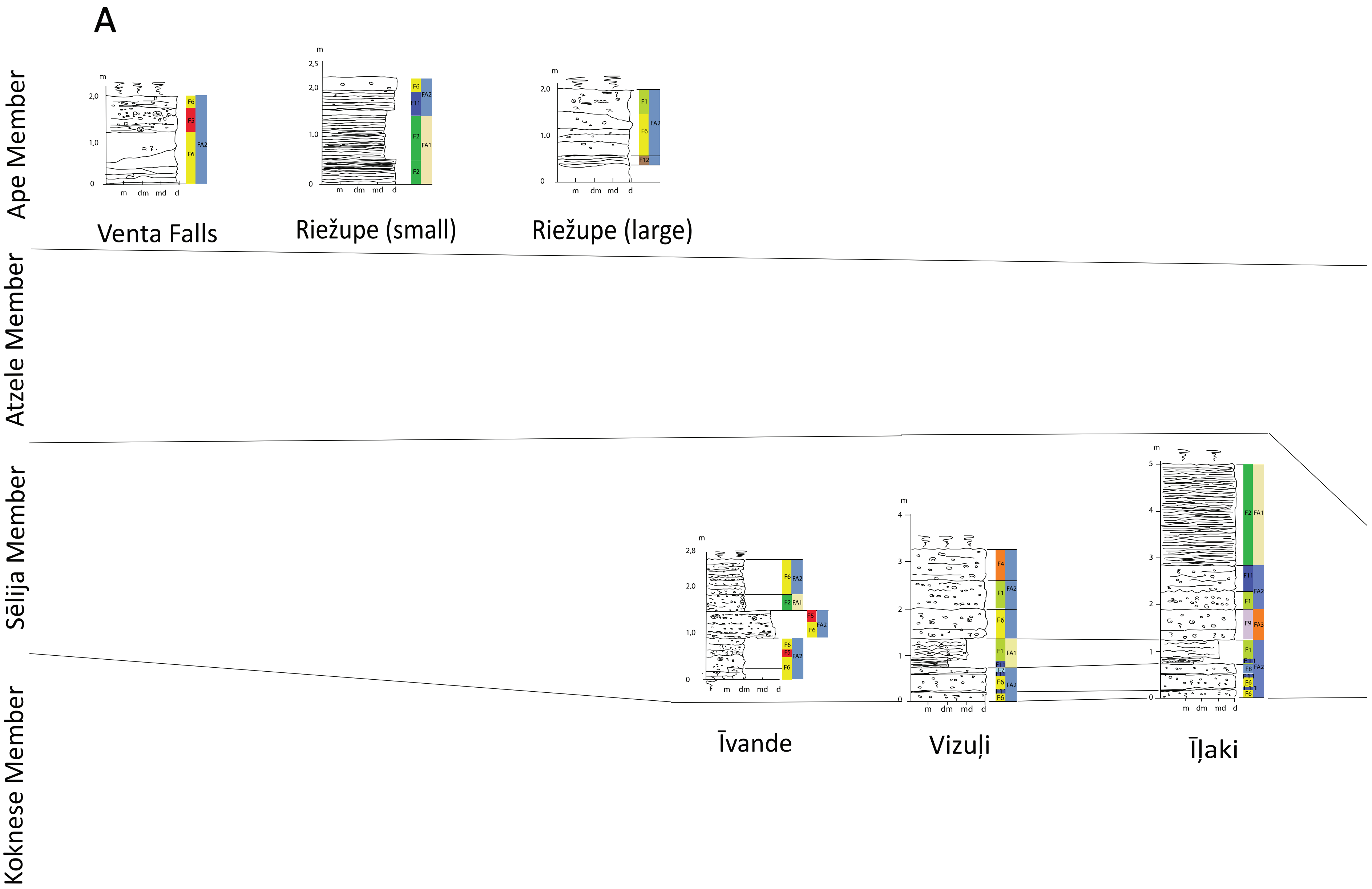

Fig. 8. Correlations for the studied geological objects based on the Pļaviņas Regional Stage members. **A–B** – see the geological cross-section in Fig. 2. Solid line – distinguished (studied) member borders. Abbreviations: F – facies, FA – facies association, m – clay, dm – clayey dolomite, md – dolomitic marl, d – dolomite. *Continued on the next page*

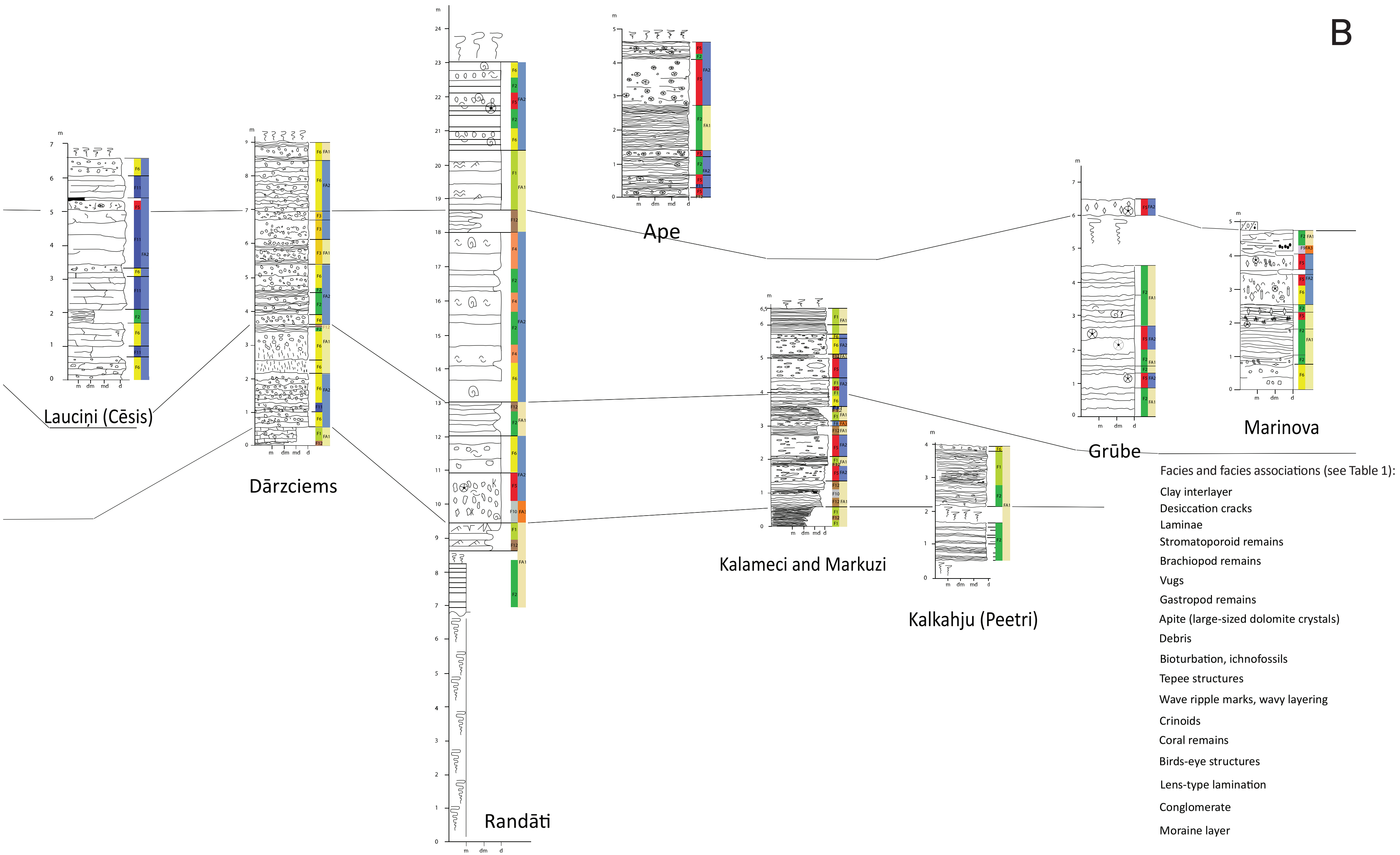

Fig. 8. *Continued*

Table 1. Facies of the Pļaviņas Formation in the study area

Facies	Bed thickness and lithology	Structure	Bounding contact surface	Fossils and ichnofossils	Interpretation	Facies association
F1 Carbonate rocks with wavy lamination and wave ripples	0.3–1.5 m Clays, clayey dolomites, dolomites and dolomitic marls	Wavy laminae and wave ripple marks and desiccation cracks; halite pseudomorphs	Even, subhorizontal to horizontal, non-erosive	No body or trace fossils found	Intertidal to supratidal zone (Flügel 2004), some tidal processes and wave influence, subaerial exposure episodes, evidence of arid climate	FA1
F2 Carbonate rocks with regular and irregular lamination	0.2–2.3 m Dolomites and limestones	Regular and irregular lamination (current/seasonal), tidal bundles	Even, subhorizontal to horizontal	No body or trace fossils found	Intertidal to supratidal zone, influence of tides	FA1, FA2
F3 Carbonate rocks with disrupted lamination	0.3–0.7 m Dolomites	Disturbed lamination	Irregular erosional surfaces	Bioturbation (ichnofossils)	Intertidal to supratidal zone, subaerial exposure episodes; disturbed lamination and rare bioturbation marks suggest deposition in tidal flat or tidal channel environments (Mešķis 2013)	FA1, FA2
F4 Carbonate rocks containing biodetritus	0.5–1.0 m Dolomites	Even layering, homogenous	Even, subhorizontal	Gastropod and brachiopod biodetritus	Presence of biodetritus indicates high-energy environments and material rewashing	FA2
F5 Stromatoporoid carbonate rocks	0.15–1.5 m Dolomites and dolomitic marls	Stromatoporoids of rounded shape, some evidence of overturning	Uneven surfaces, with small erosional pits	Stromatoporoids, with a diameter of up to 30 cm	Normal salinity, shallow water (Garland 1997)	FA2
F6 Carbonate rocks containing various invertebrate fossils and bioturbation	0.15–1.5 m Clayey dolomites, dolomites and dolomitic marl	Bioturbation and even layering	Even, subhorizontal	Gastropods, brachiopods, signs of bioturbation (traces of *Planolites*, *Lockeia* and *Thalassinoides*, also rare vertebrate fossils)	Shallow water episodes (Mešķis 2013); trace fossils suggest sedimentation in tidal flats or tidal channels, rewashed fossils indicate active hydrodynamic regime (Shen et al. 2008)	FA2

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Table 1. *Continued*

Facies	Bed thickness and lithology	Structure	Bounding contact surface	Fossils and ichnofossils	Interpretation	Facies association
F7 Ooidal carbonated rocks	0.1–0.2 m Dolomites	Uneven distribution of ooids	Uneven	No body or trace fossils found	Presence of ooids indicates shallow-water, high-energy environment (Li et al. 2019)	FA2
F8 Carbonate rocks with interlayers of sandy material	One 0.2 m thick layer	Alteration of clastic material and dolomite	Even, subhorizontal or wavy bedding	No body or trace fossils found	Shallow-water carbonate sedimentation with periodic clastic material influx	FA3
F9 Carbonate rocks composed of lithoclasts	0.3–0.6 m	Lithoclasts of dolomite of various shapes and degrees of roundness, located in the dolomite matrix	Uneven surfaces with small erosional pits	No body or trace fossils found	Storm events; the predominant presence of faceted lithoclasts suggests minimal transport of material and the prevalence of active hydrodynamic environments (Immenhauser 2009)	FA3
F10 Karstified carbonate rocks	0.3–0.5 m Dolomites and dolomitic marls	Carbonate rock breccias	Uneven surfaces with small erosional pits	No organism remains or trace fossils found	Paleokarst during subaerial exposure (Immenhauser 2009)	FA3
F11 Carbonate rocks with clayey interlayers	0.05–1.6 m Clays, clayey dolomites and dolomites with clay interlayers	Clayey and carbonate (mostly dolomite) material alteration	Even, subhorizontal to horizontal	No organism remains or trace fossils found	Periodic influx of clay in carbonate sedimentation area; bedding pattern indicates tidal influence (Nichols 2007)	FA1, FA2
F12 Clayey carbonate rocks	0.1–0.7 m Clayey dolomites and clayey dolomitic marls	Regular layering	Even, subhorizontal	No organism remains or trace fossils found	Rather thick clay layers suggest an increase in clay input and low-energy environments	FA1, FA2

In the Riežupe cliffs, FA1 is found only in the smallest section, specifically in the lower part. These units consist of dolomitic marl with laminae (layer thickness ranging from 0.5 cm to 2 cm), featuring crinoid remnants in a chaotic arrangement. The upper part of the unit comprises clayey dolomites and marlstones displaying signs of glauconite formation.

Finally, in the Vizuļi cliffs, FA1 was identified solely in layer 6, consisting of dolomitic marl and clayey dolomite, with occasional small clay interlayers. Clayey material is more prevalent in the lower part of the layer, whereas the upper part exhibits small voids and sporadic wave ripple marks.

Interpretation

Laminated carbonate deposits with even and uneven laminae usually form in intertidal to supratidal environments (Nichols 1999). Current-induced laminae can be identified by wavy thin layering and seasonal laminae by clayey interlayers, desiccation cracks, and tepee structures (Flügel 2004).

The deposition of laminae occurred under tidal influence, as evidenced by symmetrical rhythms or tidal bundles. This facies association is characterized by an increased clay inflow into the basin, probably resulting from the proximity of sedimentary areas to land. The only climate evidence for this facies association is halite pseudomorphs found in the central part of the study area (Īļaki cliffs). Trace fossils are also present in places, indicating marine environments. They are most typical of supra tidal zones; however, an intertidal environment is also possible, particularly in the case of tidal flat and tidal channel environments (Flügel 2004).

FA2: shallow-water, normal salinity, open basin carbonate sedimentation – fossiliferous and ooidal carbonate rocks (facies F2, F3, F4, F5, F6, F7, F11, F12)

This facies association was extensively studied at the majority of geological sites under investigation. The association is characterized by units with thicknesses ranging from approximately 0.45 to 6.7 m. These units are composed of eight distinct facies: F2, F3, F4, F5, F6, F7, F11, and F12.

In the Ape abandoned dolomite quarry, FA2 is present in both the lower and upper portions of the section, primarily composed of dolomites enriched with stromatoporoid remains. The uppermost layers of the section are characterized by stromatoporoids often arranged in chains.

In the Dārzciems dolomite quarry, FA2 appears in three distinct units. The first unit comprises dolomite layers rich in organism remains, predominantly gastropods (found as vugs in places of dissolved remains), along with occasional discoveries of trace fossils (possibly *Planolites*). The second unit, located in the middle section, consists of dolomite with vugs of various sizes, mostly formed by dissolved brachiopod and gastropod remains. The upper part of this unit also contains laminated dolomite. The third unit is composed of vuggy dolomites, often found in locations where brachiopods are dissolved, along with detritus and gastropods. Trace fossils are present in the middle part of this unit (although specific taxa remained undistinguished), as well as fish remains, organism debris, and desiccation cracks. The uppermost part of the third unit consists of vuggy dolomites, with vugs resulting from dissolved gastropod remains.

In the Grūbe dolomite quarry, FA2 is represented in three small units, all comprising dolomite with stromatoporoid remains, some of which reaching sizes of up to 30 cm in diameter. The uppermost layer (layer 7) consists of coarse crystal dolomites (apites) with stromatoporoid remains, some reaching up to 5 cm in size.

In the Īļaki cliffs, FA2 is composed of two units. The first unit is located at the bottom section and consists of three dolomite blocks separated by clay interlayers. Trace fossil signs are present in the dolomite layers, and the upper part of layer 1 is characterized by wavy bedding, where clastic and dolomite materials alternate. Wave ripple marks are visible in the upper part of this layer. The second unit, corresponding to FA2, consists of dolomite with clay interlayers and vugs in places of dissolved brachiopod remains.

The entire Īvande Falls section is characterized by FA2, primarily composed of massive dolomite with small vugs and aggregations of various organism remains. This is followed by layer 1 – vuggy dolomite, possibly formed in places of dissolved gastropod remains, with many distributed in chains. The upper part of layer 2 indicates the presence of stromatoporoids. The subsequent layer (layer 3) consists of massive dolomite with varying amounts of vugs and a heterogeneous dolomite composition. The upper layer (layer 4) is represented by dolomitic marl, which is vuggy in nature and displays signs of layering and heterogeneity.

In the Kalameci and Markuzi ravine, FA2 is represented in four units. The first unit corresponds to the third layer and consists of vuggy dolomite with numerous corals and vugs resulting from the dissolved stromatoporoid and brachiopod remains. The second unit includes vuggy dolomite with brachiopod remains, stromatoporoid remains (up to 10 cm in diameter), and detritus. The third unit comprises three layers with a total thickness of 1.45 m. This includes dolomite with wave ripple marks and ichnofossil *Rhizocorallium* remains, followed by dolomite rich in stromatoporoid remains, wave ripple marks, desiccation cracks, and *Rhizocorallium* remains. The last layer of this unit consists of dolomite rich in small vugs, stromatoporoid and gastropod remains, and occasional organism debris (possibly brachiopod remains). The fourth unit contains vuggy dolomite with small clay interlayers, gastropod remains distributed in chains, and unidentified trace fossils.

The Lauciņi (Cēsis) dolomite quarry section is entirely characterized by FA2 and includes dolomite and marl layers of various thicknesses. The upper part of the section features vugs and organism remains, with vugs ranging from 1 to 15 cm in diameter, indicating the presence of stromatoporoids. The lower portion of the section also exhibits signs of trace fossils.

In the Marinova dolomite quarry, only the middle part corresponds to FA2, which consists of limestone rich in stromatoporoids, crinoids, gastropods, brachiopods, and coral remains. A few laminae are also present in the middle part of this unit, and the upper part of the unit features large dolomite crystals (apites).

In the Randāti cliffs, FA2 is represented in three units across the section. Several dolomite intervals are rich in brachiopod and gastropod remains, and detritus. The uppermost part of this section consists of medium-layered dolomite (laminated dolomite in some intervals) and vuggy dolomite (vugs in the places of dissolved brachiopods, gastropods, and even stromatoporoid remains).

The Riežupe cliffs prominently display FA2. The initial segment of this section is comprised of layered dolomite with coral remnants. This layer transitions into organogenic dolomite, characterized by a substantial abundance of organism remains, with brachiopods being the only identified specimens. In certain instances, evidence of wave ripples has been reported. The upper section of this unit consists of laminae.

Similarly, the Venta Falls section fully embodies FA2. The initial portion of this section is dominated by massive dolomite lacking any discernible indications of organism remnants or voids. The subsequent segment is characterized by vuggy dolomite, often organized as chains. Occasionally, voids can be identified in places of dissolved stromatoporoids.

The Vizuļi cliffs reveal three units with FA2 present. The lower unit consists of three dolomite blocks separated by clay interlayers containing numerous small-sized voids instead of dissolved ooids. Trace fossils have also been identified in this layer.

Interpretation

This facies association was formed in a marine, normal saline environment, mostly within a subtidal zone, as indicated by widespread invertebrate fossils, such as mollusks, brachiopods, and stromatoporoids.

Carbonate rocks rich in stromatoporoid remains suggest that during sedimentation, the basin was rather shallow, ranging from approximately 5 to 20 m in depth. Stromatoporoids are a typical and abundant species of the Devonian and Silurian periods. In most cases, they are reef-building organisms, but are often found also outside reef systems (De Vleeschouwer et al. 2011). In the studied sections, stromatoporoid remains were mostly found in overturned positions, which indicates dynamic environments, most likely influenced by waves or storm action. It is possible that these overwashed remains were distributed in tidal channels or shoals (Immenhauser 2009).

In several previous studies, biodetritus has been found, indicating the overwashing of carbonate organism material, which can occur in the case of wave processes, mostly in reef settings, within the Y or Z hydraulic energy zone (Azami et al. 2021; Irwin 1965).

Trace fossils have been found on several occasions. These fossils are characteristic of various environments, but in most cases, they occur in shallow marine, tidally influenced environments, probably tidal flats (Meškis 2013). Among the found trace fossils, only *Chondrites* and *Planolites* have been identified.

Ooids, which are rarely found, are typical of shallow, normal-salinity basins with active hydrodynamic regimes (Tucker and Wright 1990). Ooidal carbonate rocks likely formed in tidal channels or channels between shoals. Alternating wave-bedded dolomite and dolomitic sandstones are typical of epeiric basins and can form in tidal channels or surrounding tidal flats (Guangquan and Lidong 2021).

FA3: high-energy environments (facies F8, F9, F10)

This particular facies association was identified in only some of the studied locations, including the Īļaki cliffs, the Marinova dolomite quarry, the Kalameci and Markuzi ravine, and the Randāti cliffs. This facies association is characterized by relatively thin layers with thicknesses ranging from approximately 0.3 to 0.6 m. These layers are composed of three distinct facies: F8, F9, and F10.

In the Īļaki cliffs, FA3 (F9) is characterized by vuggy dolomite, featuring voids ranging in size from 5 mm to 3 cm, with a chaotic composition.

In the Kalameci and Markuzi ravine, this facies association is present only in a small layer in the middle part of the section, with a thickness of 20 cm. The dolomite in this layer contains sandy (clastic) material and numerous overwashed brachiopod remains (F8).

In the Marinova dolomite quarry, FA3 is exclusively present in the lower part of layer 7 and is composed of dolomitic conglomerates (F9).

Interpretation

Carbonate rocks containing lithoclasts of various sizes, shapes, and degrees of roundness are indicators of high-energy environments, most likely storm beds (Immenhauser 2009). In the case of the Īļaki cliffs, the storm bed is proved by visible graded bedding. In the Kalameci and Markuzi ravine, dolomitic breccias suggest paleokarst events and mostly shallow sea environments with periodic and even subaerial exposure.

Faceted lithoclasts suggest minimal transport of materials and active hydrodynamic environments (Immenhauser 2009).

Ichnofossil data

In the study area, the diversity of ichnofossils found in dolomite, dolomitic marl, and limestone is limited to only six ichnogenera. These ichnofossils primarily belong to the *Glossifungites* ichnofacies. The formation and preservation of ichnofossils are influenced by factors such as the rate of lithification, surface leaching, and environmental conditions, which may not be conducive for a wide range of organisms.

Detectable ichnofossils in the deposits of the Pļaviņas Formation are relatively rare. Although markings on ichnofossils are frequently observed, precise taxonomic identification is often challenging. Ichnofossils were discovered in the Dārzciems dolomite quarry and Ape abandoned dolomite quarry. *Planolites*, in particular, were observed in various layers of both the Dārzciems and Ape quarries, as well as in a dolomite cliff along the Amata riverbank. However, it is worth noting that only in the Lauciņi (Cēsis) dolomite quarry, researchers were able to confidently identify *Lockeia*, *Planolites*, and *Thalassinoides* trace fossils (Meškis 2013). In the uppermost part of the Kalkahju (Peetri) section, *Chondrites* were identified during the later stages of the study.

Facies associations analysis

When analyzing distinct facies associations, several diagrams (Figs 9–11) were created to visually assess their proportions in the study area, considering both spatial and temporal relationships. These diagrams only depict three of the four members – Sēlija, Atzele, and Ape –, as the Koknese Member deposits are not consistently present throughout the study sites.

In Fig. 9, it becomes evident that during the Sēlija period, the dominant facies associations are FA1 and FA2. Specifically, in the Īvande Falls, FA1 carbonate rocks account for 13% of the cases, whereas FA2 represents 87% of the cases. Similarly, in the Vizuļi cliffs, FA1 appears in 20% of the cases, whereas FA2 is present in about 80%. In the Īļaki cliffs, FA1 and FA2 occur in 43% and 45% of the cases, respectively, with FA3 making up 12%. In the Dārzciems dolomite quarry, FA1 is distinguishable in 54% and FA2 in 46% of the cases. Meanwhile, the Randāti cliffs exhibit a prevalence of FA1 in 28%, FA2 in 56%, and FA3 in 17% of the cases. Data from the Kalameci and Markuzi ravine indicate FA1 in 47%, FA2 in 47%, and FA3 in only 6% of the cases. Finally, in the

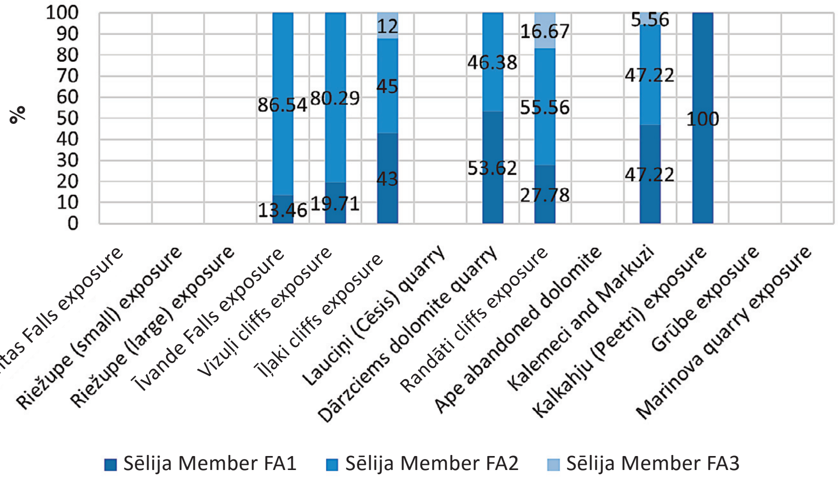

Fig. 9. Distribution of the distinguished facies associations within the Sēlija Member carbonate rocks in the studied geological objects (data presented from southwest to northeast).

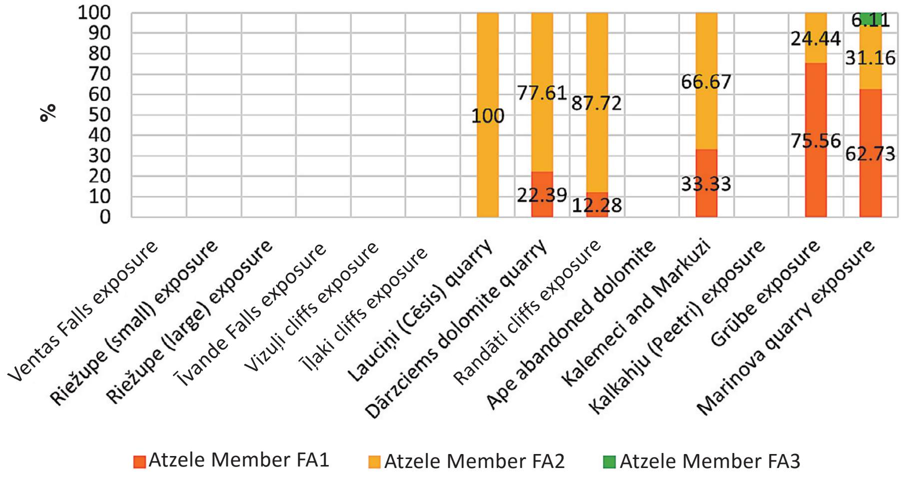

Fig. 10. Distribution of the distinguished facies associations within the Atzele Member carbonate rocks in the studied geological objects (data presented from southwest to northeast).

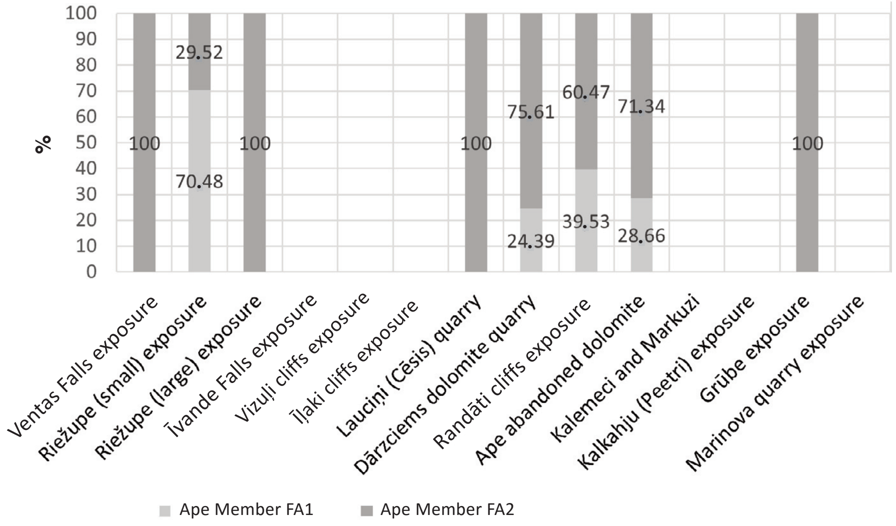

Fig. 11. Distribution of the distinguished facies associations within the Ape Member carbonate rocks in the studied geological objects (data presented from southwest to northeast).

Kalkahju (Peetri) section, all carbonate rocks can be classified as FA1, constituting 100% of the total.

The authors conclude that FA1 corresponds roughly to the Z zone, whereas FA2 aligns with the X zone, based on Irwin's water hydraulic energy zones (Irwin 1965; James and Jones 2015). During the Sēlija period in the Pļaviņas Formation, the basin depth was shallower in the northeast direction.

In Fig. 10, it is evident that deposits from the Atzele Member are primarily distributed in the northeastern part of the study area; nevertheless, this does not mean that the Atzele Member carbonates have not deposited there – they could be a result of glacial erosion. Specifically, in the Lauciņi (Cēsis) dolomite quarry, the entire section is categorized as FA2, accounting for 100%. In the Dārzciems dolomite quarry, FA2 dominates with 78%, while FA1 represents 22% of the cases. In the Randāti cliffs, the situation is similar to Dārzciems, with FA2 accounting for 12% and FA1 for 88% of the cases. The Kalameci and Markuzi ravine reveals FA1 in 33% and FA2 in 67% of the cases. In the Grūbe dolomite quarry, FA1 is dominant at 76%, whereas FA2 makes up approximately 24%. In the Marinova dolomite quarry, FA2 prevails in 63% of the cases, with FA1 present in 31% of the cases studied. In addition, FA3 is discernible in the uppermost part of the Marinova dolomite quarry and accounts for approximately 6% of the cases.

Based on these observations, it can be concluded that during the Atzele stage in the Pļaviņas time, the basin was shallower in the northeast (corresponding to the Z zone, as per Irwin's classification, 1965). Furthermore, the presence of FA3 suggests an episode of storm activity and can be classified as part of the Y zone, in line with Irwin's categorization (Irwin 1965; James and Jones 2015).

The data presented in Fig. 11 indicate that during the Ape period in the Pļaviņas time, there were notable changes in sedimentary environments. There were four section sites in total: two in the western and two in the northeastern part of the study area. Specifically, in the small Riežupe cliffs, FA1 dominates at 70%, while FA2 is identifiable in 30% of the cases. In the Dārzciems dolomite quarry, FA2 is the dominant facies association, accounting for 76%, while FA1 represents approximately 24% of the studied carbonate rocks. The Randāti cliffs show FA1 in 40% and FA2 in 60% of the cases. In the Ape abandoned dolomite quarry, the situation is similar to Dārzciems, with FA1 at 71% and FA2 at 29%.

In this context, the authors conclude that during the Ape period, the entire study area can be classified as the X zone based on Irwin's classification (Irwin 1965; James and Jones 2015), as FA2 dominated. Instances with FA1 present suggest the formation of local shoals.

Results of stable isotope analysis

In the studied carbonate rocks, carbon and oxygen stable isotope values are as follows: δ^{13}C values range from –4.82 to 0.73‰, while δ^{18}O values range from –8.57 to –3.09‰ (Fig. 12 and Table 2).

The stable isotope values of carbon and oxygen in dolomites originating from epeiric carbonate platforms exhibit the following ranges: δ^{13}C –3 to 3‰ and δ^{18}O –10 to 3‰, as reported by Land (1980) and Colombié et al. (2010). The average δ^{13}C values for the Phanerozoic era typically fall within the range of –1 to 4‰, but during the Devonian period, they are around 2‰, as indicated by Mackensen and Schmiedl (2019).

It can be concluded that the carbon values of the measured samples are depleted compared to the typical range, while the oxygen stable isotope values are only slightly affected.

Discussion

Interpretation of sedimentary environments

The analysis of sedimentary environments in the studied deposits of the Pļaviņas Formation in Latvia and Estonia within the Baltic Devonian Basin faces limitations due to extensive dolomitization. In the Baltic States, a vast majority of Frasnian carbonate rocks have been transformed into dolomites, resulting in the preservation of only a small portion of the original rock structures and organisms. Furthermore, organic remains have largely been dissolved, disturbed, or converted into dolomite.

During the peak of the Middle Devonian transgression, a shallow sea gradually developed, characterized by carbonate sedimentation processes. Starting from the Pļaviņas time in the Early Frasnian, there was a significant shift in sedimentary environments from siliciclastic to predominantly carbonate sedimentation (Brangulis et al. 1998). These carbonate sediments were deposited in a shallow epeiric sea (Sorokin 1997).

The widespread evidence of intertidal-supratidal regime and other features of shallow-water sedimentation observed in all studied areas and members of the Pļaviņas Formation

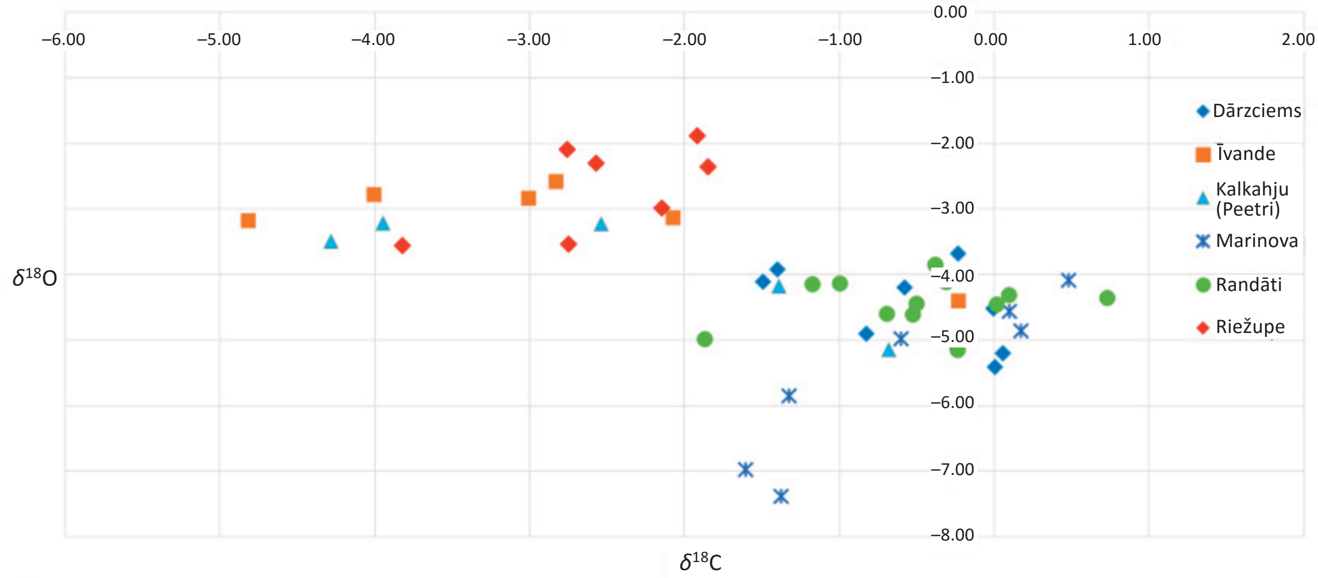

Fig. 12. Correlation between stable carbon and oxygen isotope results in carbonate rock samples collected from various locations, including the Dārzciems dolomite quarry, Īvande Falls, Kalkahju (Peetri section), Marinova dolomite quarry, Randāti cliffs, and Riežupe cliffs.

Table 2. Carbon and oxygen stable isotope results of the Pļaviņas Formation

Member	Section	Sample No.	Sample location, m from section bottom	Carbonate rock type	δ^{13}C, %	δ^{18}O, %
Atzele	Marinova dolomite quarry	M1	0.5	Dolomite	0.48	–5.28
		M2	1.0	Dolomite	0.17	–6.05
		M3	1.8	Dolomite	0.10	–5.76
		M4	2.3	Dolomite	–1.32	–7.05
		M5	3.0	Dolomite	–1.61	–8.16
		M6	3.8	Dolomite	–1.38	–8.57
		M7	4.4	Dolomite	–0.60	–6.18
Koknese	Dārzciems dolomite quarry	D1	1.0	Dolomite	0.06	–6.40
Sēlija		D2	2.0	Dolomite	0.01	–6.61
		D2-2	3.0	Dolomite	–0.24	–6.27
Atzele		D3	4.0	Dolomite	–0.23	–4.88
		D4	5.0	Dolomite	0.00	–5.72
		D5	6.0	Dolomite	–1.49	–5.31
		D6	7.0	Dolomite	–1.40	–5.12
Ape		D7	8.0	Dolomite	–0.58	–5.40
		D8	8.9	Dolomite	–0.83	–6.10
Sēlija	Īvande Falls	Ī-0	0.2	Dolomite	–2.07	–4.33
		Ī-1	0.7	Dolomite	–2.83	–3.78
		Ī-2	1.4	Dolomite	–3.01	–4.04
		Ī-3	1.8	Dolomite	–4.01	–3.97
		Ī-4	2.4	Dolomite	–4.82	–4.37
		Ī-5	2.6	Dolomite	–0.23	–5.59
Sēlija	Kalkahju (Peetri section)	P1	0.7	Dolomite	–3.95	–4.41
		P2	1.4	Dolomite	–4.29	–4.70
		P3	2.1	Dolomite	–2.54	–4.43
		P4	2.8	Dolomite	–0.68	–6.34
		P5	3.5	Dolomite	–1.39	–5.37
Koknese	Randāti cliffs	2	7.0	Dolomite	–0.38	–5.04
		5	7.7	Dolomite	–1.87	–6.18
		7	9.2	Dolomite	–0.53	–5.80
Sēlija		2A	10.7	Dolomite	–0.31	–5.31
		3B	12.2	Dolomite	0.09	–5.50
Atzele		4B	13.7	Dolomite	–0.50	–5.64
		6A	15.2	Dolomite	–0.70	–5.79
		6B	16.7	Dolomite	–1.00	–5.33
		6C	18.2	Dolomite	–0.24	–6.34
Ape		6E	19.7	Dolomite	0.01	–5.65
		8B	21.2	Dolomite	–1.17	–5.34
		9A	22.7	Dolomite	0.73	–5.55
Ape	Riežupe (small) exposure	R0	0.1	Dolomite	–2.15	–4.19
		R2	0.6	Dolomite	–2.76	–3.30
		R1	1.6	Dolomite	–1.92	–3.09
		R3	1.8	Dolomite	–1.85	–3.55
	Riežupe (large) exposure	R2-1	0.3	Dolomite	–2.57	–3.50
		R2-2	0.4	Dolomite	–2.75	–4.74
		R2-3	1.8	Dolomite	–3.82	–4.76

indicate epeiric platform to epeiric slope settings during this time (Stinkulis et al. 2020). Both of these environments are characterized by zones spanning from two to hundreds of kilometers in width, where relatively calm hydrodynamic conditions prevail. Between these two zones, there is typically a dozens of kilometers wide area characterized by an active hydrodynamic regime, largely influenced by tidal processes and wave action (James and Jones 2015).

Opinions regarding the impact of tidal processes on carbonate sedimentary environments vary within epeiric platforms. Irwin (1965) suggested that tidal influence is negligible, whereas later studies proposed that tidal influence has a significant impact on carbonate sediments (Pratt and James 1986). Tidal influence may be linked to other factors, such as the location of the epeiric basin or specific weather conditions at a given time.

In the studied geological objects, tidal bundles have been identified in the Īļaki cliffs and in the Kalkahju (Peetri) section (Tänavsuu-Milkeviciene and Plink-Björklund 2009), the Dārzciems dolomite quarry, and the Kalameci and Markuzi ravine, where continuing cycles have been discovered. Tidal bundles have also been detected in several intervals of the Randāti cliffs. In the Marinova dolomite quarry, bird-eye structures (known as fenestrae) have been studied, suggesting sedimentary conditions typical of the middle tidal zone (Tucker and Wright 1990). Additionally, previous studies on siliciclastic sedimentology in the Baltic Devonian Basin during the deposition of the Pļaviņas Formation widely mention tidal influence (Pontén and Plink-Björklund 2009; Lukševičs et al. 2011; Vasiļkova et al. 2012).

The abundant presence of ooid packaging in the Īļaki and Vizuļi cliffs suggests the formation of ooid shoal during carbonate sedimentation in Sēlija time, as a similar basin was described by Li et al. (2019). Studies conducted in contemporary carbonate sedimentary environments in the Bahamas Archipelago and Florida Peninsula indicate that these environments are generally tranquil, with only occasional storm events affecting the sedimentation in these areas (Tucker and Wright 1990).

In all these studies, carbonate rocks with poorly preserved organism remains were periodically replaced by layers of clayey sediments or laminae, suggesting periodic sea-level changes and potential influences from tidal processes. The authors have documented several "meter-sized cycles" across the study area, which are quite common in epeiric carbonate platforms (Tucker and Wright 1990). Some studies suggest that these cycles result from tidal flat progradation (Pratt and James 1986), eustatic sea-level changes, and regional tectonic processes (Tucker and Garland 2010). These "meter-sized cycles" can also be referred to as "5th order cycles" based on their thickness, as suggested by Tucker and Wright (1990).

These cycles observed in the studied objects vary in thickness, ranging from 0.5 to 0.8 m in the Dārzciems dolomite quarry, from 0.5 to 1.5 m in the Kalameci and Markuzi ravine, and merely from 0.2 to 0.4 m in the Kalkahju (Peetri) section. Immenhauser (2009) stated that cycle thickness is closely aligned with basin depth if sea levels remain stable during sedimentation. As the present cycles are not varying that much, this leads to the conclusion that the basin is shallower in the northeastern direction.

During this study, the authors determined the zones where sedimentation might have been affected by storm events. The most prominent storm layer has been identified in the uppermost part of the Marinova dolomite quarry in southeastern Estonia, deposited during the Atzele stage in the middle of Pļaviņas time. This does not exclude the episodic occurrence of smaller storm events or heavier waving throughout the entire duration of the Pļaviņas time, as evidenced by the widespread presence of over-washed organism remains in logged carbonate rocks, including crinoids and detritus from various organisms. It is noteworthy that over-washed organism remains were mostly found in carbonate rock sections in the central or northeastern parts of the study area, corresponding to northeastern Latvia and southeastern Estonia. The authors consider this area to correspond to the Z and Y zones of the carbonate platform (James and Jones 2015), as evidenced by similarities in other analog carbonate models. One such model is the Eucla Basin in the southern part of the Australian continent, which is very similar to the Baltic Devonian Basin in terms of features such as laminae and stromatoporoids, excluding the heavy dolomitization seen in the Baltic Devonian Basin.

In the southern part of Iran's Zagros mountain ridge, Xu et al. (2023) studied a wide mid-Cretaceous carbonate platform. This platform is rich in coral reef formations, similar to those found in the modern-day Bahamas and the Great Barrier Reef in Australia. These carbonate rocks formed in shallow sea environments, mainly in lagoons and carbonate shoals, which resemble the environments present in the central part of the Baltic Devonian Basin during the Pļaviņas time. However, in our study, we did not find such large reef formations, with the exception of organogenic layers observed in the Marinova dolomite quarry (upper part of the Atzele Member), as well as in the Ape abandoned dolomite quarry (Ape Member).

In previous studies (Stinkulis and Lukševičs 2018; Pontén and Plink-Björklund 2007), it was concluded that so far there are no definitive indicators of water exchange between the shallow epeiric sea of the Baltic Devonian Basin and the rest of the world ocean. Nevertheless, in this study, various features such as laminae, laminated dolomites with signs of local tidal influence, and wave ripple marks were identified in the northern and northeastern parts of the study area. Conversely, fewer laminae were found in the southwestern part of the study area, alongside carbonate rocks rich in organism remains. These characteristics suggest a potential connection between the Baltic Devonian Basin and the world ocean, with a probable increase in sea depth towards the southeast, as suggested by the presence of storm layers in the northeast, reef formations, and increased marks of tidal influence on sedimentation.

Interpretation of stable isotope analysis results

Comparing our data with a study conducted by Kleesment et al. (2013), we observed depleted isotope values for both carbon and oxygen. Kleesment et al. (2013) suggested that a decrease in carbon stable isotope values over time indicates an increase in the influx of freshwater into the basin. Conversely, in line with the findings from the uppermost layer of the Īvande Falls section, where an abnormal increase in carbon stable isotope values is evident, it suggests that there was a rapid increase in water salinity within the basin.

These findings partly align with the results obtained in our study, suggesting that the diagenesis of dolomite was caused by secondary fluids and other factors.

In most of the geological sites examined, the carbon isotope values are similar, except for the central and western parts of the study area, particularly in the Īvande Falls and Riežupe cliffs, where the values range from –2‰ to –4‰. Conversely, the Ape abandoned dolomite quarry exhibits higher values, approximately 1‰. These variations can be attributed to the influx of freshwater from the western region (Amthor et al. 1993), given that such inflows in marine basins, such as the shallow epeiric sea in this case, consistently result in lower δ^{13}C values, as noted by Colombié et al. (2010).

Stable oxygen isotope values are known to change more rapidly during post-sedimentation processes, primarily because these changes require a lower water-to-rock ratio, as explained by Sharp (2017). The δ^{18}O values display significant variation, ranging from –4‰ to –6‰ in an eastward direction, possibly due to post-sedimentation processes and increased atmospheric water influence in the eastern part of the study area.

Conclusions

Based on all the collected evidence, it was concluded that during the deposition of the Pļaviņas Formation, marine environments with significant tidal influence on sedimentation prevailed. During the Pļaviņas time, these carbonate sedimentary environments experienced periodic storm events. The authors also observed various subaerial episodes, during which desiccation cracks and other structures were formed. In some instances within the studied geological sites, the authors identified "meter-sized cycles", which can be categorized as "5th order cycles". Carbonate rock layers frequently alternate with laminae or clayey layers, indicating periodic changes in water levels and shallow sea basin depths, potentially accompanied by tidal processes. Laminae were more prevalent in the northernmost and northeastern parts of the study area, while dolomites with organism remains were predominant in the western part of the study area. This is also supported by the evidence of storm layers, reef formations, and marks of tidal influence on sedimentation in the northeastern part of the study area. This led to the conclusion that the basin was connected to the ocean in the southwestern direction within the Baltic Devonian Basin.

The composition, structures, and the presence of organism remains in the carbonate rocks did not vary significantly across the study area, suggesting that the central part of the Baltic Devonian Basin during the Pļaviņas time resembled an epeiric platform. Notably, the study sites in the northernmost area, including the Dārzciems dolomite quarry, the Ape abandoned dolomite quarry, the Kalameci and Markuzi ravine, and the Kalkahju (Peetri) section, exhibited a relatively high number of laminae, suggesting the presence of the Z zone of the epeiric platform in that direction. This zone supports the tidal-flat sedimentation hypothesis.

The carbon and oxygen stable isotope results partly confirmed sedimentation in marine environments with the possibility of freshwater influx, thus corroborating the hypothesis of a connection with the world ocean. However, further conclusions regarding carbon and oxygen stable isotope results are impossible due to value depletion based on the influence of secondary fluids.

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