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Dolocretes in the uppermost Famennian to Mississippian siliciclastic deposits (Šķervelis Formation, Latvia)

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ABSTRACT

Siliciclastic deposits and dolostones of the Šķervelis Formation in southwestern Latvia were studied in outcrops, polished slabs, thin sections, and by geochemical methods, including stable isotope analyses. Siliciclastic fluvial deposits alternate with soils and carbonates. As the soil processes became dominant, up to 6 m thick dolocretes formed, but they still preserve remnant sedimentary structures and textures. The strong role of soil processes is indicated by the presence of ooids and pisoids together with fine laminar layers, chert and phosphatic inclusions, rhizoids, and stable isotope values. Peculiar vertical clay-dolomite structures, up to 1.7 m long, are root structures or their combination with Vertisol-like soil development. The extensive development of soil processes and formation of the vertical structures was stimulated by seasonally wet monsoon climate. The scarcity of fossils in the studied deposits does not allow their age to be determined precisely, but probably the thick dolocrete unit in the upper part of the studied succession formed during the end-Devonian glaciation and the period of related sea regression.

Introduction

Dolocretes are carbonate-rich deposits formed either in soils or at groundwater levels. In all cases, their formation is related to the subaerial exposure of deposits and processes acting in the vadose zone or in its contact with the phreatic zone. By structure, texture, and formation they are analogues of calcretes, but composed of dolomite. Dolomitic palaeosols and dolocretes, in general, are considered rare in the geological record (Kearsey et al. 2012).

The Palaeozoic succession of the Baltic Basin (sensu Poprawa et al. 1999) includes the Famennian and Mississippian deposits; it is studied from sedimentological, palaeontological, and stratigraphic points of view, and mainly interpreted as marine, estuarine, and deltaic formations (Sorokin 1981; Kurshs 1992; Pontén and Plink-Björklund 2009; Lukševičs et al. 2012). However, in the upper part of the Famennian (probably in the Lower Carboniferous), namely in the Šķervelis Formation (Fm), deposits with abundant structures indicating their subaerial exposure are present (Stinkulis and Spruženiece 2011). The thickness of this succession is at least 12 m, making it an excellent example of dolocretes.

Global events such as glaciation, sea-level fluctuations, changes in sediment composition, and a mass extinction marked the end of the Devonian Famennian Stage and its transition to the Carboniferous (Brand et al. 2004; Kaiser et al. 2016). The role of these events in the development of the Baltic Basin is not well understood due to difficulties in stratigraphic subdivision of the Upper Famennian to Carboniferous succession of this basin, related to the siliciclastic composition of deposits and rare fossils, probably due to their poor preservation.

The aim of this study is to reconstruct the subaerial exposure processes and environments that led to the formation of dolocretes and their host deposits in the

Šķervelis Fm in the Baltic Basin. The objectives are: (a) description and interpretation of the structures and textures, mineral composition, and geochemical characteristics of these deposits; (b) discussion on changes in the deposits due to variations in climate, global ocean-level fluctuations, subaerial exposure events, and soil processes during the Devonian–Carboniferous transition.

Geological setting

The Devonian deposits are widely distributed in the Main Devonian Field, which corresponds to the north-western part of the East European Platform. The western part of the Main Devonian Field is also known as the Baltic Devonian Basin (Fig. 1) according to Pontén and Plink-Björklund (2009) and Lukševičs et al. (2012). During the Famennian, this epeiric basin occupied the Latvian-Lithuanian Depression and was periodically connected with the ocean to the west and southwest. The provenance of the siliciclastic material was located in the north (or northwest in the Devonian period, due to the rotation of the Euramerican continent). During maximum transgressions, the basin was probably also connected to a basin in Middle Russia through the Pripyat Deep (Savvaitova 1977). The relative amount of marine fossiliferous limestones increases towards the south and southwest, while the sequence in the north is characterized by a high content of sands and clays, as well as an abundance of dolostone (Savvaitova 1977; Lukševičs et al. 2012).

The studied stratigraphic interval is the Šķervelis Fm, which has a thickness of 20–24 m, and is considered by most authors to be the uppermost part of the Devonian succession (Savvaitova 1977; Gailīte et al. 2000; Lukševičs et al. 2012). Fossils in the Šķervelis Fm are represented by rare, poorly preserved fish remains. P. Liepiņš identified fishes *Holoptychius* cf. *nobilissimus* Ag. in the Šķervelis Fm. in the Otaņķi drill hole (Liepiņš 1959). These fossils do not allow to specify the geological age of this formation. The underlying Ketleri Fm is richer in vertebrate fossils and corresponds to the *Bothriolepis ciecere* Zone, which is correlated with the lower and middle part of the *Palmatolepis expansa* conodont Zone (Esin et al. 2000; Lebedev and Lukševičs 2018). The Šķervelis Fm is covered by siliciclastic and dolomitic deposits, up to 83 m thick, which are conditionally attributed to the Mississippian based on rare, unconvincing vertebrates and spores (Birger 1979; Savvaitova and Žeiba 1981). Thus, the lower limit of the Šķervelis Fm is the middle-upper part of the *Palmatolepis expansa* Zone, while its upper limit is uncertain, ranging from the uppermost Famennian to the Tournaisian or even the Visean. The Šķervelis Fm and the overlying siliciclastic and dolomitic deposits are obviously older than the Upper Mississippian, as deposits younger than the Visean were eroded due to the Variscan uplift and erosion (e.g. Skompski 2017). The Stratigraphic Commission of Latvia considers the Šķervelis Fm to correspond to the Famennian and to be the uppermost part of the Devonian in Latvia (Gailīte et al. 2000), but this age determination is not sufficiently precise for correlations with global events.

The Šķervelis Fm consists of two members with different lithologies. The lower one, namely the Gobdziņas

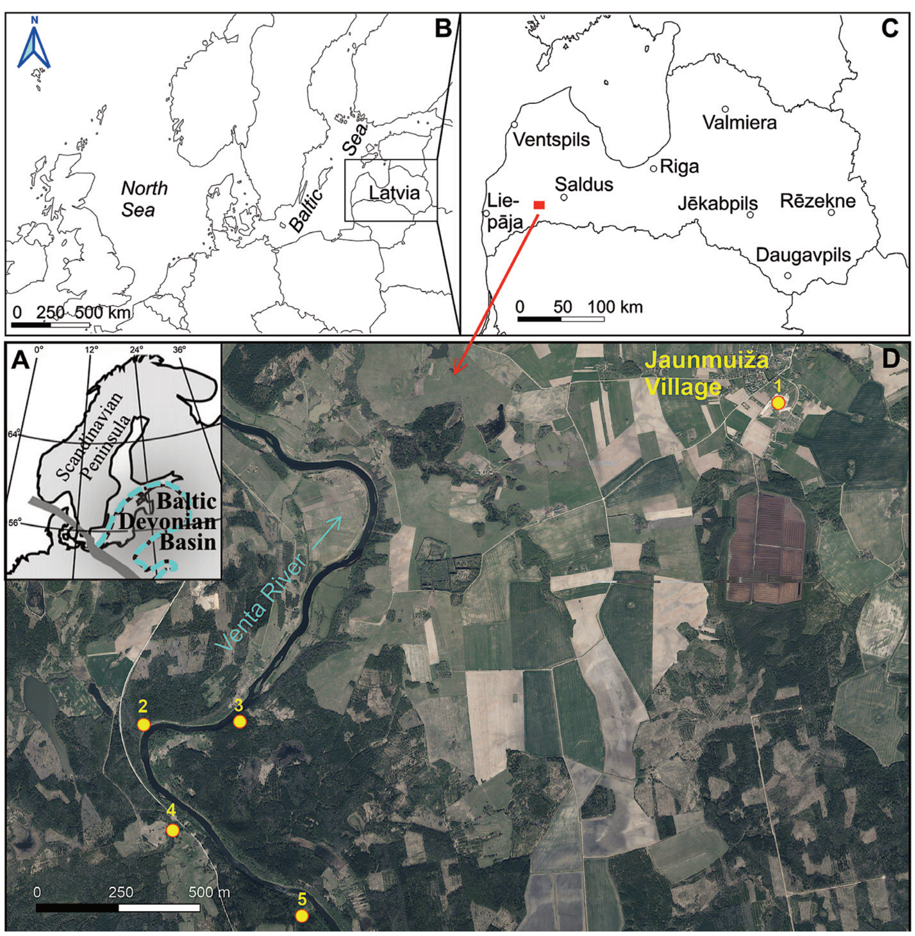

Fig. 1. Study area and sites. **A** – sketch map of northern Europe with the location of the Baltic Devonian Basin. **B** – location of the territory of Latvia in northern Europe. **C** – location of the study area (contours from https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units). **D** – location of the study sites (orthophoto of Latvia; kartes.geo.lu.lv): 1 – dolostone quarry 'Salnas', coordinates 56°36'38.6"N 22°04'22.1"E; 2 – Ātrais kalns (*Rapid Mountain*) outcrop, coordinates 56°34'55.8"N 21°58'48.5"E; 3 – Gobdziņas cliffs, coordinates 56°34'56.5"N 21°59'23.2"E; 4 – Šķervelis outcrop, coordinates 56°34'24.2"N 21°58'51.1"E; 5 – Lētīža outcrop, coordinates 56°33'56.4"N 22°00'03.2"E.

Member (Mb), up to 16 m thick, is composed of fine-grained, cross-stratified sandstones with dolomite cement. The upper one, Nīkrāce Mb, 3–6 m thick, consists of sandy dolostones that are exposed in outcrops over an area of at least 2–3 km^2 (Savvaitova 1977).

Materials and methods

The deposits of the Nīkrāce Mb of the Šķervelis Fm were documented and sampled in three exposures, namely the Ātrais Kalns, Šķervelis, and Lētīža outcrops (Fig. 1). The deposits of the Gobdziņas Mb of the same formation were studied and sampled only at the Ātrais kalns exposure, as they are not present at the other studied sites. Macrostructures were documented in detail in the sedimentological logs of the studied outcrops. Additionally, peculiar vertical structures were documented in both members at the Gobdziņas cliffs on the right bank of the Venta River and in the Salnas dolostone quarry (Fig. 1).

The grain size of the siliciclastic deposits from the Gobdziņas Mb in the Ātrais kalns outcrop was determined in the field, and nine samples of siliciclastic material from this outcrop were analysed, using a combined sieving and hydrometer (sedimentation) method at the Faculty of Geography and Earth Sciences of the University of Latvia. The sedimentological features of the Nīkrāce Mb were documented in 51 polished slabs, representing different beds within the sections. Mineral composition, paragenesis, grain size of siliciclastic admixture, and micromorphological features were studied in 28 thin sections, which were made at the Faculty of Geography and Earth Sciences of the University of Latvia. A Leica DM 4500P microscope connected to a Leica DFC 495 digital camera was used for thin-section study and photographs.

Ratios of stable isotopes $\delta^{18}O$ and $\delta^{13}C$ were determined in 113 carbonate samples (26 from Lētīža, 31 from Šķervelis, and 56 from Ātrais kalns outcrops). Samples from the Lētīža outcrop were analysed at the University of Tartu, and samples from the Šķervelis and Ātrais kalns outcrops at Tallinn University of Technology. In all cases, the samples were powdered and treated with 99% phosphoric acid at 70 °C for 2 h, then analysed by a GasBench II preparation line connected to a Thermo Scientific Delta V Advantage continuous flow isotope ratio mass spectrometer.

At Tallinn University of Technology, the samples were measured using three standards (for each GasBench row three standards and five samples): laboratory standard TLN-C1 $\delta^{13}C$ = 2.2‰, $\delta^{18}O$ = –9.11‰; KH-2 (DDR) $\delta^{13}C$ = 1.97‰, $\delta^{18}O$ = –2.96‰; NBS-18 (IAEA) $\delta^{13}C$ = –5.01‰, $\delta^{18}O$ = –23.0‰. TLN-C1 was calibrated using IAEA standards: NBS-19 $\delta^{13}C$ = 1.95‰, $\delta^{18}O$ = –2.2‰; LSVEC $\delta^{13}C$ = –46.6‰, $\delta^{18}O$ = –26.47‰; NBS-18 $\delta^{13}C$ = –5.01‰, $\delta^{18}O$ = –23.0‰. At the University of Tartu, the measurements were performed according to international standards (IAEA): NBS-19 $\delta^{13}C$ = 1.95‰, $\delta^{18}O$ = –2.2‰; LSVEC $\delta^{13}C$ = –46.6‰, $\delta^{18}O$ = –26.47‰; NBS-18 $\delta^{13}C$ = –5.01‰, $\delta^{18}O$ = –23.0‰. Analytical precision (2σ) was 0.1‰. The results are expressed as per mil deviation relative to Vienna Peedee Belemnite (VPDB) scale for oxygen and carbon. The reproducibility of replicate analyses was better than ± 0.1‰ for $\delta^{18}O$ and ± 0.1‰ for $\delta^{13}C$. In all cases, oxygen isotope values were corrected for dolomite.

The deposits of the Nīkrāce Mb in the Lētīža outcrop were analysed using scanning electron microscope (SEM) and X-ray diffraction (XRD) methods at the Department of Geology, Faculty of Science and Technology, University of Tartu. Four selected samples were studied for micromorphological features by SEM. Polished slabs coated with a ca 5 nm thick carbon layer were studied using a Zeiss EVO 15MA SEM instrument. The chemical composition was determined by an Oxford AZTEC X-MAX energy dispersive spectroscopy (EDS) system.

The mineral composition of 25 bulk rock samples was studied by XRD. The samples were pulverized in a planetary mill, and random powder preparations were scanned using a Bruker D8 Advance diffractometer with a Vario1 focusing primary monochromator with *CuK*α radiation, two 2.5° Soller slits and a LynxEye line position sensitive detector. Scanning was performed in the range of 2°–70° 2θ with a step size of 0.02 and a total counting time of 1 s per step. The mineral quantitative composition was modelled in software Siroquant-3, which is based on the Rietveld and relative intensity methods (Taylor 1991).

The clay mineral identification in the three most clayey samples was also performed by the XRD method. The clay fraction was separated by the sedimentation method and air-dried on glass mounts. Three different oriented specimens were made for each sample: air dried, saturated with ethylene glycol for 24 h, and heated at 550 °C for 2 h (Moore and Reynolds 1997). Data was collected from 3 to 55° 2θ with a counting time of 0.5 s and a scanning step size of 0.05° 2θ.

Results

Geological section

Gobdziņas Mb

The Gobdziņas Mb was documented in one outcrop, Ātrais kalns. Approximately the upper half of the succession (8 m thick) is exposed there, but the lower part is not available for documentation (Fig. 2). The deposits are represented by four sedimentary cycles (0.7–3.9 m thick) with erosional boundaries. Their number changes in lateral direction, as many sedimentary surfaces are inclined, which corresponds to the migration of fluvial channels, bars, and cross-beds. The lower part of each cycle is composed of cross-bedded and parallel-bedded medium-grained to very fine-grained sandstone, and the upper part is made of mixed-composition clayey-sandy to dolomitic sedimentary rocks or massive dolocretes. The latter are present only in the upper cycle of the Gobdziņas Mb.

The sandstones of the lower parts of the cycles contain dolomite cement, vertical dolomite veins, and honeycomb structures. The bed boundaries are rather parallel and regular. In the lower part of the upper cycle, the original structure of cross-bedded sandstone is well-preserved and has not been obliterated by diagenetic processes. The thickness of the cross-

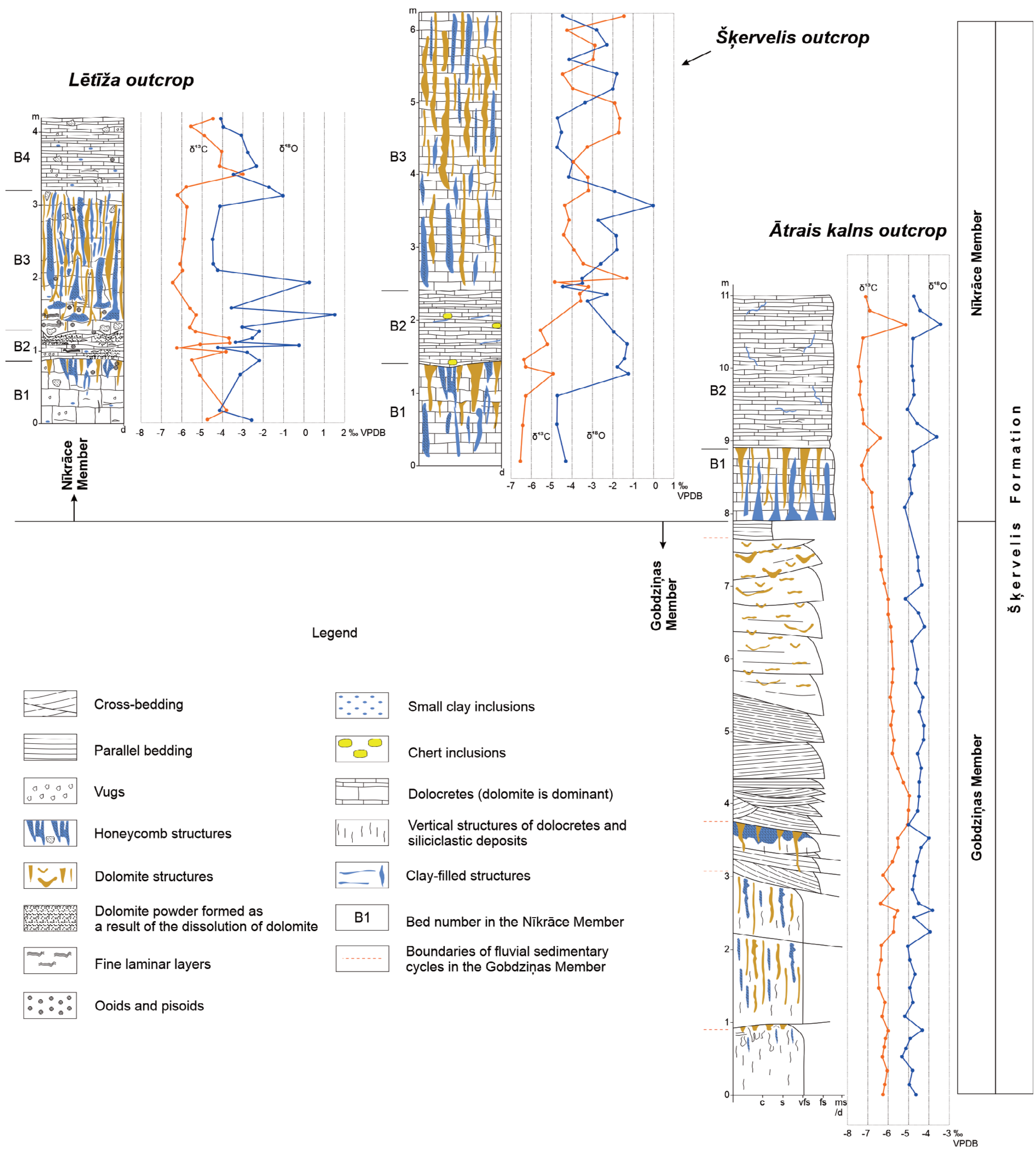

Fig. 2. Geological sections with stable isotope curves. They are approximately correlated according to lithological features and stable isotope data.

beds ranges from 10 to 50 cm. The measurements of cross-bedding (8 in total) demonstrate variable palaeocurrent directions: N, NE, S, and W. There are no tidal structures in the bed. In the upper parts of the intervals, net-like and honeycomb structures occasionally occur, as well as circumgranular fractures. Subvertical dolomite structures narrow down from the tops of the beds.

The uppermost part of the Gobdziņas Mb in the Ātrais kalns exposure is composed of red and blue, stratified, non-carbonate clayey siltstones, 0.4 m thick.

Nīkrāce Mb

The member is described in three outcrops: Lētīža, Šķervelis, and Ātrais kalns. The Nīkrāce Mb is composed of alternating beds of platy, sandy dolostones and sandy dolostones with vertical structures, in places with the admixture of clay and chert.

The platy, sandy dolostones are 0.3–1 m thick, microcrystalline to finely crystalline, light greyish, greyish-green, pink, yellow, and orange, occasionally spotty-coloured. The deposits in some places are rich in chert nodules that range from several millimetres to several centimetres in size. Honeycomb structures are present, but are rarer than in the sandy dolostones with vertical structures.

The sandy dolostones with vertical structures are 0.5–3.8 m thick, microcrystalline to finely crystalline, from yellow to orange and greenish-grey, occasionally spotty-coloured. Honeycomb structures are often present in the dolostones, mostly in association with the clayey parts of the vertical structures. These dolostones are dominant, forming 65% of the Nīkrāce Mb in the Lētīža, 70% in the Ātrais kalns, and 85% in the Šķervelis sections.

In the Lētīža outcrop, the Nīkrāce Mb is divided into four beds. Bed 1 (B1) and B3 are represented by sandy dolostones with vertical structures, and B2 and B4 are made of platy, sandy dolostones. In the Šķervelis outcrop, the Nīkrāce Mb is represented by three beds, with B1 and B3 composed of sandy dolostones with vertical structures, and B2 composed of platy, sandy dolostones. In the Ātrais kalns exposure, the Nīkrāce Mb is represented by two beds, with B1 composed of sandy dolostones with vertical structures and B2 made of platy, sandy dolostones.

In the Lētīža exposure, the vertical structures penetrate in places at least 50 cm from B3 down to B2. The upper parts of the vertical-structured B3 in Lētīža and B2 in Šķervelis are rather parallel and cut by the base of parallel-oriented B4 in Lētīža and B3 in Šķervelis. In the Lētīža outcrop, bar-like and trough-like structures are present throughout B2 and B3 and are best exposed there.

In the Ātrais kalns section, a platy, sandy dolostone layer is covered by a layer of sandy dolostones with vertical structures.

The original sedimentary structures in the Nīkrāce Mb are poorly preserved due to obliteration by intense and widespread diagenetic processes, especially the formation of carbonate minerals. However, the bed surfaces are often inclined in various directions, and in places cross-bedding is preserved.

Mineralogical and textural features

The Gobdziņas Mb consists of sandstones and siltstones that contain the admixture and inclusions of clayey-silty material and dolomite. Rarely, they contain ellipsoidal nodules, up to 30 cm thick and 80 cm long, which have secondary quartz cement. The content of silt-clay fraction (< 0.063 mm) in sandstones is 10–34%. Mixed-composition deposits from the upper parts of sedimentary cycles and clayey lenses from sandy dolocretes contain equal fractions of < 0.063 mm and > 0.063 mm (very fine- to fine-grained sand) – 40–60%.

The Nīkrāce Mb consists of dolostones, sandy dolostones, and dolomitic sandstones. Dolomite is the dominant mineral, but the silt- to fine-grained sand admixture was also found. Its content is usually 10–30%, but there are great variations in the analysed samples – from 1–2% to 70%. Fine laminae rich in siliciclastic material often alternate with pure dolomitic laminae. There are typical floating-grain structures, as the quartz grains are not in contact but are surrounded by microcrystalline dolomite. Clay to silt inclusions and admixtures are abundant in all parts of the Nīkrāce Mb, with a total of approximately 10–20% in the platy, sandy dolostones and 10–30% in the sandy dolostones with vertical structures.

The dominant mineral in the silt to sand material is quartz, but detrital K-feldspar and muscovite/illite are also present (Fig. 3B, C). In the Lētīža outcrop, corroded quartz grains were found in sandy dolostone of B2.

Authigenic silica (chert) occurs in 30% of the platy, sandy dolostones in B2, Lētīža outcrop. Calcite reaches 5% in both B1 and B2 in the Lētīža outcrop (Fig. 3D). Calcite is present as secondary cement post-dating dolomite, as seen in thin-sections.

The clayey material associated with the honeycomb structures and vertical structures (1.60, 2.50 and 3.10 m above the base of the Lētīža section) is characterized by a diverse mineral composition: quartz, dolomite, K-feldspar, muscovite, and clay minerals of illite, mixed-layered illite-smectite and palygorskite, as documented by XRD analysis (Fig. 3E). Traces of chlorite (< 3 wt%) occur in some places.

Palygorskite is a common clay mineral in most of the samples from the Lētīža outcrop, with the highest concentration (up to 11 wt%) found in B1 and B3 (Fig. 3D, E). It is closely associated with the vertical structures and particularly with honeycomb structures and thin lamination. However, various amounts of palygorskite were recognized in clayey infillings in dolocrete throughout the geological section of the Nīkrāce Mb in the Lētīža outcrop (Fig. 4A).

In platy dolostones of the Nīkrāce Mb (B2 in the Lētīža outcrop), amorphous phosphorus-rich inclusions were identified (Fig. 4B). These inclusions are small spherules, 1–5 μm in diameter, with a P content of ~20%.

Vertical structures

One of the most peculiar features of the Šķervelis Fm is vertical structures, defined by relationships of carbonate and sandy to clayey material. The structures are present in both members of the Šķervelis Fm in all the study objects.

In the sandy deposits of the Gobdziņas Mb, vertical dolomite structures are present. They often become narrower and bifurcate downwards. In the Salnas quarry, the vertical structures present in the upper part of the Gobdziņas Mb usually have a columnar shape (Fig. 5). Their rims with outer diameters of up to 30 cm and inner diameters of up to 6 cm are formed by sandy dolostone, while their cores consist of loose sandy material with a small admixture of dolomite (Fig. 5). In places where the structures are exposed in full thickness, they are up to 0.8 m long.

In the Nīkrāce Mb, the structures are 0.1–1.7 m long and 0.02–0.2 m wide (Fig. 6A, D), reaching their maximum length in B3 in the Nīkrāce outcrop. These structures are characterized by a relationship of sandy to clayey, bluish material, and sandy to silty, light brown to yellow dolostone (Fig. 6C, D). In places, the structures are evenly distributed: 8–20 cm wide vertical dolomite structures alternate laterally with 2–15 cm wide similarly vertical clayey material and honeycomb clay-dolomite veins. This gives the dolocrete a peculiar vertically columnar-tubular structure (Fig. 6). In places, the carbonate columns or tubes are placed close together, with almost no clay in between. The initial structure

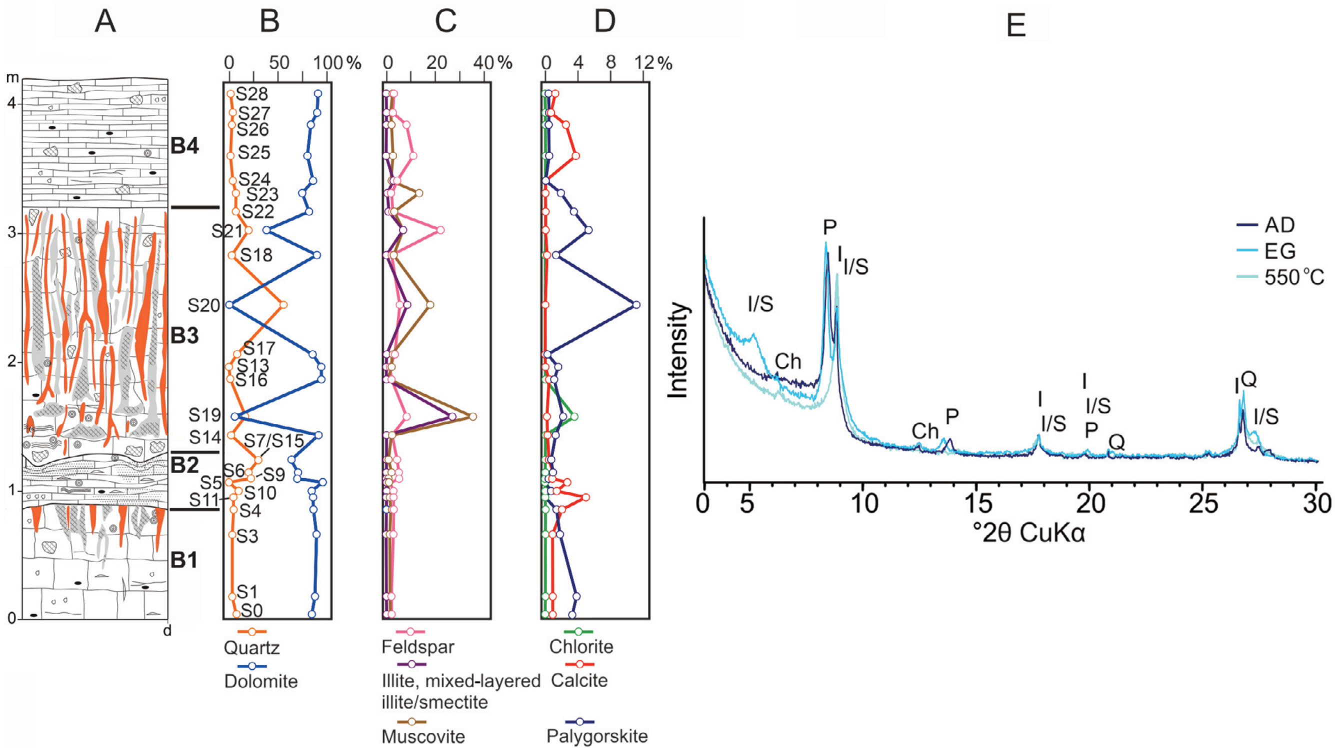

Fig. 3. Mineralogical composition of the deposits of the Šķervelis Fm, Nīkrāce Mb, Lētīža outcrop. **A** – generalized geological section of the Nīkrāce Mb. B1–B4 are layer numbers. For the legend of the section, see Fig. 2. **B–D** – mineralogical composition of dolocretes. **E** – mineralogical composition of the clayey material from the clayey infilling of dolocrete (X-ray curve): I – illite, S – smectite, I/S – illite/smectite, Ch – chlorite, P – palygorskite, Q – quartz, AD – air-dried sample, EG – sample processed with ethylene glycol, 550 °C – the sample was heated at a temperature of 550 °C.

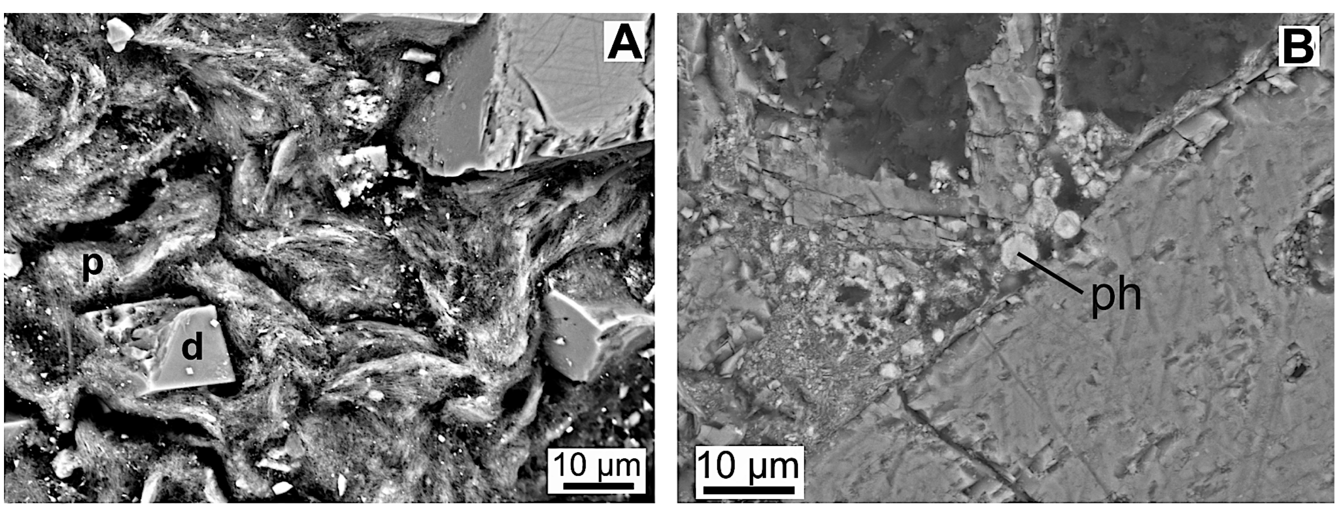

Fig. 4. Microfabric of dolocretes of the Nīkrāce Mb, Šķervelis Fm in the Lētīža outcrop, SEM images. **A** – fibrous fabric of palygorskite (p) among dolomite crystals (d), sample S.16. **B** – globules of amorphous phosphate (ph) in weathered dolostone, sample S.5.

of the vertical formations is somewhat obscure due to diagenetic changes and the rather fractured fabric of the dolocretes, but they likely have a rim of dolomite and an infill of sandy to clayey material. Honeycomb structures are often present in the infill. The upper and lower parts of the beds with the vertical structures are slightly irregular, with an amplitude of approximately 10 cm.

Features of dolocretes

The deposits of the Nīkrāce Mb in all the study objects are rich in features typical of dolocretes. In all the studied polished slabs and thin sections, an irregular distribution of dolomite can be seen. Microcrystalline to fine-crystalline dolomite forms variously oriented veins that differ in size, from parts of millimetre to some millimetres in width, and up to several centimetres long. Dolomite forms ooids and pisoids, laminar layers, and rhizoids. The relationships between dolomite and clay define honeycomb structures (Fig. 6B–D).

Honeycomb structures

The dolostones of the Nīkrāce Mb are rich in honeycomb structures formed by a dense network of dolomite veins

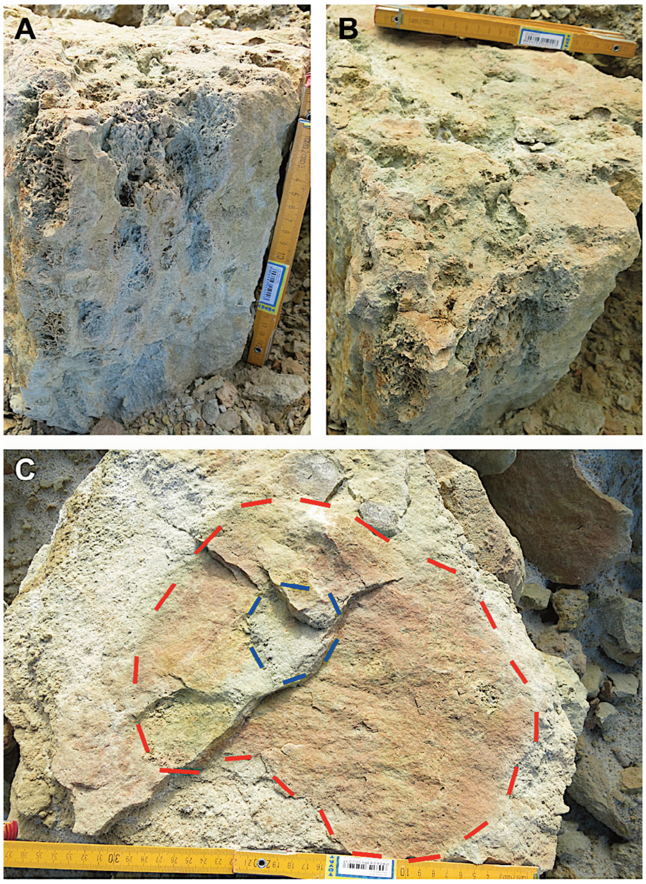

Fig. 5. Vertical structures in the Šķervelis Fm, Salnas quarry. **A**, **B** – rather regular, tubular structures filled with honeycomb dolomite-clay and surrounded by dolomitic rims (Nīkrāce Mb). **C** – cross-section of a large, subvertical root structure in the Gobziņas Mb. The outer margin of the dolomitic rim is marked by red dashed line and the core of loose sandy material by blue dashed line.

(~1 mm wide) with voids between them (Figs 6B–D, 7D). The cells between the branching dolomite veins vary in size, but are typically 0.5–1.5 cm in diameter and filled with greyish-blue clay and silt with the admixture of fine-grained sand. The honeycomb structures can be found not only in relation to the vertical structures but also in other areas of massive dolostone.

Vadoids (ooids and pisoids)

There are various classifications of coated grains, which are typical constituents of calcretes and dolocretes, but also form in many other settings (Wright 1990). Most authors suggest that ooids (oolites, ooliths) are coated grains with a rim of concentric fabric <2 mm in size, while pisoids (pisolites, pisoliths) are similar but often less regular in shape and larger than 2 mm (Wright 1990). We adopt the terminology used in a study of coated grains in calcic pedogenic formations (Robins et al. 2015) that coated grains smaller than 2 mm are called ooids, but those larger than 2 mm are called pisoids. All these coated grains can also be called vadoids, as they formed in the vadose environment (Peryt 1983). In the Lētīža outcrop, ooids occur in the topmost part of B1, as well as in B2 and B3. In the Šķervelis outcrop, ooids are present in B3, interval 2.4–5.5 m.

The centres of ooids and pisoids are usually composed of dark microcrystalline or transparent, very fine-crystalline dolomite. The admixture of siliciclastic material and small vugs formed as a result of the dissolution of dolomite are also present in the centre of the ooids and pisoids. Microcrystalline dolomite fragments and smaller, compressed, collided ooids form the growth centres of several larger ooids and pisoids. The rims of the grains are composed of microcrystalline dolomite.

The ooid zones consist of densely packed coated grains with diameters of 0.1–1 mm (Fig. 7A–C). In rare cases (Šķervelis outcrop, B3, interval 5.5 m), pisoids with diameters of up to 5 mm are present. In places, ooids exhibit a reverse grading pattern, with their grain size increasing upwards (Fig. 7C). Many of these grains have slightly subvertically oriented elongated shapes and bridge-like contacts. In some cases, the lower parts of the ooids are pendant and form microstalactite structures. SEM has identified some suspicious ooids in association with fine laminar structures in dolomite. They have diameters of 50–500 µm and consist of siliciclastic material coated with micritic dolomite.

The lenticular zones of ooids vary in size, from a few millimetres to 5 centimetres in length, and from a few centimetres to 5–10 centimetres in thickness, with wavy, concave and convex boundaries. The ooids lie in close contact with thin lamination (Fig. 7B, C). The parts of dolocrete that are rich in ooids and pisoids usually contain a relatively small amount of siliciclastic material (<7%).

Thin lamination

In both the Lētīža and Šķervelis outcrops, the same dolocrete layers that contain vadoids are also rich in thin laminated deposits (Figs 7A–C, 8A–C). Some ooid zones are even confined by thin laminated beds, and ooids are found in pockets within these laminated deposits. These structures range in thickness from 0.1 cm to 1 cm and are several centimetres wide, on average 1–10 cm. The individual laminae are twisted and wrinkled, only 10–20 µm to 1 mm, on average 200 µm thick.

The laminae alternate between microcrystalline dolomite, fine-crystalline euhedral porous dolomite, and clays in some places. Some laminae also contain very fine-grained sand and silt grains (Fig. 8B, C). The pore-filling matrix of crystalline dolomite and the thickest clayey laminae are usually composed of illitic clays with an admixture of mica and palygorskite. In some laminae, the clay phases are represented only by palygorskite.

Rhizoids

Besides the decimetre- and metre-scale vertical structures, branched structures (Fig. 8A, D) filled with clayey material occur in the microcrystalline dolostone of the Nīkrāce Mb. The thickness of individual branches is up to 0.5 mm, and they are several centimetres long. These zones are characterized by linear or slightly arcuate/bent features, which are 100–150 µm long and ~10 µm wide. The fabric of these structures allows us to suggest that they are rhizoids.

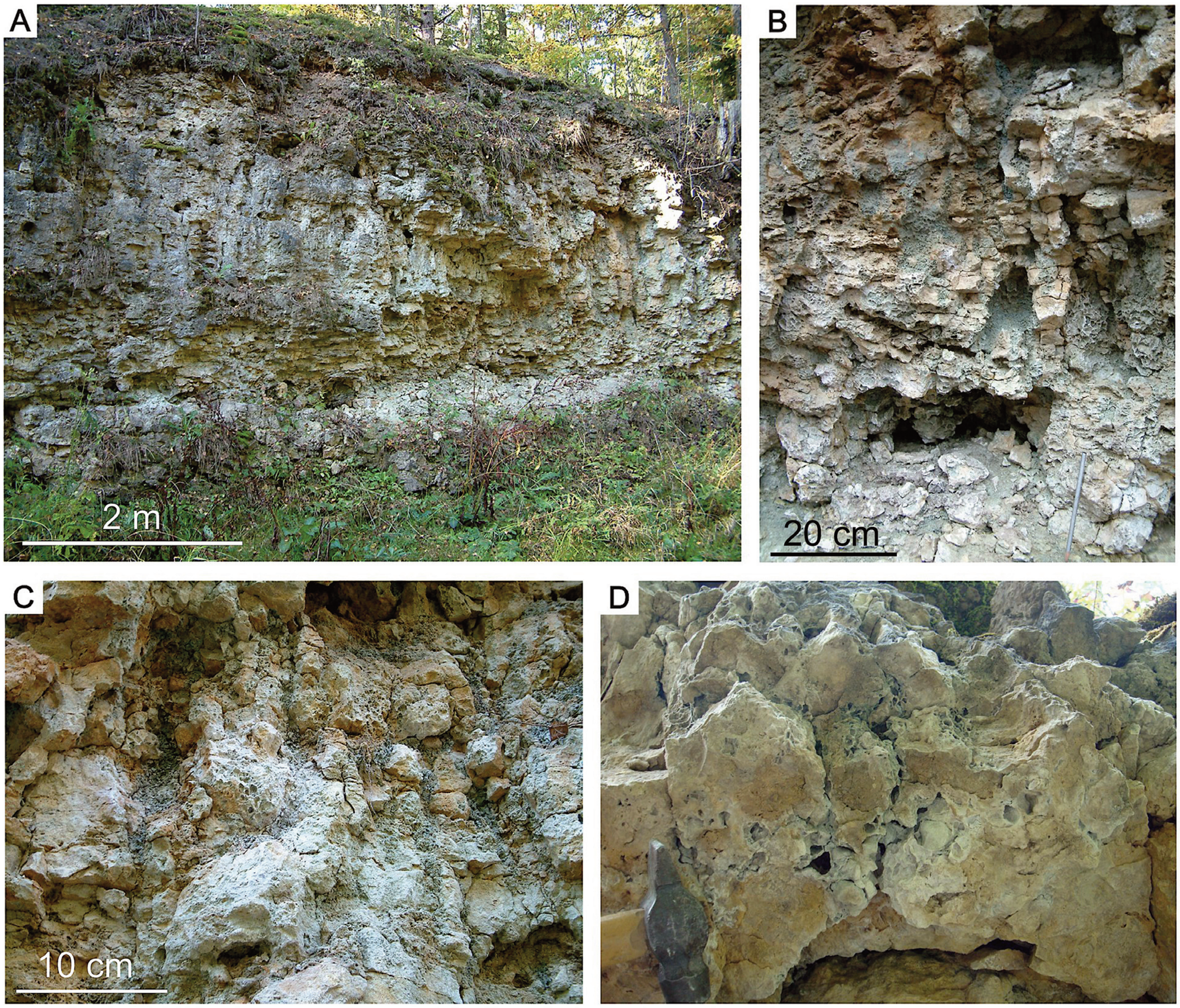

Fig. 6. Vertical structures and dolomite-clay honeycomb structures, B3 in the Nīkrāce Mb, Lētīža outcrop. **A** – vertical structures with the maximum length of 1.7 m. **B**, **C** – several vertical dolomite structures alternated with clayey zones, where the honeycomb structure is present. **D** – plan view from below, which allows us to see several round and ellipsoidal dolomite columns (brown), which are the vertical carbonate structures in cross-section. Fissures filled with clayey-dolomite material with honeycomb structures are between the dolomite columns.

Stable isotopes

In the lower part of the Šķervelis Fm (Gobdziņas Mb), in the Ātrais kalns outcrop, the value of $\delta^{13}C$ in the dolomite inclusions of the siliciclastic host rock ranges from –6.50 to –4.97‰ and $\delta^{18}O$ from –5.37 to –3.85‰ (Fig. 2). In the upper part of the Šķervelis Fm (Nīkrāce Mb), the value of $\delta^{13}C$ in the dolostone of the Lētīža succession ranges from –6.09 to –2.98‰ and $\delta^{18}O$ from –4.48 to +0.35‰. In the Šķervelis outcrop, the value of $\delta^{13}C$ in the dolostone ranges from –6.55 to –1.32‰ and $\delta^{18}O$ from –4.47 to +0.02‰. In the Ātrais kalns outcrop, the value of $\delta^{13}C$ in the dolostone ranges from –7.55 to –5.12‰ and $\delta^{18}O$ from –5.15 to –3.44‰.

In the Ātrais kalns exposure, in the most complete of the studied sections, the value of $\delta^{13}C$ is quite stable (–6.5 to –5‰) in the lower part of the Gobdziņas Mb, then gradually decreases from –5 to –7.5‰ from the middle of the Gobdziņas Mb to the upper part of the Nīkrāce Mb.

Negative excursions of the values of $\delta^{13}C$ for about 1 to 2.5‰ occur at intervals of 2–4 in the dolocretes of the Nīkrāce Mb in each of the studied outcrops (Fig. 2).

In the whole section of the Ātrais kalns exposure, the curve of $\delta^{18}O$ values often changes consistently with the curve of carbon isotope values (Fig. 2). In contrast, in several intervals of the Nīkrāce Mb, the oxygen isotope curves change in the opposite manner to the carbon isotope curves below the documented unconformity surfaces (B1 and B3 at the Lētīža site; B1 at the Šķervelis site).

Discussion

The fluvial processes were alternated with subaerial exposure and soil formation events in the studied deposits. The sedimentary and diagenetic processes were likely influenced by seasonally changeable climate and the increasing role of terrestrial environment.

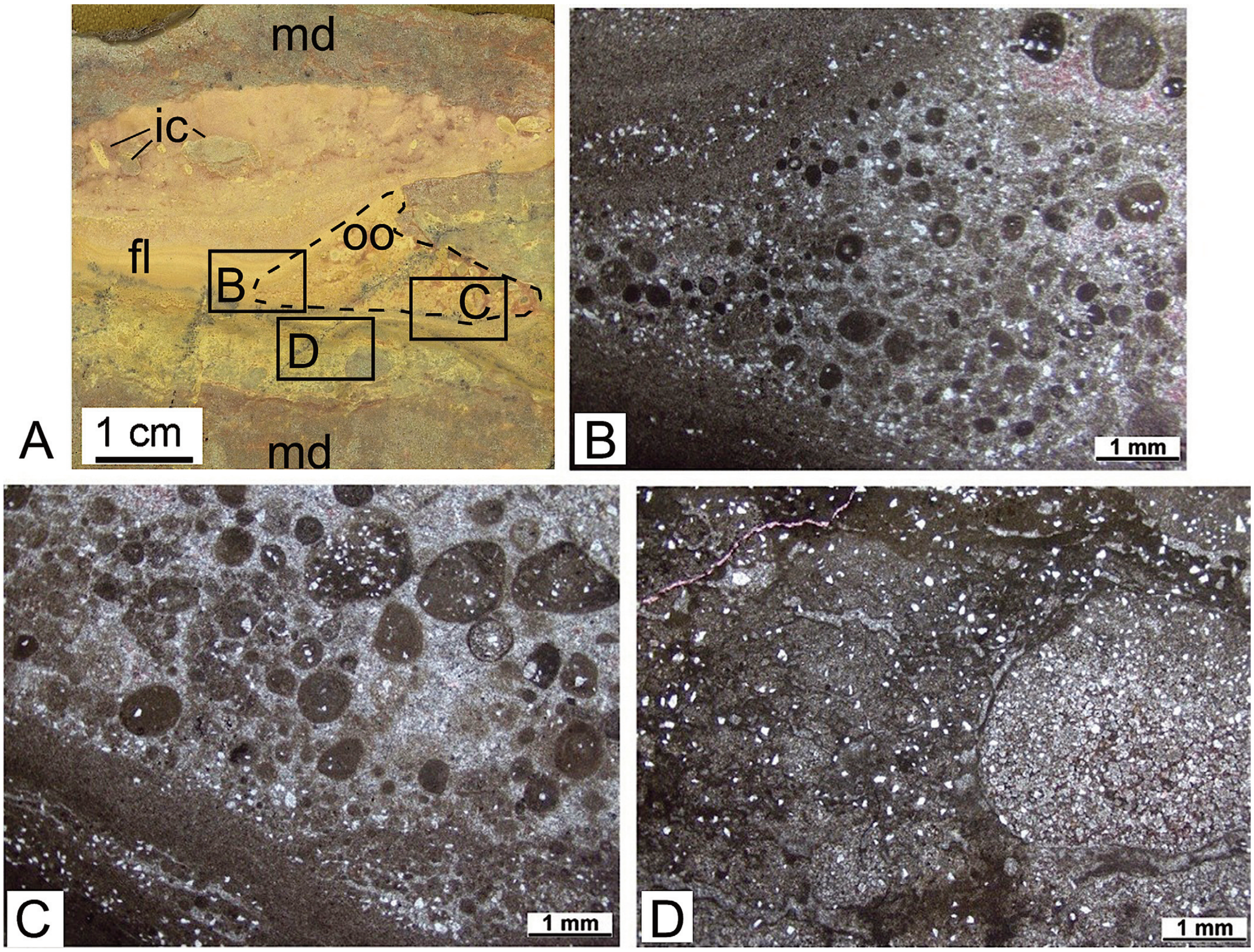

Fig. 7. Macro- (A – polished slab) and microfacies (B, C, D – thin sections, parallel polarisers) of the dolocretes of the Nīkrāce Mb, Lētīža outcrop. **A** – massive dolocrete which contains a pocket of ooids bordered by thin laminated deposits. Black rectangles – location of thin sections (B, C, D); fl – thin laminae, oo – ooids, ic – intraclasts, md – massive dolostone. **B** – pocket of ooids surrounded by thin laminated dolocrete. **C** – pocket of reversely graded ooids underlain by thin laminated dolostone. **D** – irregular clay, silt, and dolostone relationships in honeycomb dolocrete.

Origin of vertical structures

The interpretation of vertical structures present in both the dominantly siliciclastic deposits of the Gobdziņas Mb and the silty to sandy dolocretes of the Nīkrāce Mb is essential for understanding the palaeoenvironment of the study area, as they are abundant in all the sections studied.

The vertical dolomite structures in the siliciclastics of the Gobdziņas Mb resemble by shape (irregular, slightly nodular, narrow, and bifurcated downwards) the root structures described in the literature (e.g. Algeo et al. 2001). During the Late Devonian, intense evolution of plants occurred and archaeopterid forests developed widely. Trees with trunk diameters greater than 1.5 m and maximum heights of over 30 m developed (Beck 1981). Taller plants required more advanced rooting systems to obtain more water and nutrients, and it is reported that the diameter of root traces reached 10–15 cm, and their depth 1.5 m (Mora and Driese 1999; Algeo et al. 2001; Driese and Mora 2001).

The origin of the vertical columnar or tubular structures abundant in the Nīkrāce Mb is difficult to interpret, as their fabric and relationships with the surrounding dolocretes are not so clear due to diagenetic changes and the fractured fabric of the dolocretes. However, they could be plant root structures similar to those in the Gobdziņas Mb. After decay of a root, carbonate minerals can precipitate in root channels and extend outwards, cementing the surrounding deposits. Carbonate minerals usually form in and around root channels due to episodic drying of the soil over a sufficiently long period (Kraus and Hasiotis 2006). While roots as long as 1.7 m are unlikely to have been documented in the Devonian, several authors mention the possible depth of roots exceeding 1 m (e.g. Mora and Driese 1999). The presence of many small rhizoids in the dolocretes of the Nīkrāce Mb (Fig. 8D) suggests the development of vegetation in the studied deposits.

Driese et al. (1997) documented casts of tree stumps with diameters of 35–55 cm at the base and attached roots in the Famennian oxidized sandy palaeosols of the Catskill Delta Complex. The authors suggest that the tree stumps were surrounded and filled with sediment during later depositional stages. Some of the structures in the Gobdziņas Mb (Fig. 5C) may also be tree stumps, but the structures in the Nīkrāce Mb do not appear to be of this origin. They seem to cross primary sedimentary structures, indicating that they formed after the active sedimentation stages and likely developed from

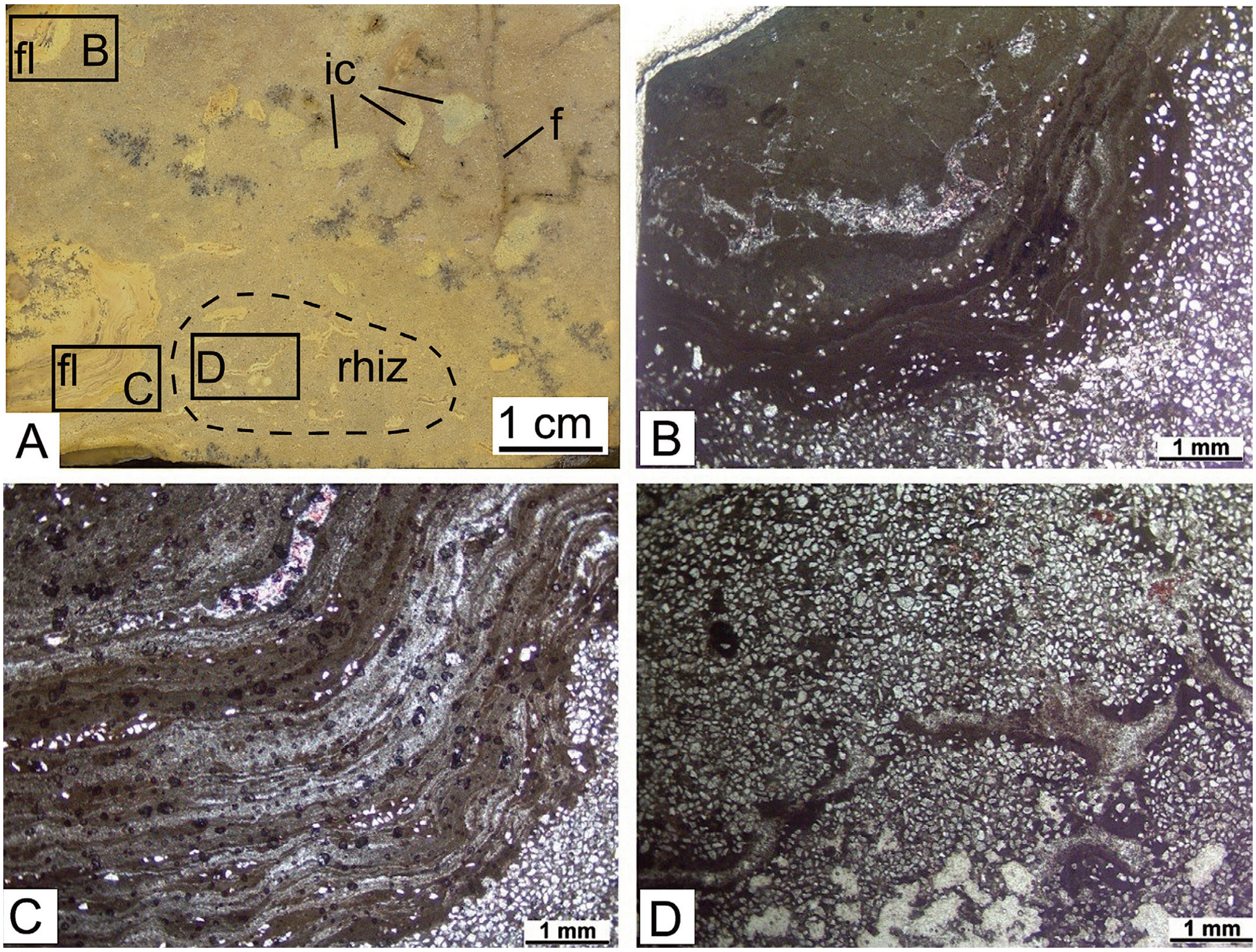

Fig. 8. Macro- (A – polished slab) and microfacies (B, C, D – thin sections, parallel polarisers) of the dolocretes of the Nīkrāce Mb, Lētīža outcrop. **A** – zones of rhizoids, thin laminated dolostone, and intraclasts in a massive dolocrete; fl – thin laminae, ic – intraclasts, rhiz – rhizoids, f – fissure. **B** – dense micrite core with a small vein network is surrounded by microcrystalline, thin laminated dolostone. **C** – microcrystalline, thin laminated dolostone with rarer irregular fine-grained sand. Calcite (pink) is crystallized in an elongated vug (upper part of the image). **D** – rhizoids in fine-grained sandy, microcrystalline dolostone.

the floodplain surface. Additionally, they are closely and regularly placed, which resembles fissure fillings or root systems.

The close and regular distribution of the structures could point to their development as a result of the shrinkage of clay-rich deposits during their subaerial exposure. Clayey soils that are influenced by cyclic shrinking and swelling, producing vertical open channels and other desiccation structures where carbonate veins can form, are called Vertisols (Tabor et al. 2017) and typically develop in seasonally wet climates (Algeo et al. 2001). Carbonate veins associated with fractures in Vertisol are documented in Triassic deposits by Dawit (2016), and calcic Vertisols are described in Carboniferous deposits by DiMichele et al. (2010). Vertisols usually consist of swelling smectite-dominated clays, but palygorskite-dominated Vertisols are also described (Heidari et al. 2008). We have not found such typical Vertisol features as slickenplanes and hummock-swale (gilgai) relief (Tabor et al. 2017), but they were probably obliterated or are difficult to distinguish due to intense diagenetic changes. The intense development of dolocretes caused the remigration and irregular distribution of clayey material in the deposits, especially in the Nīkrāce Mb, making it difficult to precisely reconstruct the initial fabric of the deposits.

The vertical structures in the Nīkrāce Mb are unlikely to be palaeokarst pipes, as they do not have the typical funnel shape (Grimes 2009). The formation of carbonate structures in soils and karstification of such deposits could not have occurred simultaneously, as different climatic conditions are required for the processes.

Prismatic (columnar, tubular) forms are typical of the B horizon of palaeosols and are also often noted in calcisols. In this case, they can form either in Vertisol along vertical cracks or as rhizocretions (Tabor et al. 2017).

In the Salnas quarry, the vertical structures are round in shape in both the sandstones of the Gobdziņas Mb and the dolocretes of the Nīkrāce Mb, most likely being plant root structures. We suggest that the vertical structures in the Šķervelis Fm are either root structures or a combination of root development and carbonatization in the vertical channels of shrunk, deeply desiccated Vertisol or Vertisol-like soils. In any case, they are obviously related to ancient soil development processes during subaerial exposure times, requiring a seasonally changeable climate (Algeo et al. 2001; Kraus and Hasiotis 2006).

Recognition of the role of fluvial and soil processes

The structures, textures, and composition of the whole Nīkrāce Mb and dolomite-containing parts of the Gobdziņas Mb indicate that they are dolocretes (Wright and Tucker 1991; Alonso-Zarza 2003; Zhou and Chafetz 2009). The values of $\delta^{13}C$ and $\delta^{18}O$ in the Gobdziņas Mb and Nīkrāce Mb fall within the typical range of those carbonate soil-groundwater formations, as described in Kearsey et al. (2012), Díaz-Hernández et al. (2013) and Casado et al. (2014): $\delta^{13}C$ ranges from –11 to 1‰ for calcretes and from –8 to 3‰ for dolocretes; $\delta^{18}O$ ranges from –14 to –2‰ for calcretes and from –8 to 2‰ for dolocretes.

Both calcretes and dolocretes can form through pedogenic (soil) processes and precipitation from groundwaters, and many structures present in carbonate crusts can form in both environments (Wright and Tucker 1991; Alonso-Zarza 2003). It is also considered that calcretes and dolocretes are often the result of a combination of both pedogenic and groundwater processes (Wright and Tucker 1991).

The downward-narrowing and branching dolomite structures present in the Gobdziņas Mb are likely root structures that grew in the ancient soil. Several features in the dolocretes of the Nīkrāce Mb indicate soil processes. The formation of clay mineral palygorskite is typically associated with soil processes in an arid climate (Alonso-Zarza 2003; Jiménez-Espinosa and Jiménez-Millán 2003; Meunier 2005), phosphorous-rich inclusions found in the Lētīža outcrop are characteristic of subaerial exposure processes (Sánchez-Román et al. 2011), and floating grains are indicative of soil processes, as they develop during the formation of carbonate minerals when siliciclastic material is moved and replaced (Kearsey et al. 2012). An increased amount of chert along with corroded quartz grains points to the dissolution of quartz, migration, and recrystallization of silica, which is a typical process for soils, particularly in the arid climate environment (Wright and Tucker 1991; Smith et al. 1997; Ringrose et al. 2005). Rhizoids are another indicator of soil processes and plant activity.

The presence of ooids and pisoids does not necessarily indicate a soil environment, but their bridge-like contacts and pendant micro-stalactite structures suggest that they are vadoids (Peryt 1983), formed in the vadose environment (Wright 1990) related to subaerial exposure surfaces. Furthermore, the thin laminated carbonate deposits alternating with zones of pisoids and ooids are typical of the upper parts of pedogenic (soil) profiles (Theriault and Desrochers 1993; Alonso-Zarza 2003; Candy et al. 2004).

The stable isotope data support the results of lithological and mineralogical studies. Several negative excursions of the values of $\delta^{13}C$ for about 1 to 2.5‰ occur in the dolocretes of the Nīkrāce Mb. The decay products of plant material have a relatively high proportion of light carbon, therefore the shift of the carbon isotope ratio to negative values represents soil intervals. This can be accompanied by the maximum influence of meteoric waters at the ground surface, indicating subaerial exposure processes (Díaz-Hernández et al. 2013; Casado et al. 2014).

In the Ātrais kalns exposure, the value of $\delta^{13}C$ is quite stable (–6.5 to –5‰) in the lower part of the Gobdziņas Mb, and gradually decreases (–5 to –7.5‰) from the middle of the Gobdziņas Mb to the upper part of the Nīkrāce Mb. This likely shows an increase in the role of meteoric waters and soil processes during the formation of these deposits (Díaz-Hernández et al. 2013; Casado et al. 2014). The trend is consistent with the lithological properties of the deposits.

The $\delta^{18}O$ values at a subaerial unconformity tend to increase due to evaporation and a decrease in the percentage of lighter ^{16}O, so the oxygen isotope curves below the unconformity surfaces change in an opposite manner to the carbon isotope curves (Goldstein 1991). In our study, such opposite change trends of both curves are characteristic of the three intervals of the Nīkrāce Mb (Lētīža and Šķervelis sites), which confirms the presence of subaerial exposure surfaces. What is more complicated to interpret is the curve of oxygen isotope values being often consistent with the curve of carbon isotope values for the Ātrais kalns site. We suppose this phenomenon reflects later diagenetic changes that partly erased the original oxygen isotope signals.

The oxygen isotope composition of carbonate rocks is highly susceptible to alteration and may reflect the composition and temperature of the fluid that acted during diagenetic processes. Thus, the oxygen isotope values of recrystallized carbonate rocks may record a relatively late episode in their water-rock interaction history (Melezhik et al. 2004).

The amount of dolocrete and soil formation features increases upwards in the geological section of the Šķervelis Fm, consistent with the changes in the amount of dolomite in the deposits, which reaches dominance (approximately 70% of the rock volume) in its upper part, Nīkrāce Mb.

Root structures were rarely found in the Devonian shallow marine carbonate and carbonate-siliciclastic deposits and were not recognized in such deposits of Famennian age (Kabanov 2021). In contrast, abundant remains of plants and their root structures were documented in the Devonian deposits formed in terrestrial lowland environments, such as river floodplains (Algeo et al. 2001; Kabanov 2021).

The Devonian succession of Latvia has been considerably influenced by marine processes (Lukševičs et al. 2012), but fluvial deposits are part of the Givetian Gauja Fm (Pontén and Plink-Björklund 2009). We suggest that the initial deposits of the Šķervelis Fm were also fluvial siliciclastics, which can be recognized by several features.

Fluvial cycles, represented by an erosional, often channel-like base, overlain by cross-bedded sandstones that formed in lingoid subaqueous dunes and bars, and topped by finer-grained sandy and silty floodplain deposits (Ponten and Plink-Björklund 2009; Nichols 2009), are present in the Ātrais kalns section of the Gobdziņas Mb (C1 to C4 in Fig. 9A). The vertical structures and other inclusions of dolomite formed on the upper surfaces of the cycles and were partially eroded during the development of subsequent fluvial channels. The irregular distribution of dolomite, its presence in vertical structures, and relation to the upper parts of the sedimentary cycles indicate that it was formed as a result of

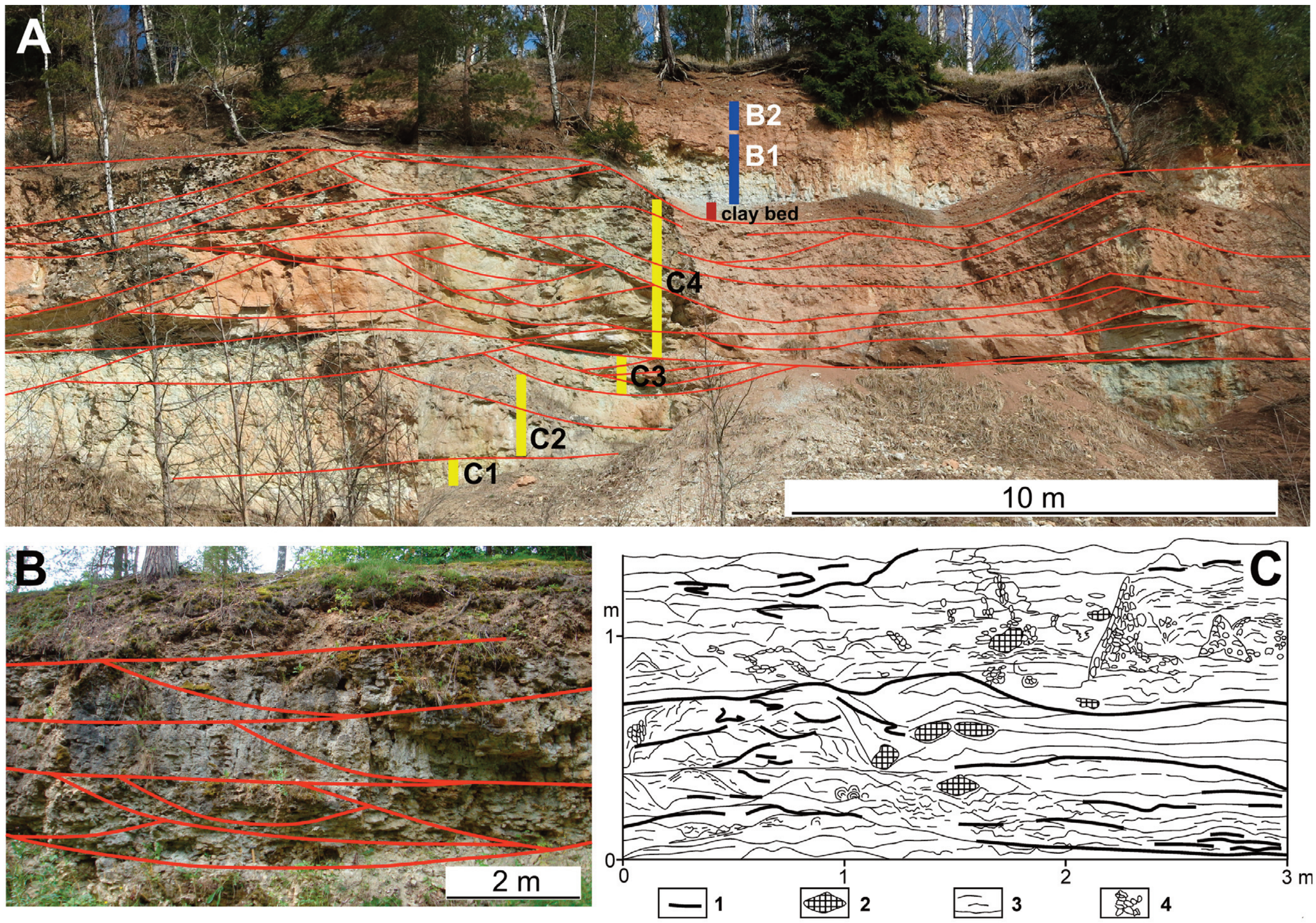

Fig. 9. Initial bedding planes and other structures recognized in the deposits of the Šķervelis Fm. **A** – Ātrais kalns outcrop. Channel structures, inclined surfaces of sand bars, and cross-bedding in the Gobdziņas Mb (red lines). Sedimentary cycles C1, C2, C3, and C4 are marked by yellow bars. Clay bed (red bar) is the upper part of the Gobdziņas Mb. Blue bars (B1 and B2) demonstrate the beds of the Nīkrāce Mb. **B** – initial channel structures (red lines) in the dolocretes of the Nīkrāce Mb in the Lētīža outcrop. **C** – structures of dolocretes of the Nīkrāce Mb in the Lētīža outcrop: 1 – bedding planes marked by clay, 2 – vugs, 3 – various sedimentary structures, 4 – honeycomb structures.

secondary processes, after the accumulation of the host siliciclastic deposits.

No structures indicative of tidal processes were found in the deposits of the Šķervelis Fm, unlike many stratigraphic units in the Middle and Upper Devonian of Latvia (e.g. Pontén and Plink-Björklund 2009; Vasiļkova et al. 2012; Stinkulis et al. 2020), including the Ketleri Fm lying immediately below the Šķervelis Fm (Lukševičs and Zupiņš 2004).

Despite the dominant dolomite and widespread secondary structures in the Nīkrāce Mb, the original sedimentary structures such as inclined, diagonal bed surfaces and cross-bedding relic fabric are often preserved (Fig. 9B, C). The irregular distribution of siliciclastic material, the presence of floating-grain structures and corroded quartz grains in the dolostone matrix also indicate that the deposits were primary siliciclastics that were obliterated by carbonate mineral formation during soil processes. Chert cement and concretions, which are often present in the dolocretes, most possibly formed as a result of dissolution of primary siliciclastic material and secondary migration of silica (Wright and Tucker 1991; Smith et al. 1997; Ringrose et al. 2005).

The possibility that the dolocretes in the Nīkrāce Mb are at least partly calcimagnesian soils, formed in host shallow marine carbonate-siliciclastic deposits (Kabanov 2021), cannot be excluded. However, no evidence of primary water-lain carbonate sedimentation has been found in the Šķervelis Fm. Instead, inclined beds and channel-like surfaces occur in all the studied successions, suggesting fluvial sedimentation.

Palaeoclimate and the unclear geological age of studied deposits

Calcretes and dolocretes typically form in semi-arid, rarer in arid climates (Alonso-Zarza 2003). A moisture deficit is necessary for carbonate mineral to accumulate in soil during dry seasons and to remain preserved from dissolution in wet seasons. Studies of root structures also indicate that drying of soil for an extended period is required for carbonate minerals to precipitate in and around root channels (Kraus and Hasiotis 2006).

During the Middle and Late Devonian, the study area was situated in a vast epeiric basin covering the eastern part of the Euramerican continent, at about 5–10° of southern latitude (Scotese 2014). Climate modelling shows strong influence of seasonally wet monsoonal climate in the region (De Vleeschouwer et al. 2012, 2014). However, the situation for the territory of Latvia is complicated due to its proximity to the large Euramerica landmass, making the dominant temperature and moisture regime unclear (De Vleeschouwer et al. 2014). Interpretation of the Famennian palaeoclimate in the Baltic Devonian Basin is problematic due to the lack of clear climate indicators, making the dolocretes of the Šķervelis Fm valuable for evaluating the palaeoclimate.

The Appalachian foreland basin during the Late Devonian and Carboniferous developed in low latitudes under a monsoonal climate (Mora and Driese 1999; Driese and Mora 2001). Such a warm, changeable moisture climate is believed to be favourable for the development of Vertisols and other vertic structures in soils, as well as for the accumulation of carbonate minerals in fissures and root channels (Mora and Driese 1999; Driese and Mora 2001). Our interpretation of soil development and carbonate mineral distribution in vertical structures supports the idea of a monsoonal climate in southeastern Euramerica during the Late Devonian (De Vleeschouwer et al. 2012, 2014).

The deposits of the Šķervelis Fm formed after some regression of the basin, as there are no indications of tidal processes, unlike the slightly older tidally influenced, likely deltaic deposits of the Ketleri Fm (Lukševičs and Zupiņš 2004). The deposits of the Gobdziņas Mb formed in a fluvial environment alternating with soil processes, affecting the deposits of each observed fluvial cycle. However, it is challenging to evaluate the relative timing of either process. The amount of dolomite increased over time, and the youngest deposits studied (Nīkrāce Mb) are well-expressed dolocretes with only remnants of siliciclastic deposit structures and textures.

A wider use of the study results is limited due to the unclear age of the studied deposits. The lower possible limit of the Šķervelis Fm is the middle-upper part of the *Palmatolepis expansa* Zone (Upper Famennian), but its upper possible limit is uncertain – from the uppermost Famennian to the Tournaisian or even Visean. The intense accumulation of siliciclastic material of the Šķervelis Fm is a probable reason why the environmental and lithological changes documented for the Devonian and Carboniferous transition, for example the Hangenberg event (Kaiser et al. 2016), could not be recognized in the studied deposits.

The intensification of soil processes and carbonatization of the studied deposits was probably influenced by a short-term, intensive glaciation at the end of the Famennian, which caused a drop in the water level (Brand et al. 2004). The regression may have allowed more space and time for the soil processes. The impact of glaciation on the climate near the palaeoequator is unclear, but aridification or more intense seasonality cannot be excluded. The positive carbon isotope excursion between –6.5 and –4 to –2‰ documented for the Nīkrāce Mb in the Šķervelis outcrop may coincide with similar carbon isotope value trends associated with the Hangenberg event (Brand et al. 2004; Kaiser et al. 2016).

Conclusions

The deposits of the Šķervelis Fm (Upper Famennian to Tournaisian) in southwestern Latvia formed as a result of the repeated alternation of fluvial siliciclastic sedimentation and formation of carbonate-rich soils. Over time, soil development became more intense, leading to the development of dolocretes with remnant structures and textures of siliciclastic deposits.

The vertical, columnar to tubular dolomite structures in the deposits of the Šķervelis Fm are either root structures or combined root and Vertisol-like soil development features. They are related to ancient soil development processes that occurred during subaerial exposure in a seasonally changeable climate.

The monsoonal, seasonally wet climate of the Late Devonian in the eastern part of the Euramerica continent was favourable for alternating fluvial and soil processes, as well as for the preservation of carbonate material in the dolocretes. The end-Famennian glaciation and associated sea-level fall may have contributed to the more prolonged period of soil formation and the intensification of dolocrete development.

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Dolokreedid Läti Devoni Šķervelise kihistu ränirikastes purdkivimites

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Edela-Lätis asuva Šķervelise kihistu ränirikkaid purdkivimeid ja dolomiite uuriti paljandites, poleeritud/lihvitud palade ja õhikute abil ning geokeemiliste meetoditega, sealhulgas stabiilsete isotoopide analüüsiga. Vooluveelised räni purdsetete kuhjed vaheldusid korduvalt mulla moodustumise ja karbonaatide settimisega. Kui mulla protsessid muutusid domineerivaks, moodustusid kuni 6 m paksused dolokreedid, säilitades siiski ka algseid struktuure ja tekstuure. Mullaprotsesside olulist rolli näitab ooidide ja pisoidide olemasolu koos õhukeste vahekihikeste, ränikivide, fosfaatsete suletiste ja risoididega ning stabiilsete isotoopide väärtused. Omapärased kuni 1,7 m pikkused vertikaalsed savi-dolomiidi struktuurid on juure struktuurid või nende kombinatsioon vertisoli-sarnase mulla arenguga. Mullaprotsesside laialdast levikut ja vertikaalsete struktuuride moodustumist soodustas hooajaliselt niiske mussoonkliima. Fossiilide vähesus uuritud setetes ei võimalda vanust täpselt määrata, kuid tõenäoliselt moodustus uuritud läbilõike ülemises osas olev paks dolokreetide kiht Devoni lõpuperioodil toimunud jäätumise ja sellega seotud mere regressiooni ajal.