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Dolocretes in the Amata Formation of Latvia as indicators of climate aridification during the Givetian–Frasnian transition

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ABSTRACT

This study focuses on the description and interpretation of the origin of dolocretes and their siliciclastic host rocks in the upper part of the Amata Formation (Fm) in four exposures in Latvia. The dolocretes occur in at least four intervals. The composition and structure, as well as stable oxygen and carbon isotope data of the two upper dolocrete intervals, suggest that they developed in soils. The dolocretes correspond to an episode of climate change from warm, moist to drier and hotter conditions, which started in the Late Givetian and continued to the Early–Middle Frasnian. They formed during a short-lived sea-level fall, which took place after a longer sea-level rise trend. The diversity of vertebrate fossils decreases from the lower to the upper part of the Amata Fm, which is consistent with the sea-level fall and gradual climate change marked by the studied dolocretes in the upper part of the Amata Fm.

Introduction

The Amata Formation (Fm) of Latvia and Estonia corresponds to the lowermost part of the Frasnian (Fig. 1). In terms of lithologic composition, it belongs to the uppermost part of a dominantly siliciclastic succession representing the Lower Devonian to the lowermost Upper Devonian. The sites studied here are in the Main Devonian

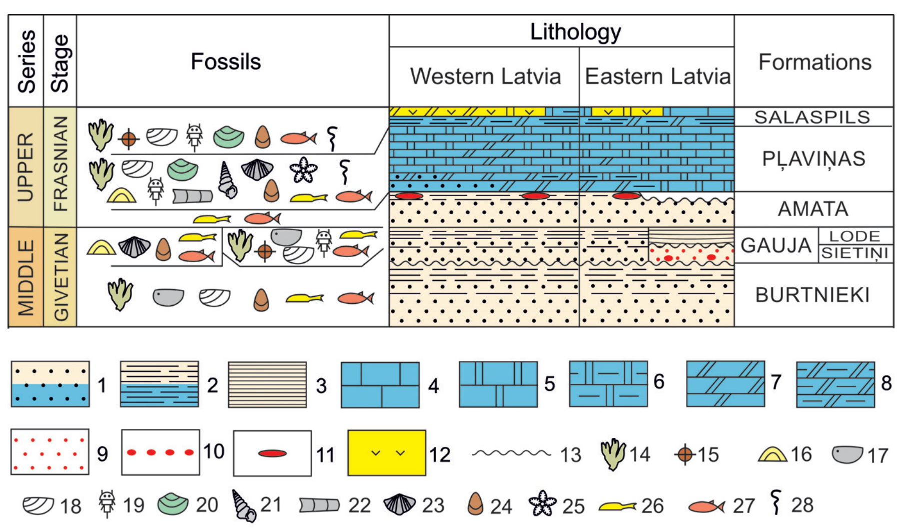

Fig. 1. Lithology and fossils of the Givetian and Lower–Middle Frasnian deposits in Latvia (modified from Lukševičs and Stinkulis 2018). 1 – sandstone, 2 – siltstone and clay, 3 – grey very fine clay, 4 – limestone, 5 – dolostone, 6 – clayey dolostone, 7 – dolomitic marl, 8 – clayey dolomitic marl, 9 – quartzose sandstone, 10 – quartz gravel and pebbles, 11 – dolocretes, 12 – gypsum rocks, 13 – unconformity surfaces, 14 – algae and plant macroremains, 15 – spores of algae, 16 – stromatopores, 17 – ostracods, 18 – conchostracans, 19 – eurypterids, 20 – bivalves, 21 – gastropods, 22 – cephalopods, 23 – articulate brachiopods, 24 – lingulate brachiopods, 25 – echinoderms (crinoids), 26 – agnathans, 27 – fishes, 28 – trace fossils.

Field (MDF), which covers the territory of the Baltic States and the Pskov, Leningrad, and Vologda oblasts of Russia. The western part of the MDF (WMDF) was a shallow epeiric basin in the southeastern part of the Euramerica continent (Lukševičs et al. 2012; Scotese 2014). The Amata Fm is composed of fine-grained sandstones and clayey deposits, and is considered as a transgressive unit (Kuršs 1992) and interpreted as tidally dominated estuarine deposits (Pontén and Plink-Björklund 2009).

Carbonate formations in the upper part of the Amata Fm of Latvia were noted (Kuršs et al. 1981a; Kuršs 1992), but the conditions of formation of carbonate nodules were usually not interpreted. However, such nodules were never reported from the Amata Fm of Estonia (Kleesment and Mark-Kurik 1997) or from the upper part of the Šventoji Fm of Lithuania (Narbutas 1981, 2004). Recently, such carbonate nodules and layer-like bodies interpreted as dolocretes were found at almost every site in Latvia where the upper part of the Amata Fm is exposed, suggesting that the dolomitic formations discussed here were probably formed over an area of hundreds to thousands of square kilometres. Dolocretes were documented in the western part of Latvia, the historical region of Kurzeme (Stinkulis and Spruženiece 2011; Fig. 2), and at several levels in the upper part of the Amata Fm in Vizuļi

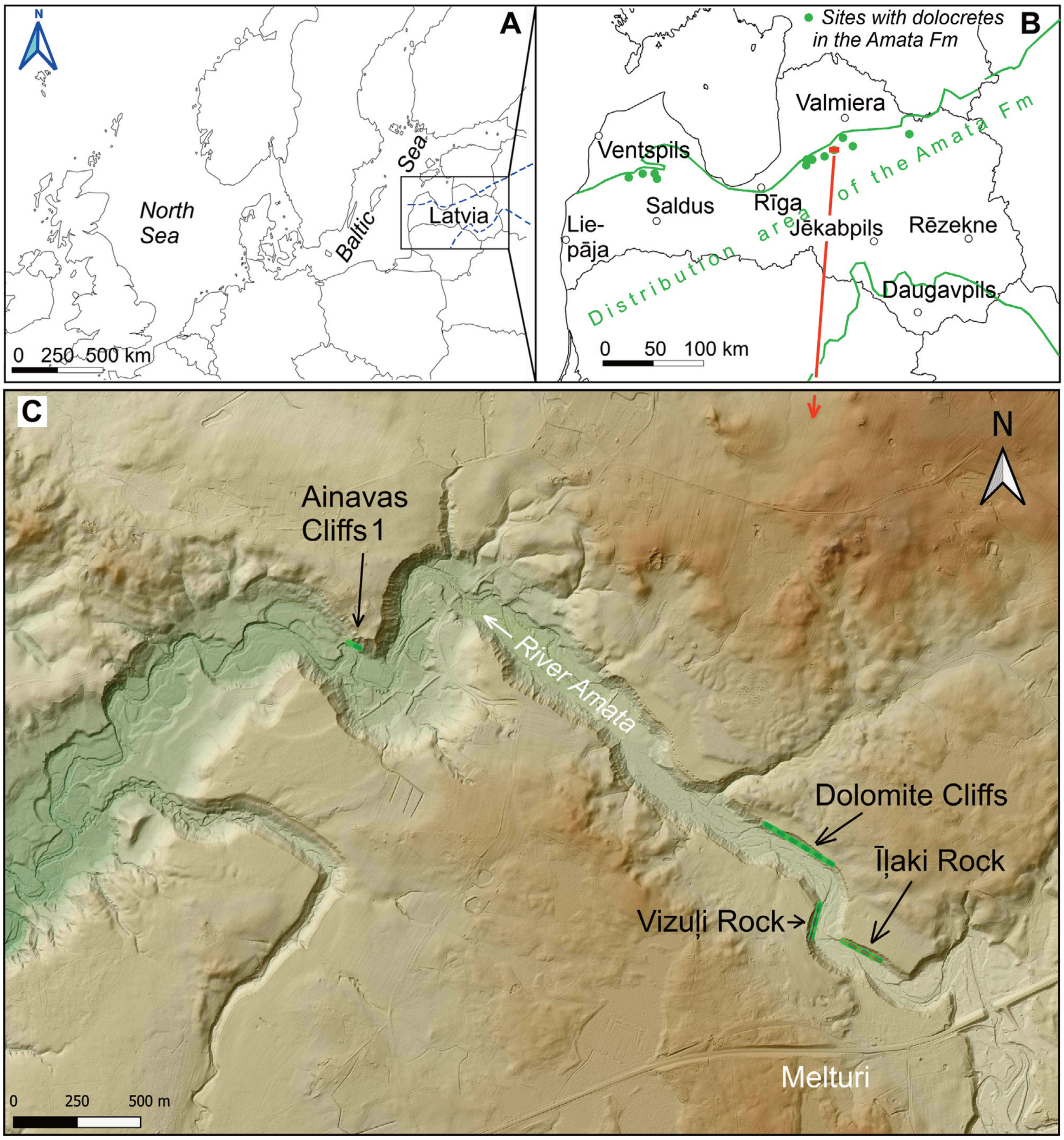

Fig. 2. Study area and sites. **A** – location of Latvia in northern Europe. The blue dashed line marks the distribution limit of the Upper Devonian deposits in the western part of the Main Devonian Field. **B** – location of the study area and sites with dolomite concretions in the upper part of the Amata Formation (contours from Eurostat). **C** – location of the study sites (LiDAR of Latvia; kartes.geo.lu.lv). Coordinates of the study sites: Īļaki Rock 57°13′29.2″ N, 25°13′33.4″ E; Vizuļi Rock 57°13′30.4″ N, 25°13′24.2″ E; Dolomite Cliffs 57°13′39.8″ N, 25°13′26.4″ E; Ainavas Cliffs 1 57°14′08.8″ N, 25°11′38.7″ E.

Rock (Pipira et al. 2015) in the historical region of Vidzeme. Detailed field and laboratory studies in the upper part of the Amata Fm in Vizuļi Rock allowed us to suggest that groundwater processes most likely influenced dolocrete formation in the lower part of the outcrop, while soil processes and subaerial exposure influenced the formation of massive and nodular dolocretes in two intervals in the upper part of the outcrop section (Pipira et al. 2015). The features of soil processes testify to a regressive development in the upper part of the Amata Fm. The general interpretation of the Amata Fm as tidally dominated estuarine deposits (Pontén and Plink-Björklund 2009) and the occurrence of dolocretes in the upper part of the formation (Pipira et al. 2015) make the situation at the end of the Amata time controversial, as to when and how the transgressive development turned into regressive development.

Dolocretes are carbonate crusts composed mainly of dolomite of groundwater-related or pedogenic origin. Calcretes or caliche, which consist mainly of calcium carbonate minerals, are the better known, more frequently documented, and more widespread analogues of dolocretes. However, both types of carbonate crust form near the Earth's surface due to the influence of phreatic (groundwater calcretes and dolocretes) or vadose (pedogenic calcretes and dolocretes) conditions, and the precipitation of authigenic calcium carbonate in the host rock (Wright and Tucker 2009). The identification of the origin of a carbonate crust – groundwater or pedogenic – is often not an easy task. Pedogenic calcretes can be identified by several features, mostly their pattern of vertical changes in the soil profile (Goudie 1973), as well as by abundant biogenic features (Wright and Tucker 2009). Groundwater calcretes are often of massive fabric. They lack internal horizons and biogenic features but have sharp boundaries (Wright and Tucker 2009).

Subsequent diagenetic processes may preserve the original mineral composition of the calcretes or transform them into dolocretes, e.g. due to fast precipitation of calcium carbonate, which causes a systematic decrease in the Ca/Mg ratio in groundwater and the progressive replacement of calcite by dolomite (Dixon 2010). Nowadays, calcretes usually form in arid to semiarid climates with a mean annual precipitation of less than 500−600 mm (Alonso-Zarza 2003). During the Pleistocene, dolocretes developed even as far from the equator as southern Australia (Dixon 2010), where the climate cycled rapidly between icehouse phases with cold, dry conditions and greenhouse phases with warmer and wetter conditions. The presence of calcretes and dolocretes indicates possible breaks in sedimentation and subaerial exposure over time; they are thus important indicators of certain palaeogeographic and palaeoclimatic conditions (Wright and Tucker 2009). However, the causes of dolocrete formation at the end of the Amata Regional Stage (RS) still remain poorly understood.

The composition of deposits within the WMDF changes from mainly sandy sediments of the Middle Devonian section, including the Gauja Fm, and quartz sands of the Sietiņi Fm, to gypsum-rich deposits of the Salaspils Fm (Fig. 1), obviously indicating a climate change from humid to arid. The dolocretes of the Amata Fm formed just before the basin-wide conversion from siliciclastic to carbonate deposition, and their study can help to understand the reasons for these changes. The aim of this study is the interpretation of the conditions of dolocrete formation and the sedimentary environment of their siliciclastic host rocks in the upper part of the Amata Fm. Data on the sea-level and global climate changes close to the Givetian–Frasnian boundary are also briefly discussed. The distribution of fossils in the Amata Fm is analysed as well. This study should allow the identification of the transgressive or regressive development trends during the formation of the deposits of the Amata Fm and the trends of climate changes during the same time.

Geological setting

The Amata Fm in Latvia and Estonia forms the upper unit in the Lower Devonian to lowermost Upper Devonian dominantly siliciclastic succession, cropping out in a relatively narrow belt known as the MDF, in the northwestern part of the East European Platform. This area of exposed Devonian deposits consists of two parts separated during the post-Visean denudation. The WMDF continues through Estonia, Latvia, Lithuania, the eastern part of the Baltic Sea floor, and the northern part of Belarus, which is sometimes referred to as the Devonian Baltic Basin (Pontén and Plink-Björklund 2009) or the Baltic Devonian Basin for convenience (Lukševičs et al. 2012). The eastern part corresponds to the territory of the Leningrad, Pskov, Novgorod, and Vologda regions of northwestern Russia (e.g. Lukševičs et al. 2018). The Devonian succession in the WMDF is represented by various siliciclastics, dolomites, limestones, gypsum rocks, and mixed-type deposits. There are distinct changes in the composition of deposits from the upper Givetian to the Lower–Middle Frasnian in the WMDF.

The deposits corresponding to the Gauja RS, upper Givetian, are represented by fine- to coarse-grained sandstones, as well as siltstones and clays (Kuršs et al. 1981c). Three formations correspond to the Gauja RS in Latvia (Fig. 1). The Gauja Fm (western and central part of the WMDF) is composed of quartz-feldspar sandstone, illite clays, and siltstones. The Sietiņi Fm (lower part of the Gauja RS in the northeastern part of the WMDF) is represented by white quartzose sandstones. High quartz content in the light mineral fraction, as well as dominance of zircon, tourmaline, and staurolite in the heavy transparent mineral fraction, indicates that the deposits were influenced by strong chemical weathering (Kuršs 1992). The Lode Fm (upper part of the Gauja RS in the northeastern part of the WMDF) is composed of clays and siltstones. The content of kaolinite is higher in the clayey deposits in comparison with other intervals of the Devonian siliciclastic succession of the WMDF, which also indicates the influence of continental chemical weathering (Kuršs 1992). The deposits of the Gauja RS formed in delta plain to delta slope settings (Pontén and Plink-Björklund 2007). Both the Gauja and Amata Fms of Latvia correspond to the undivided Šventoji Fm in Lithuania, which consists of sandstones, siltstones, and clays deposited in a lagoonal environment (Narbutas 2004).

The Amata Fm corresponds to the Amata RS, which in Latvia is attributed to the lowermost Frasnian, just above the

Table 1. Stratigraphy of the Givetian to Middle Frasnian in the Main Devonian Field (based on Narbutas 2004; Ivanov et al. 2012; Mark-Kurik and Põldvere 2012; Lukševičs and Stinkulis 2018; Lukševičs et al. 2018; Plax and Zaika 2020)

SYSTEM	SERIES	STAGES	Standard conodont zones	Regional placoderm zones	Regional stages	Formations, beds: Latvia	Formations, beds: Estonia	Formations, beds: Lithuania	Formations, beds: NW Russia	Belarus: Regional stages	Belarus: Formations
DEVONIAN	UPPER	FRASNIAN	hassi	*Bothriolepis traudscholdi*	DUBNIKI	Salaspils	Dubniki	Tatula	Dubniki	SARGAEVO	Vedrich
					PĻAVIŅAS	Pļaviņas	Chudovo	Kupiškis	Chudovo		Saria
			punctata	*Bothriolepis cellulosa*			Pskov	Suosa	Pskov		
			transitans				Snetnaya Gora	Jara	Snetnaya Gora		
			falsiovalis	*Bothriolepis prima – B.obrutschewi*	AMATA	Amata	Amata	Šventoji	Podsnetogorskie	ZHELON	Degtyarevo
									Staritsa		Zhelon
	MIDDLE	GIVETIAN	disparilis	*Asterolepis ornata*	GAUJA	Gauja: Lode	Gauja		Oredezh	UBORT	Ubort
						Gauja: Sietiņi					
			hermanni-cristatus	*Watsonosteus*	BURTNIEKI	Burtnieki	Burtnieki	Butkūnai	Upper Luga	POLOTSK	Moroch
			varcus	*Asterolepis dellei*							Stolin

Givetian–Frasnian boundary (Lukševičs and Stinkulis 2018). Deposits corresponding to the Amata RS are widely distributed in the Baltic countries and the northwestern part of Russia. Several formations correspond to the Amata RS in the territory of the MDF (Table 1).

The overlying Pļaviņas Fm (Lower–Middle Frasnian) in Latvia is composed of dolomites, dolomitic marls, and clays (Fig. 1). Dolomite pseudomorphs after halite are present in dolomitic marls of the lower part of the Pļaviņas Fm (Sorokin 1981), indicating at least episodic development of a hypersaline environment. The dominant part of the formation is composed of pure dolostones, rather often containing stromatoporoid, gastropod, and brachiopod fossils. These deposits formed in a marine basin with normal salinity (Lukševičs et al. 2012).

The Pļaviņas Fm is followed by the Salaspils Fm (Middle Frasnian), represented by carbonate deposits, clays, and gypsum rocks (Fig. 1). The composition of sedimentary rocks varies significantly both in individual sections and across the distribution area. The gypsum-rich deposits likely accumulated in restricted hypersaline lagoons or bays, which developed among the parts of the basin with less saline water. The association of organisms is much poorer than in the Pļaviņas Fm (Sorokin 1981; Lukševičs et al. 2012). After the accumulation of deposits of the Salaspils Fm until the end of the Frasnian, the composition of the deposits changed several times from carbonate to sandy and clayey, and back. During the Famennian, the epicontinental basin retreated to the southwest, but the composition of the deposits changed several times from predominantly carbonate to mainly siliciclastic (Lukševičs et al. 2012).

The factors that influenced such repeated, considerable changes in the composition of deposits during the development of the WMDF basin have not been studied in detail. Nevertheless, the above-mentioned changes from sandy sediments of the Gauja Fm and quartz sands of the Sietiņi Fm to gypsum-rich deposits of the Salaspils Fm obviously indicate a climate change from more humid to arid. The dolocretes of the Amata Fm formed just before the basin-wide conversion from siliciclastic to carbonate deposition, and their study can help to understand the reasons for these changes.

Due to the lack of conodonts in the siliciclastic deposits of these formations and the impossibility of precisely correlating miospore and regional vertebrate zones with standard conodont zonation, the age of the Amata RS in the territory of the MDF is still controversial (Lukševičs et al. 2012, 2018). At least four versions of the position of the boundary between the Middle and Upper Devonian in the MDF have been proposed in the past: between the Burtnieki and Gauja RSs, between the Gauja and Amata RSs, within the Amata RS at the base of the Podsnetogorskie beds, and at the base of the Snetnaya Gora beds of the Pļaviņas RS (for a detailed discussion see Esin et al. 2000; Mark-Kurik and Põldvere 2012; Lukševičs et al. 2018).

In the most recent studies, the base of the Amata RS has been usually accepted as the boundary between the Middle and Upper Devonian. The deposits corresponding to the Amata RS – the Amata Fm in Latvia and Estonia, the upper part of the Šventoji Fm in Lithuania, the Zhelon beds and Degtyarevo Fm in Belarus, and the Staritsa and Podsnetogorskie beds in northwestern Russia, or at least their upper part – have most commonly been treated as the earliest Late Devonian in age (Kruchek et al. 2001; Lukševičs et al. 2012, 2018; Mark-Kurik and Põldvere 2012; Glinskiy and Mark-Kurik 2016; Plax and Zaika 2020).

All these lithostratigraphic units are characterised by a moderately diverse fossil fish assemblage corresponding to the *Bothriolepis prima* and *B. obrutschewi* vertebrate zones for the lower and upper parts of the Amata RS, respectively (Esin et al. 2000; Lukševičs et al. 2018). At least 21 vertebrate taxa were reported from the Amata RS (Esin et al. 2000), but only 18 of them were recorded in the Amata Fm in Latvia (Lyarskaya and Lukševičs 1992). Invertebrates have not been found in the deposits of the Amata Fm; there are only rare records of conchostracans in the upper part of the formation (Lyarskaya 1981).

All four sections described in this study are located on both banks of the River Amata downstream of the Melturi settlement and bridge, at a total distance of 2 km from each other (Fig. 2). This outcrop belt is likely the best exposure area for the Amata Fm in Latvia, especially its dolocrete-bearing upper part. Dolocrete samples from Īļaki Rock, Dolomīti Cliffs, and Ainavas Cliffs 1 were collected for sedimentological, mineralogical, and geochemical analyses, including the analysis of stable carbon and oxygen isotopes. The site Ainavas Cliffs 1 is named differently from another exposure known as Ainavas Cliffs, which is located 300 m to the northeast of Ainavas Cliffs 1. Dolocretes from Vizuļi Rock were analysed and interpreted in previous studies (Pipira et al. 2015), and these data are used here for comparison.

Materials and methods

Detailed logging of the Devonian succession was carried out for four outcrops along the River Amata downstream of the Melturi settlement and road bridge in northern Latvia (Fig. 2). During the field studies, the macrostructures, texture, and bedding of the Amata Fm deposits were studied and geological sections were compiled. Vizuļi Rock was documented by Daiga Pipira and Ģirts Stinkulis in 2013, Ainavas Cliffs 1 by Ginta Vasiļevska and Ģirts Stinkulis in 2016, and Īļaki Rock and Dolomīti Cliffs by Marianna Meire-Kārkle in 2017. The sedimentological logs were constructed for the upper part of the Amata Fm (5.2–7.9 m thick) and the lowermost part of the overlying Pļaviņas Fm. Lower portions of the Amata Fm were not documented, because the deposits do not contain notable dolomite nodules, veins, or other features of pedogenic or groundwater-related geological processes. The siliciclastic deposits of the Amata Fm in their whole thickness have been documented in detail by Pontén and Plink-Björklund (2009).

Vizuļi, Īļaki, and Dolomīti sections were sampled for further analysis of dolocretes in polished specimens, thin sections, and for geochemical investigation. Samples were taken from every part of the successions that contain dolomite concretions and veins. Due to the presence of metres-thick pure siliciclastic intervals and the irregular distribution of carbonates, the frequency of sampling varies considerably in the sections. Dolocretes were documented in polished slabs and thin sections (11 from Vizuļi, 13 from Dolomīti, and 24 from the Īļaki site) prepared at the Department of Geology, Faculty of Science and Technology (previously the Faculty of Geography and Earth Sciences), University of Latvia.

Stable carbon and oxygen isotope compositions ($\delta^{18}O$ and $\delta^{13}C$) were analysed in the dolomicritic material of dolocrete samples. The dolocrete material taken from the Īļaki (24 samples) and Dolomīti (13 samples) outcrops was analysed by Tõnu Martma at the Tallinn University of Technology. The dolocrete material from Vizuļi Rock (11 samples) was analysed at the University of Tartu. The weight of samples was 0.4–1.9 g. Sampling was performed on the surface of polished specimen slabs, with a drill designed for ceramic and glass drilling. Veins were mainly sampled, but some admixture of matrix material may have occurred. The material was taken from dolomicrite, possibly also from coarser-crystalline dolomite, but without admixture of clay or calcite. In both laboratories (Tallinn University of Technology and University of Tartu), the samples for stable carbon and oxygen isotope analyses were powdered to a fine silt size with a ceramic pestle and mortar and then treated with 99% phosphoric acid at 70 °C for 2 h in a GasBench II preparation line connected online to a Thermo Scientific Delta V Advantage continuous flow isotope ratio mass spectrometer.

At the Tallinn University of Technology, the samples were measured using three standards (for each GasBench row there were three standards and five samples): laboratory standard TLNC1 $\delta^{13}C = 2.2‰$, $\delta^{18}O = –9.11‰$; KH2 (DDR) $\delta^{13}C = 1.97‰$, $\delta^{18}O = –2.96‰$; NBS18 (IAEA) $\delta^{13}C = –5.01‰$, $\delta^{18}O = –23.0‰$. TLNC1 was calibrated using international IAEA standards: NBS19 $\delta^{13}C = 1.95‰$, $\delta^{18}O = –2.2‰$; LSVEC $\delta^{13}C = –46.6‰$, $\delta^{18}O = –26.47‰$; NBS18 $\delta^{13}C = –5.01‰$, $\delta^{18}O = –23.0‰$. At the University of Tartu, the measurements were performed according to IAEA standards: NBS19 $\delta^{13}C = 1.95‰$, $\delta^{18}O = –2.2‰$; LSVEC $\delta^{13}C = –46.6‰$, $\delta^{18}O = –26.47‰$; NBS18 $\delta^{13}C = –5.01‰$, $\delta^{18}O = –23.0‰$. Analytical precision (2σ) was 0.1‰. The results are expressed as per mil deviations relative to the 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 acid–CO_2 fractionation; the factor $\alpha = 1.00913$ (Rosenbaum and Sheppard 1986).

The geological logging and the results of field and laboratory analyses of Vizuļi Rock have been partly published previously (Pipira et al. 2015). These data are also used for comparison and additional interpretations, which are provided in the present study.

Results

Siliciclastic deposits of the upper part of the Amata Formation

A general fining-upward trend occurs in the studied upper part of the Amata Fm. The lower part of the documented interval of the Amata Fm, 1.8–4.2 m thick, is composed of very fine-grained to fine-grained trough cross-bedded sandstones, with 0.1–0.3 m thick cross-beds (Fig. 3). The sandstones are light coloured, rich in an admixture of greenish-grey mica material. Trough cross-bedded sand accumulated in lingoid subaqueous dunes, which migrate in rapid traction currents (Pontén and Plink-Björklund 2007). More rarely, the

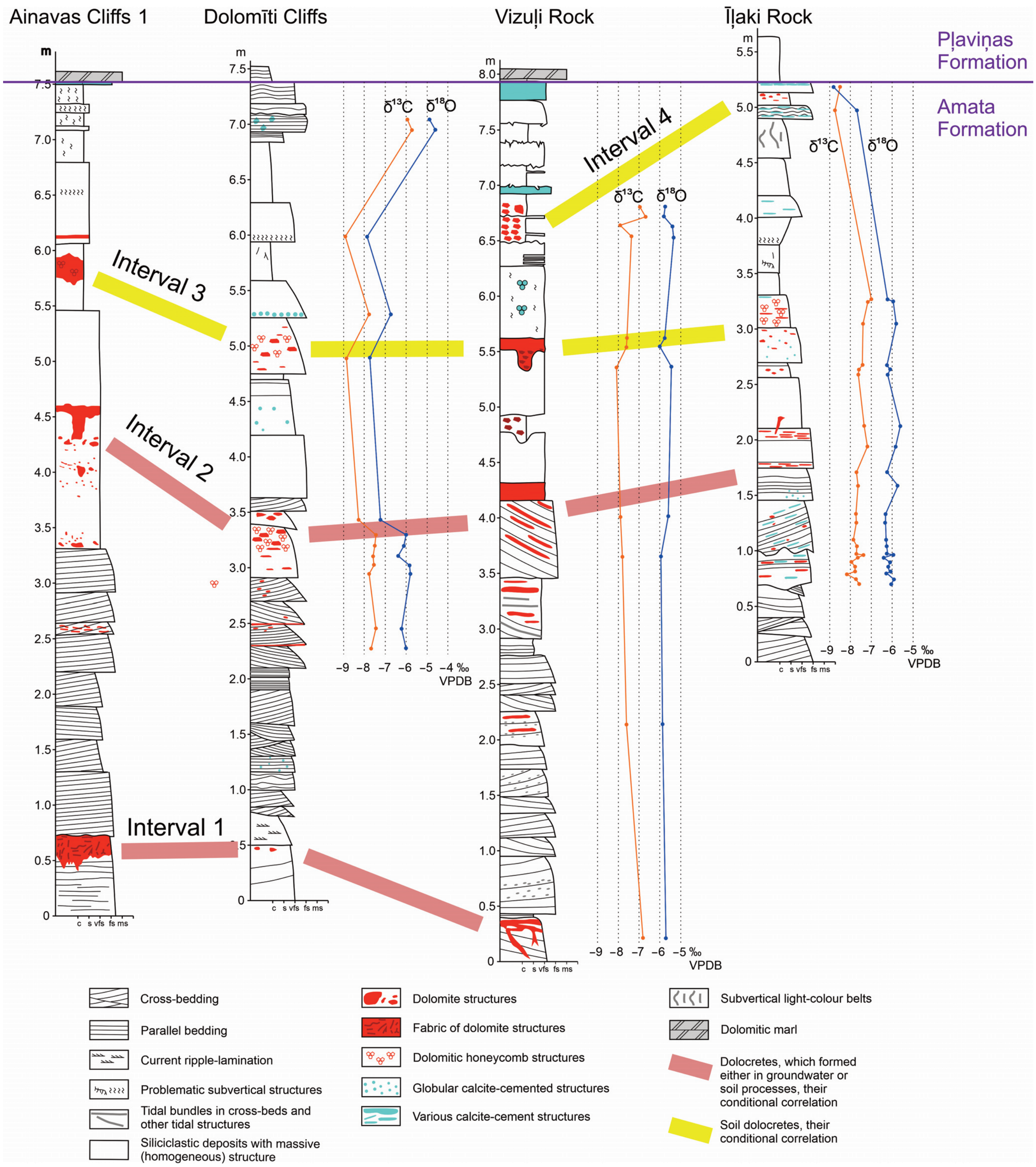

Fig. 3. Geological sections with stable isotope curves. They are approximately correlated according to lithological features. Abbreviations: c – clay, s – silt, vfs – very fine-grained sand, fs – fine-grained sand, ms – medium-grained sand, VPDB – Vienna Peedee Belemnite.

deposits are parallel-bedded, which indicates either the existence of low, flat subaqueous dunes, or lower energy settings.

The mica admixture allows to distinguish well-expressed tidal rhythmites (tidal bundles), which indicate the influence of tidal processes on sedimentation (Davis 2012). Greyish and greenish clay clasts are also present in the sandstone. In rare cases, the sandstone exhibits current ripple-lamination structures. Studies of complete successions of the Amata Fm indicate that such very fine-grained to fine-grained cross-bedded sandstones with tidal features are typical of this formation in general (e.g. Pontén and Plink-Björklund 2009; Stinkulis and Upeniece 2011).

Rather homogeneous, very fine-grained, more rarely fine-grained sandstones, with a few interlayers of clayey to silty material, follow in the next 1.5–2 m of this succession (Fig. 3). The siliciclastic material of the uppermost part of the Amata Fm, 1.5–2.1 m thick, is represented by an alternation of claystones and siltstones with very fine-grained to fine-grained sandstones. The lack of sedimentary structures in the upper part of the Amata Fm complicates the interpretation of its sedimentary setting; however, the fining-upward trend of the siliciclastic deposits and the increasing importance of clayey material indicate a decrease in the energy of the environment. Tidal bundles or other structures indicating tidal processes were not found in the upper 4.5–5 m of the succession. The Amata Fm deposits do not contain any fossils in the outcrops studied, except for very rare fragmentary vertebrate bones (Fig. 4B), which are difficult to identify.

Succession of dolocretes and their peculiarities

Dolomitic nodules are rare in the lower part of the Amata Fm (Kuršs 1992), which was not examined in this study. In the upper part of the formation, 5.2–7.9 m thick, there are up to four well-expressed intervals of hard dolomite nodules and rather homogeneous, massive layer-like bodies (Fig. 3), which have been interpreted as dolocretes (Stinkulis and Spruženiece 2011; Pipira 2015). The dolocrete intervals can likely be correlated by their position in the geological section of the Amata Fm, lithological properties, and stable carbon isotope data. The main principles used in the tentative correlation were as follows:

1. Distance of dolocrete intervals from the well-expressed boundary between the Amata and Pļaviņas Fms;
2. Vertical distance of dolocrete intervals from each other;
3. Presence of a layer of siliciclastic deposits with problematic subvertical structures between the dolocrete intervals 3 and 4 (see below).

We would like to point out the existence of at least four dolocrete intervals in the documented sections. The lowermost carbonate-rich part of the documented successions (interval 1) is represented by nodular and vein dolocretes 7 m (Ainavas Cliffs 1) and 7.5 m (Vizuļi Rock) below the top of the formation (Fig. 3). The dolocrete nodules, more rarely subvertical and oblique veins, occur in very fine-grained to fine-grained sandstone. Dolomite nodules are almost absent in the next 2 m of the succession, then their content increases upwards until they form a distinct layer-like nodular to rather homogeneous body, mainly in very fine-grained to fine-grained sandstones 3–4 m below the top of the Amata Fm (interval 2). Nodules and their concentrations are present above this level, but the next considerable dolocrete (interval 3) is 1.7–2.5 m below the top of the Amata Fm. The interval is also represented by nodular to massive dolocrete, which occurs in clayey siltstone to fine-grained sandstone host rock (Figs 3 and 4A). Dolomite nodules are almost absent above this level in Ainavas Cliffs 1 and Dolomīti Cliffs, but one more nodular dolocrete formation (interval 4) occurs in clayey to silty deposits 0.2–1.2 m below the top of the Amata Fm in Vizuļi Rock and Īļaki Rock.

The maximum thickness of these dolomitic formations is 0.3 m for the massive layer-like dolocretes in Ainavas Cliffs 1 (intervals 1 and 2) and Vizuļi Rock (interval 3). Interval 2 in most of the studied outcrops (Ainavas Cliffs 1, Dolomīti, and Vizuļi sites) shows a gradual increase in dolomite abundance in a 1.2 m-thick part of the section. Siliciclastic deposits with separate dolomite nodules grade upwards into a massive, layer-like dolocrete formation.

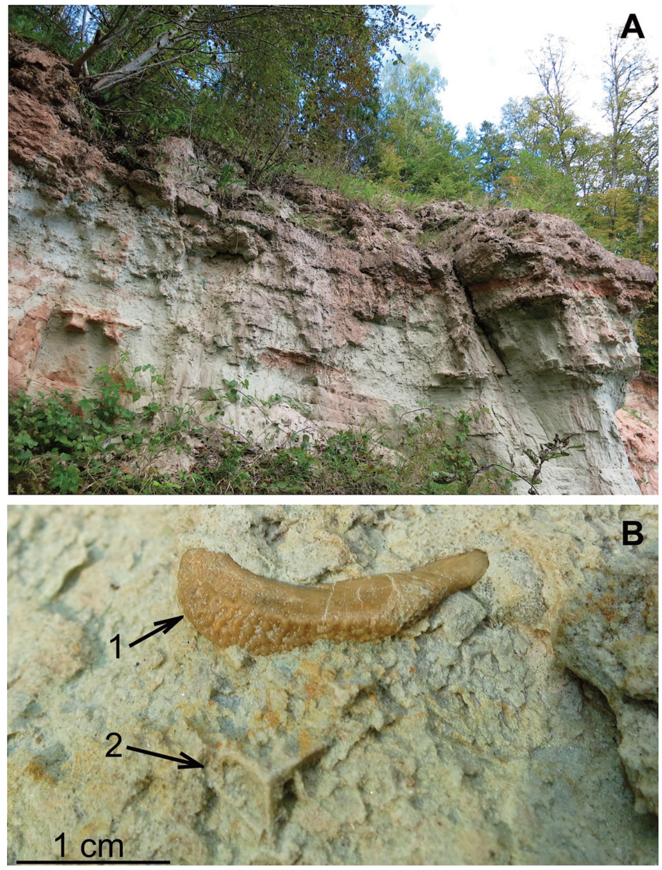

Fig. 4. Deposits of the upper part of the Amata Fm in Ainavas Cliffs 1. **A** – platy formations of dolocretes (mainly interval 3). **B** – vertebrate remains (1) and a dolomite pseudomorph after halite (2) in sandstones at the top of the Amata Fm, just below the dolomitic marls of the Pļaviņas Fm. Photos by Ģ. Stinkulis, September 2014.

A peculiar feature – a dolomite pseudomorph after halite – was found on the surface of the topmost sandstone layer of the Amata Fm in the Ainavas Cliffs 1 (Fig. 4B). Dolomite pseudomorphs after halite are rather typical of the lowermost part (the Koknese Member (Mb)) of the overlying Pļaviņas Fm (Sorokin 1981). The halite crystal remnant on the top surface of the Amata Fm indicates the existence of an arid or semiarid climate during that time.

In addition to dolomite as the main mineral of dolocretes, the Amata Fm contains quite abundant calcite admixture in the shape of globular and platy formations (Fig. 5). The calcite is usually related to porous, pure sandstones and has poikilotopic, as well as drusy, equant morphology. The size of calcite crystals changes from tens of millimetres to 2 × 3 cm. Its relationships with dolomite in thin sections allow the interpretation that crystallisation of calcite post-dated even the latest generation of dolomite (Stinkulis 1997). Based on carbon stable isotope and trace element analyses, the calcite is interpreted as having crystallised from groundwater of meteoric origin, most possibly related to palaeokarst events after the Devonian (Vernera and Stinkulis 2018). The calcite is not related to the formation of the dolocrete; therefore, we do not discuss its isotope data in this study.

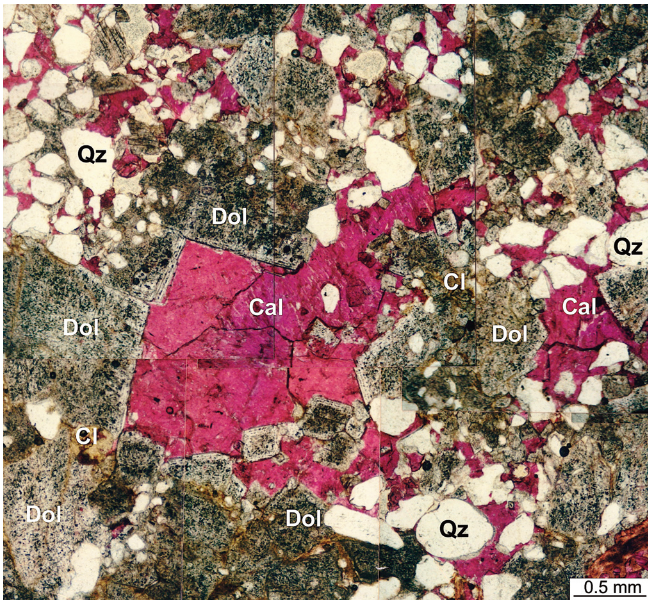

Fig. 5. Sandy and clayey dolocrete with secondary calcite. Dolomite (Dol) is associated with clayey material (Cl) and occurs as irregular, branched formations. This irregular distribution indicates that the carbonate material did not precipitate from basin water, but formed in already accumulated siliciclastic deposits. Calcite (Cal) is red due to staining of the thin section by alizarin-S solution. The distribution of calcite in sandstone pores among quartz (Qz) grains and in vugs of dolocrete indicates that it is the latest generation of carbonate minerals. Īļaki Rock, interval 3. Thin-section photomicrograph, parallel polarisers. The image was created by gluing together several printed photos. Photos and assemblage by Ģ. Stinkulis, March 1997.

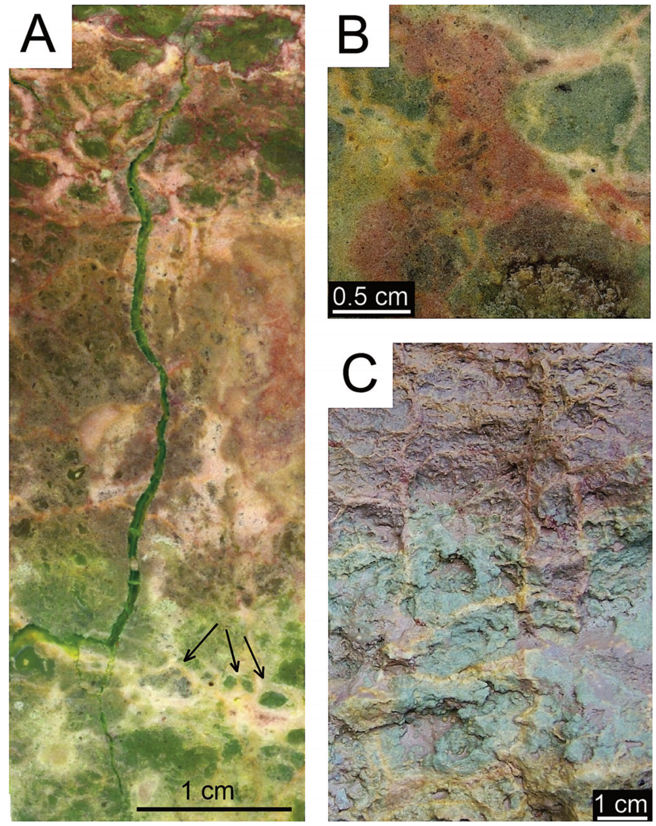

Fig. 6. Structures of dolocretes in polished specimens, under the reflected light microscope (A, B) and in outcrop (C). All samples are from Vizuļi Rock. **A** – irregular network of dolomite veins with a tendency towards a downward direction in massive dolocretes. Circumgranular cracks in the lower part of the figure are indicated by arrows. **B** – irregular dolomite veins and roundish honeycomb structures in massive dolocretes. **C** – honeycomb structures developed on the surface of a massive dolocrete layer. Radially branching dolomite veins are in the upper right corner of the photo. Photo A modified from Pipira et al. (2015); photos B and C by D. Pipira, January 2013.

Internal structure and texture of dolocretes

Studies of polished samples and thin sections supplement the descriptions and interpretations of dolocretes mentioned above. Under a microscope, it can be seen that dolomite is distributed as veins in the massive, layer-like dolocretes (Figs 6A–C and 7A–C). The matrix of massive, layer-like dolocrete bodies is looser than the veins and is represented by almost non-cemented to medium-cemented siliciclastic deposits. The matrix of the dolocretes depends on the host rock composition. In clay- and silt-dominated deposits, it is similar to non-carbonate clayey rocks, but sandstones contain irregularly, patchily distributed dolomite cement. Often the dolocrete matrix is of mixed clayey to sandy composition, and then the dolomite cement is mainly associated with the sand material.

The texture of the veins also depends on the siliciclastic host rock. In sandstones, they are not pure veins, but parts of the sandstone matrix with micritic or dense, equant, pore-filling to poikilotopic cement with crystal sizes up to 1 mm. In clayey and silty deposits, the veins are of pure dolomitic composition or contain irregularly distributed inclusions of the surrounding material. The dolomite is represented by micrite to crystals up to 0.4 mm in size. The dolomite veins are irregular, often radially branched (Fig. 6C), but they form a circumgranular pattern (Figs 6A, 7A, 9A, B). Boundaries between the veins and the matrix are quite sharp in clayey deposits (Fig. 7A), but rather gradual in sandy deposits (Fig. 7B).

Honeycomb structures are widespread in the dolocretes of the Amata Fm, especially in intervals 2 and 3 (Fig. 6B, C). The structures are formed by a network of dolomite veins, which are usually 1–2 mm wide. Bluish and greenish clayey material forms infillings ranging from several millimetres to 2 cm wide between the veins. The clayey fraction is dominated by illite with minor chlorite (Pipira et al. 2015); however, the origin of the colour has not been studied yet. This is probably related to the presence of Fe (II) oxides in the deposits, as discussed by Kuršs (1992).

The dolocrete intervals 3 and 4 are better developed and richer in indicative structures than intervals 1 and 2. Thus, dolocrete interval 3 in the Ainavas Cliffs 1 (Fig. 4A) and Vizuļi Rock shows the well-developed profile:

1. The nodular dolocretes in the lower part;
2. A massive dolocrete horizon in the upper part;
3. Honeycomb structures with poorly pronounced features of laminar (fine lamination) structures, as well as incipient laminar structures on the surface of the massive dolocrete.

Dolocrete interval 4 (nodular dolocrete) in Vizuļi Rock also demonstrates honeycomb structures. Microkarst pockets are recognised on the surface of a dolomite nodule (Fig. 7D).

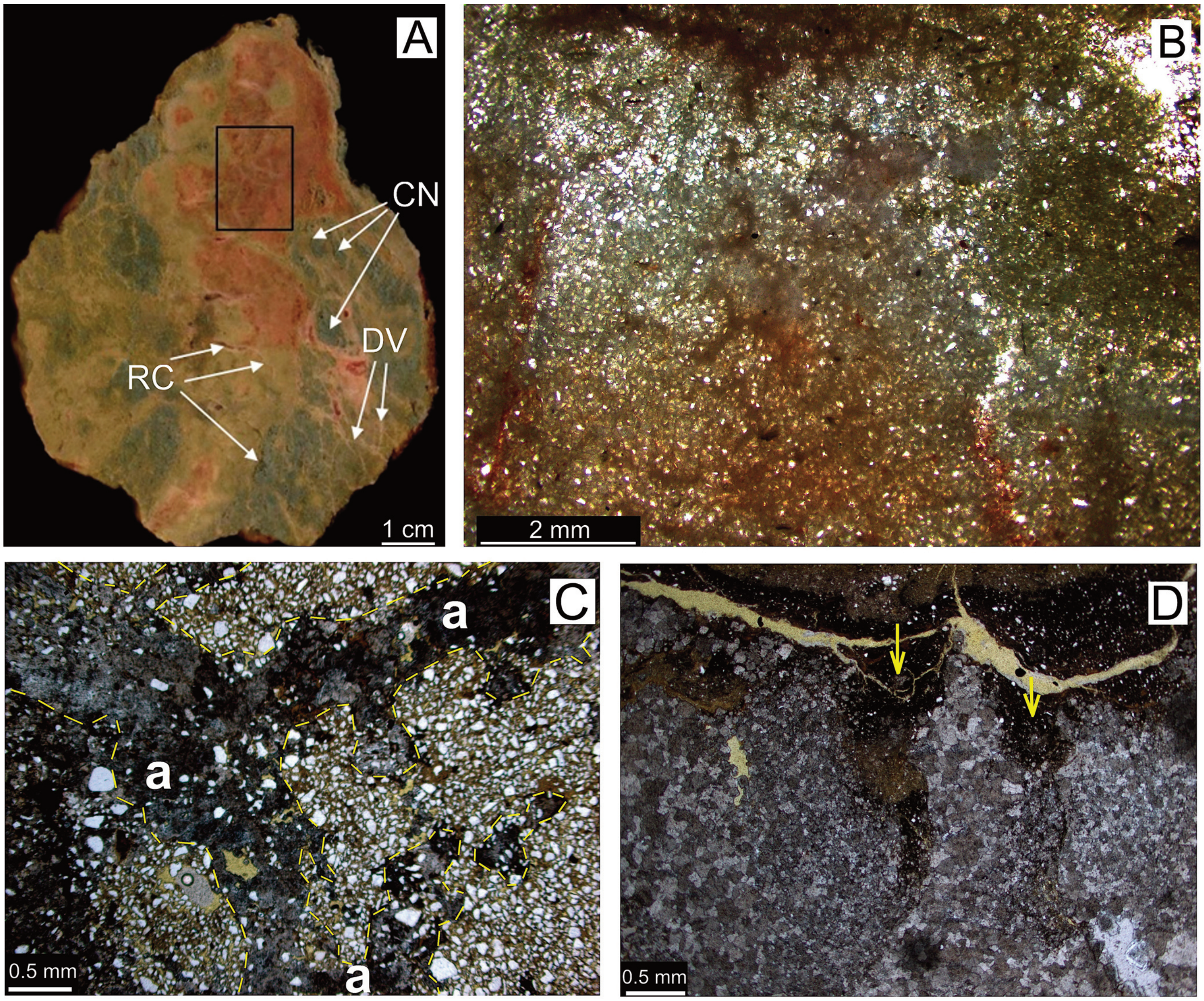

Fig. 7. Dolocrete microstructures in a polished specimen (A) and thin sections (B–D). **A** – relationships between dolomite and clay in dolocrete: DV – dolomite veins, CN – clay within the network of dolomite veins, RC – rounded, circumgranular veins. Īļaki Rock, interval 3. The rectangle shows the location of the thin section (B). **B** – thin, irregular, dolomicrite veins in the matrix of fine-grained sandstone with dolomite cement. Īļaki Rock, interval 3. Thin section, transmitted light, parallel polarisers. **C** – network of dolomite veins (a; marked with yellow dashed lines) within a fine sandy to clayey matrix. Massive dolocretes in Vizuļi Rock, interval 3. Thin section, transmitted light, parallel polarisers. **D** – microkarst features (indicated by arrows) on the upper surface of a dolomite nodule (nodular dolocretes) in Vizuļi Rock, interval 4. Thin section, transmitted light, parallel polarisers. Photos A and B by M. Meire-Kārkle, March 2018; photos C and D from Pipira et al. (2015).

These are V-shaped depressions in the dolomitic material, 0.5–1 mm wide and 1–2 mm long, which developed in dolomite and are filled with clayey material (Pipira et al. 2015).

Stable isotope data

The stable carbon isotope ($\delta^{13}C$) values for the studied dolocretes of the Amata Fm range from –8.9 to –5.7 ‰, and the stable oxygen isotope ($\delta^{18}O$) values range from –8.8 to –4.7 ‰ (Fig. 8). The most negative $\delta^{13}C$ values in the dolocretes of the Amata Fm are documented in the upper parts of intervals 3 (Dolomīti and Vizuļi outcrops) and 4 (Vizuļi and Īļaki outcrops). This is consistent with evidence of subaerial exposure found exactly in intervals 3 and 4 (Fig. 3). Moreover, the dolomite formations of these intervals are among the best-expressed, most massive ones. Conversely, the two most positive values of both $\delta^{13}C$ (–5.7 to –5.9 ‰) and $\delta^{18}O$ (–4.9 to –4.7 ‰) in the Dolomīti Cliffs correspond to the uppermost part of the section, but the dolomite concretions there are sparsely distributed.

Dolocrete $\delta^{18}O$ values in the documented sections are on average 1–1.5 ‰ higher (more positive) than $\delta^{13}C$ values. There is a general covariance between $\delta^{13}C$ and $\delta^{18}O$ (Fig. 8); Pearson's correlation coefficient is 0.76 ($N = 49$, $P = 0.01$) (Fig. 3).

Despite the overall trend, small positive excursions of oxygen values in several intervals are consistent with small negative excursions of carbon values. These trends occur in the following intervals in the studied logs: 2.6.–2.7 m and 2.9–3.0 m in Īļaki Rock, 2.5–3.0 m in the Dolomīti Cliffs, as well as 3.8–5.4 m and 6.5–6.7 m in Vizuļi Rock (Fig. 3). They correspond to the intervals of the sections where the siliciclastic deposits are enriched in dolomite concretions and veins, but not always to the upper parts of these intervals. These excursions, with a few exceptions, are only about 0.2–0.5 ‰,

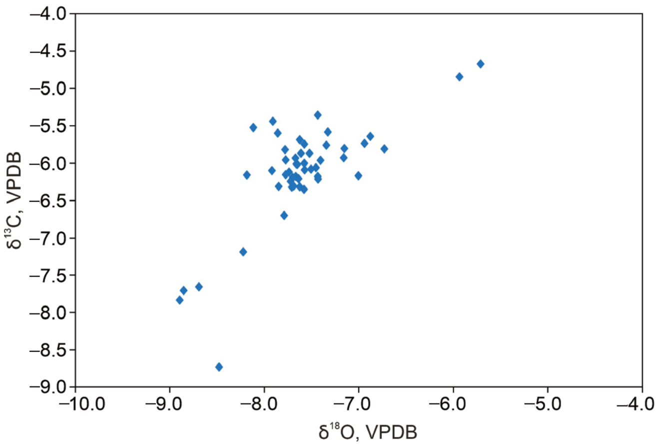

Fig. 8. Stable oxygen and carbon isotope diagram of dolomite from concretions, nodules, and platy formations of the Amata Formation in all studied sections. Abbreviation: VPDB – Vienna Peedee Belemnite.

which is close to the precision of the stable isotope analyses. Furthermore, the samples for the isotope analysis were taken from carbonate concretions, which are irregularly distributed in the geological section. Large intervals are composed of pure siliciclastic rocks. The results of oxygen isotope analyses may additionally be affected by dolomitisation and other diagenetic changes; thus, they should be rather interpreted with caution. This limits the reliability of the interpretations of isotope data, especially oxygen-isotope data, in this study.

Discussion

Influence of subaerial exposure and diagenetic changes suggested by stable isotope data

The negative stable carbon and oxygen isotope values for the studied dolocretes of the Amata Fm are typical of calcretes and dolocretes described in the literature (Kearsey et al. 2012; Rameil et al. 2012; Díaz-Hernández et al. 2013; Casado et al. 2014): $\delta^{13}C$ from –11 to 1‰ in calcretes and from –8 to 3‰ in dolocretes; $\delta^{18}O$ from –14 to –2‰ in calcretes and from –8 to 2‰ in dolocretes. As calcretes and dolocretes form from carbonates supplied either from soil or groundwater (Tucker and Wright 2009), their stable isotope values represent these environments.

The negative stable carbon isotope values indicate the presence of soil, because the decomposition products of plant material have a relatively high proportion of the light carbon isotope. This process could be accompanied by the influence of carbon from meteoric waters, which would also cause a decrease in the carbon isotope ratio. Both these features point to subaerial exposure processes (Díaz-Hernández et al. 2013; Casado et al. 2014). The most negative stable carbon isotope values, being lower than –8‰, in all studied sections of the Devonian Amata Fm occur near or at the dolocrete intervals 3 and 4 (Fig. 3), where the features of subaerial exposure were found, which support this suggestion.

The oxygen values for terrestrial carbonates, including those formed in soils and shallow groundwaters, usually are negative, because they form under the influence of meteoric waters (Sharp 2017). It corresponds well to the results of this study on the formation of dolomite concretions under the influence of surface processes.

In contrast to the carbon values, $\delta^{18}O$ values may show a positive trend near subaerial unconformity surfaces, because the ratio of $^{18}O/^{16}O$ there decreases due to evaporation. As a result, the oxygen isotope curves at unconformity surfaces reverse the carbon isotope values (Goldstein 1991). This, however, is not typical of calcretes, which form in non-carbonate substrates due to rapid downward migration of meteoric water, protecting the water from evaporation (Swart 2015). The influence of evaporation might help to explain the small positive excursions of oxygen values in several intervals of the Amata Fm, which correspond to small negative excursions of carbon values in relatively dolomite concretion-rich parts of the studied sections.

Diagenesis also lowers the $\delta^{18}O$ value (Swart 2015; Sharp 2017); therefore the explanation of the $\delta^{18}O$ values and their variation in the studied sections is more complicated to explain. Moreover, post-sedimentary processes can influence $\delta^{18}O$ values to a much larger degree than $\delta^{13}C$ values. This is related to differences in the sources of oxygen and carbon. Carbon can be supplied only from organic matter and CO_2, but oxygen is provided also by water molecules (Melezhik et al. 2004). This means that a much larger water/rock ratio is necessary to change the primary carbon isotope proportions than the oxygen isotope proportions. Thus, it is possible that the carbon values are better preserved than the oxygen values in the studied deposits of the Devonian Amata Fm.

The general trends of covariance of stable oxygen and carbon isotope values can be interpreted as linked to meteoric diagenetic fluids (Sharp 2017).

Origin of studied dolomite concretions, veins, and layer-like bodies

Layer-like horizons and nodules in the Amata Fm have in recent years been considered to be dolocretes, indicating subaerial conditions at the time of their formation (Stinkulis and Spruženiece 2011; Pipira et al. 2015). However, previous studies were either rather fragmented or focused on single exposures. This study allows us to discuss the genesis of dolomitic nodules and layer-like bodies along a rather long outcrop belt, taking into account the results of macro-sample and thin-section analysis, stable isotope data, and the tentative correlation of these dolomite formations.

In this study, the dolomite nodules and layer-like bodies in the Amata Fm are interpreted as dolocretes based on several facts. Dolomite is always distributed irregularly and never occurs as layers with definite boundaries, structures, and textures that could indicate primary sedimentation of the material. However, there are several intervals in the studied sites where hard, layer-like, platy bodies enriched in dolomite can be traced for at least 15 m (Fig. 4A), most possibly for kilometres, as indicated by the tentative correlation. Carbonate bodies with such structure and distribution are typical of both soil and groundwater calcretes and dolocretes (Alonso-Zarza and Wright 2010). It is important to note that such dolomite formations were recently found in almost every site in Latvia where the upper part of the Amata Fm is ex-

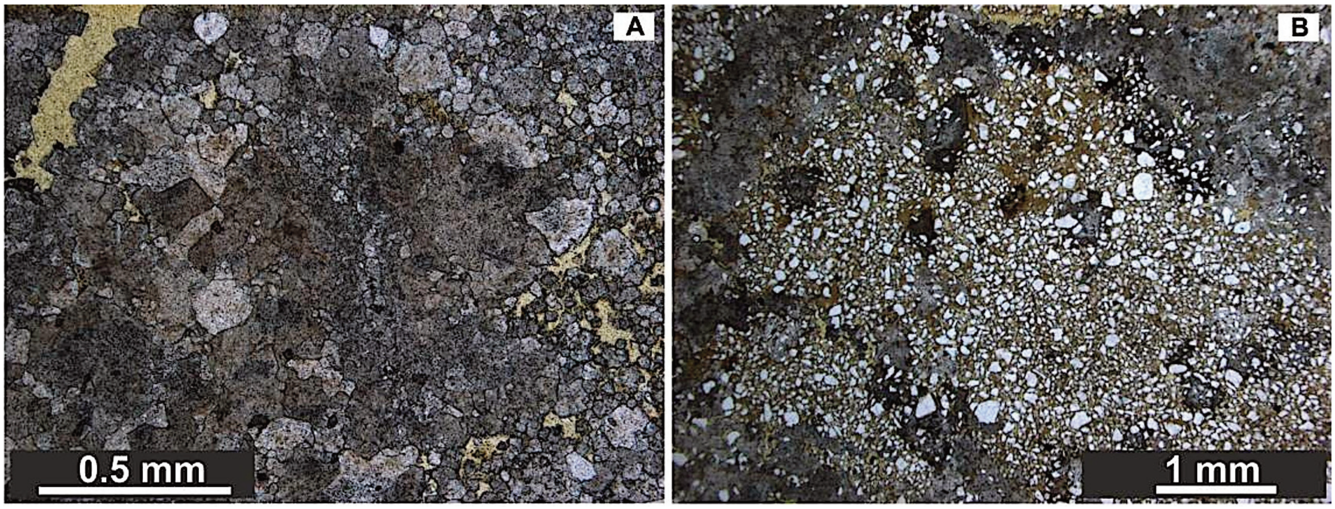

Fig. 9. Circumgranular cracks in dolocretes from Vizuļi Rock. **A** – circumgranular cracks partly filled with medium-crystalline dolomite cement in a matrix of clayey, impurity-rich dolomite. **B** – circumgranular cracks filled with pure dolomite surrounding sandy to clayey material. Some dolomite-filled cracks partly enter into the siliciclastic material. Vizuļi Rock, interval 3. Thin-section photomicrographs, transmitted light, parallel polarisers. Photos by D. Pipira, January 2013.

posed (Fig. 2) – in sites from the western to the eastern part of Latvia, at least 200 km apart from each other (Stinkulis and Spruženiece 2011; Pipira et al. 2015).

Macro-sample and thin-section studies allow us to distinguish such well-expressed and widespread features typical of calcretes and dolocretes as: 1) irregular, often subvertical, veiny distribution of dolomitic material with respect to siliciclastic material; 2) honeycomb structures. The development of veiny structures (Figs 6A–C and 7A–C) is a result of dissolution, repeated crystallisation, and cementation of mineral material (Machette 1985; Alonso-Zarza 2003; Zhou and Chafetz 2009; Alonso-Zarza and Wright, 2010). Irregular, often radially branched veins (Fig. 6C) indicate migration of carbonate solutions in radially developed desiccation cracks. The circumgranular pattern formed by veins in some places (Figs 6A, 7A, 9) is typical of calcretes and dolocretes of pedogenic (soil) origin (Theriault and Desrochers 1993; Zhou and Chafetz 2009).

The honeycomb structures are mentioned in many carbonate crust descriptions and classifications (e.g. Alonso-Zarza and Wright 2010; Pfeiffer et al. 2011; Pipira et al. 2023). They are not unequivocal indicators of groundwater or pedogenic carbonate formations; however, Goudie (1973) described honeycomb calcretes as a transitional form between nodular calcretes and hardpan calcrete in soil profiles.

The dolocrete interval 3 in the Ainavas Cliffs 1 (Fig. 4A) and Vizuļi Rock shows a profile characteristic of pedogenic dolocretes (Alonso-Zarza 2003). Furthermore, the combination of honeycomb and laminar structures present in interval 3 are characteristic of the upper part of carbonate-rich soil horizons (Alonso-Zarza 2003; Alonso-Zarza and Arenas 2004; Wright and Tucker 2009; Zhou and Chafetz 2009; Pfeiffer et al. 2011). The karsted dolomite surface (Fig. 7D) in the dolocrete interval 4 (Pipira et al. 2015) indicates that the deposits containing dolomite nodules were subaerially exposed and influenced by meteoric waters in the vadose zone (Calner et al. 2010), which also points to a soil horizon.

Further interpretation of the genesis of dolocretes is more problematic because similar carbonate formations, including nodules and massive bodies, can develop near the groundwater level and in soil (Alonso-Zarza and Wright 2010). There are also intermediate types ranging from more groundwater-controlled to more soil-water controlled variants (Chen 2002). Groundwater and soil (pedogenic) calcretes lacking specific structures such as laminar ones, pisoids, rhizoids, or karst phenomena are difficult to distinguish from one another. This is also the case for the dolocretes of intervals 1 and 2 in the studied sites. Dolomite concretions and horizons of massive to platy dolomitic material are present, which could have developed either in soil or near the capillary fringe zone due to fluctuations in the groundwater table (Wright and Tucker 2009).

A gradual increase in dolomite abundance and in the massiveness of dolocrete upwards in interval 2 in most of the study sites is indicative of pedogenic carbonate soil profiles (Wright and Tucker 2009); however, there is no further evidence of either groundwater or soil origin in intervals 1 and 2.

Thus, the dolocretes in intervals 1 and 2 could have formed both in groundwater and soil settings, but the dolocretes in intervals 3 and 4 developed in soils. The latter could also have been influenced by groundwater processes, but it is complicated to evaluate their role. These soil (pedogenic) dolocrete features indicate that during the late stage of accumulation of the siliciclastic materials of the Amata Fm at least two episodes of subaerial exposure occurred. It was not possible to provide a more detailed interpretation of the origin of the dolocretes in this study. We suppose that structures and textures indicative of the dolocrete formation mechanism could be partly obliterated by dolomitisation processes of precursor calcretes or by further diagenetic changes. A strong influence of multistage dolomitisation processes obliterating the fabrics of earlier formation stages of carbonate rocks has been suggested for the Pļaviņas Fm, which covers the Amata Fm (Kleesment et al. 2013).

Climate changes during the Givetian–Frasnian transition

The sedimentological logging, studies of polished specimens and thin sections, as well as data from stable carbon and oxygen isotope analyses, indicate the formation of dolocretes during several episodes throughout the accumulation of Amata Fm deposits. At least two episodes of subaerial exposure occurred before the end of the accumulation of Amata Fm deposits, as evidenced by the formation of soil dolocretes. This clearly marks the end of the transgressive phase characteristic of the Amata RS.

The observed decrease in grain size of siliciclastic deposits in the upper part of the geological section, which is noted in all studied sites, suggests a reduction in the energy of the sedimentary environment. Since the upper part of the section lacks well-preserved sedimentary structures – apart from problematic burrows – it is challenging to precisely interpret the sedimentary environment of the deposits containing dolocretes. However, no evidence has been found to contradict a regression at the end of the Amata Fm deposit accumulation time.

The decrease in grain size is likely due to a climate shift from wetter to drier conditions and a reduction in freshwater inflow, which also resulted in a decline in the overall hydrodynamic energy of rivers and their mouths.

Calcretes and dolocretes form in semiarid, more rarely in arid climates (Alonso-Zarza 2003). They are typical of monsoonal climate, as carbonate minerals accumulate in soils (fractures, root channels) during dry seasons, and remain fixed in the soil during moister conditions (Driese and Mora 2001). The appearance of the dolocretes in the upper part of the Amata Fm can also be considered an indication of climate change from moister to drier, more arid conditions at the beginning of the Frasnian, coinciding with a relatively short episode of sea-level fall. The same reason – climate change – likely initiated the overall transition from siliciclastic deposits with chemical weathering crust products (upper Givetian Gauja RS, Sietiņi and Lode Fms) to dolomites and gypsum-dominated deposits (Middle Frasnian Salaspils RS) in the WMDF. These longer-time changes likely led from a moist warm climate to a drier warm or even hot climate. The start of carbonate sedimentation in the Pļaviņas RS likely coincided with sea-level rise (Sandberg et al. 2002).

Changes in the fossil assemblages correspond reasonably well with changes in the geological sections and dominant deposit types. Fossil fishes from the Amata Fm of Latvia were previously described in detail only from a few localities, e.g. from the Pastmuiža site on the right bank of the River Daugava near Koknese (Klauenstein bei Kokenhusen in Gross 1942; Lyarskaya 1981), Ainavas Cliff near Kārļi (Karlsruhe in Gross 1942), and Ķūķi Cliff on the right bank of the River Gauja in the territory of the Gauja National Park (Lyarskaya 1981). The fossil-bearing beds at the Ainavas Cliff and Ķūķi Cliff are located in the lower part of the Amata Fm, whereas at the Pastmuiža site fossiliferous beds correspond to the middle part of the formation. Well-preserved but disarticulated vertebrate remains from the recently studied Zanderi Ravine near the town of Līgatne also come from the lowermost Amata Fm. The recently reported section of the Staritsa beds, cropping out on the left bank of the River Oredezh near the Borschovo village, Luga District, Leningrad Region, northwestern Russia, contains a moderately diverse vertebrate assemblage (13 taxa), plant remains, and trace fossils; this section is correlated with the lower part of the Amata Fm in Latvia (Lukševičs et al. 2018). As a result of this and previous studies (Stinkulis and Spruženiece 2011; Pipira et al. 2015), including five analysed sections, it seems that the upper part of the Amata Fm contains virtually no fossils, or only very few. This corresponds well with the distribution of dolocretes. The pattern of distribution of fossils within the Amata Fm resembles that in the sections of the Ketleri and Šķervelis Fms corresponding to the terminal Famennian. The Ketleri Fm, consisting mostly of sandy to clayey deposits accumulated in a tidal-influenced delta, yields a rather rich vertebrate assemblage, trace fossils of various invertebrates, rhizocretes, and macroscopic plant remains (Lukševičs et al. 2025), whereas the Šķervelis Fm, with strongly developed dolocretes in the same sandy to clayey host rocks, is practically fossil-free (Pipira et al. 2023).

The comparison of the fossil assemblages from stratigraphic units close to the Givetian–Frasnian boundary in Latvia demonstrates the decrease in fossil taxa diversity from the Burtnieki RS to the Amata RS, and an increase in the younger units (Table 2). The Amata Fm shows vertebrate diversity that is slightly larger than that of the Lode Fm,

Table 2. Number of fossil taxa reported from the Middle–Upper Devonian formations of Latvia (data from Kuršs et al. 1981a, b; Lyarskaya 1981; Lyarskaya and Lukševičs 1992; Kleesment and Mark-Kurik 1997; Ahlberg et al. 2000; Esin et al. 2000; Upeniece 2001; Jurina and Raskatova 2012; Mešķis 2013)

Regional stage	Number of fossil taxa			
	Vertebrates	Invertebrates	Other remains	Ichnotaxa (Mešķis 2013)
Salaspils	3	Lingulids, conchostracans, *Eurypterus lancmani*	*Chaetocladus*	Ichnofabrics
Pļaviņas	20	Stromatopores, *Aulopora*, rugose corals, conulariids, annelids, ostracods, conchostracans, 16 mollusc taxa, 19 brachiopod taxa, *Dactylocrinus*	Stromatolites (3 kinds), *Chaetocladus*	13 ichnotaxa
Amata	18	Conchostracans		
Gauja	21	Tabulate corals, stromatoporoids (3 taxa), brachiopods (3 taxa), platyhelminths, eurypterids, conchostracans, mysidaceans	*Prototaxites*, *Svalbardia banksii*, rhizocretes	
Burtnieki	24	Brachiopods, conchostracans, ostracods	Rhizocretes	

significantly larger than that of the Sietiņi Fm, but smaller than that of the Gauja Fm; however, the total diversity of organism fossils from the Gauja RS corresponding to three formations (Gauja, Lode, and Sietiņi Fms) is higher than that from the Amata RS. The overlying Pļaviņas Fm (and corresponding Pļaviņas RS) is characterised by 20 vertebrate taxa, which are unevenly distributed within the formation: 17 taxa in the lower, Koknese Mb; 13 taxa in the middle part, the Sēlija and Atzele Mbs; and only six taxa in the upper, Ape Mb (Lyarskaya and Lukševičs 1992). Besides vertebrates, a highly rich invertebrate assemblage, three different kinds of stromatolites, the green alga *Chaetocladus* (Sorokin 1981), and various trace fossils (Meškis 2013) have been reported from the Pļaviņas Fm. The Salaspils Fm, composed of rocks of different composition, including clayey dolostone, dolostone, dolomitic marl, clay, gypsum, gypsum-dolomite, and various intermediate rocks, contains rather poorly preserved and usually difficult-to-determine fossils (Sorokin 1981; Lyarskaya and Lukševičs 1992; Meškis 2013).

There are various hypotheses concerning climate changes and extinctions during the Devonian. For example, the so-called Devonian plant hypothesis (Algeo et al. 2001) postulates the influence of trees with deep root systems, and the first Middle Devonian forests on the acceleration of silicate weathering and/or organic carbon burial, resulting in several oceanic anoxic events, a decrease in atmospheric CO_2 levels, and global climate cooling during the Famennian and Carboniferous (Chen et al. 2021). However, this hypothesis does not explain the climate warming in the Givetian and Frasnian. Another hypothesis connects the cooling of the global climate close to the Frasnian–Famennian boundary with the first phase of the establishment of the Viluy traps in eastern Siberia (Ricci et al. 2013). However, the situation during the Givetian and around the Givetian–Frasnian boundary is not that clear. In accordance with the reconstruction of global palaeotemperatures for the Phanerozoic (Scotese 2015), global warming started close to the Emsian–Eifelian boundary, when the global mean annual temperature increased from 24 to about 26 °C, and the ‘hothouse climate’ conditions continued up to the Middle Frasnian. Recent reconstructions of seawater temperatures based on oxygen isotope ratios measured in marine calcitic and phosphatic fossils indicate a short but significant, 8–10 °C warming of the seawater during the interval around the Middle to Late Devonian transition (van Geldern et al. 2006; Joachimski et al. 2009; Chen et al. 2021). The main cause of the warming is still debated; it could be related to the injection of huge amounts of CO_2 that started about 390 Ma during the Acadian orogeny (Stewart and Ague 2018). If the above-mentioned climate reconstructions are correct, the climate warming coincided approximately with the early Eifelian Narva RS. It was earlier than the time of accumulation of deposits of the Gauja–Dubniki RSs.

Thus, the climate change from moister to drier from the Givetian to the Middle Frasnian has likely not been documented before outside the territory of the WMDF. Probably there are local reasons for the changing climate conditions. The climate could have been influenced by the Scandinavian Caledonides, which developed westwards from the WMDF and were oriented from north to south (Scotese 2014), perpendicular to the climate zones, thus influencing wind direction and moisture distribution. Hypothetically, the transition to a hotter climate from the Emsian–Eifelian to the Middle Frasnian (Scotese 2015) could have led to melting of the Scandinavian Caledonides’ ice cap and cessation of freshwater inflow in the WMDF. This could also have influenced the change from siliciclastic to carbonate sedimentation.

Conclusions

Dolocretes in the upper part of the Amata Fm indicate at least two subaerial exposure episodes, which mark the transition from a longer sea-level rise trend to a short episode of sea-level fall in the WMDF during the Early Frasnian.

The dolocrete formation was an indicative episode of an overall period of climate change from warm, moist to drier and hotter conditions, which started in the Late Givetian (Gauja RS) and continued to the Early–Middle Frasnian (Dubniki RS). This climate change has likely not been documented before outside the WMDF and indicates locally different environmental conditions.

The geological succession of the Amata Fm with tidal features in its lower and middle parts, their absence in the upper part, the decrease in the abundance of fossils from the lower to the upper part of the formation, as well as the presence of dolocretes only in the upper part of the formation demonstrate a similar pattern to that of the Upper Famennian Ketleri and Šķervelis Fms. These features in the Ketleri and Šķervelis Fms were interpreted as the result of climate change and sea-level fall.

Data availability statement

Data for the stable isotope analyses are available in the Zenodo database: https://doi.org/10.5281/zenodo.19129793. All other data are included in this paper.

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Läti Amata kihistu dolokreedid kui Giveti–Frasnesi üleminekuaja ariidsema kliima indikaatorid

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Uuring keskendub nelja Läti paljandi dolokreetide ja nende terrigeensete peremeeskivimite päritolu kirjeldamisele ja tõlgendamisele Amata kihistu ülemises osas. Dolokreedid esinevad vähemalt neljas intervallis. Kahe ülemise dolokreedi intervalli koostis ja struktuur ning hapniku ja süsiniku stabiilsete isotoopide andmed viitavad sellele, et need tekkisid mullas. Dolokreedid vastavad kliimamuutuste episoodile soojast-niiskest kuivemaks-kuumemaks, mis algas hilis-Givetis ja jätkus kesk-Frasnesini. Need tekkisid pärast pikemat meretaseme tõusutrendi toimunud lühiajalise meretaseme languse ajal. Amata kihistus väheneb selgroogsete fossiilide mitmekesisus kihistu alumisest osast ülemise osani, mis on kooskõlas meretaseme languse ja järkjärgulise kliimamuutusega, mida näitavad ka Amata kihistu ülemises osas uuritud dolokreedid.