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Environmental changes in the declining Middle Miocene Badenian evaporite basin of the Ukrainian Carpathian Foredeep (Kudryntsi section)

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Abstract: The Kudryntsi section in West Ukraine documents a major environmental change from hypersaline to marine conditions during the Middle Miocene. There are very few (or no) specimens of foraminifers in samples of the siliciclastic series (4 m thick, with limestone intercalations) which occurs above the gypsum (and below the transgressive deposits) in the southern part of quarry. The limestone intercalations are first sparitic and microsparitic, and then become pelletal. The pelletal depositional textures are interpreted as originated in restricted environments in contrast to mixed-fossil lithoclastic packstones/grainstones overlying the siliciclastic series. The diversity of fauna increases up section. Foraminifers, bivalves, ostracods and gastropods appear first and then, additionally, brachiopods, bryozoans, crinoids, and echinoids occur. Foraminiferal assemblages are dominated by elphidiids forming 70 to 90 % of the population. The most common species are *Elphidium crispum* (Linné) and *E. macellum* (Fichtel & Moll). The limestones show a wide range of $\delta^{13}C$ values (from −1.6 ‰ to −18.2 ‰) and $\delta^{18}O$ values (from −0.2 ‰ to −9.4 ‰) indicating that the cementation and some recrystallization took place in meteoric-water-dominated fluid but the restriction-controlled trend can be recognized. The siliciclastic series was deposited in an evaporitic lagoon influenced by large inflows of continental waters carrying the siliciclastic and other detrital material from the older Badenian rocks as well as from their substrate. The Kudryntsi section documents a stepwise decrease in water salinity — from ca. 150–300 ‰ during the Badenian gypsum precipitation, through ca. 80–150 ‰ during deposition of the siliciclastic series to ca. 35 ‰ during sedimentation of the basal transgressive deposits. The basal deposits originated in shallow subtidal (0–20 m) environments of normal marine salinity (30–35 ‰) and temperate to warm waters (8–18 °C) as indicated by requirements of the *E. crispum* association in recent seas.

Key words: Middle Miocene, Upper Badenian, Central Paratethys, carbon and oxygen stable isotopes, evaporite basin, limestones, foraminifers.

Introduction

The Middle Miocene Badenian evaporite basin of the Carpathian Foredeep was located in a depression apparently lying below the contemporaneous sea level and thus an important sea-level rise could have resulted in quick flooding and deposition of marine sediments (Peryt 2006). Apart from this major seawater inflow event, terminating evaporite deposition, there were minor incursions of seawater into the Badenian evaporite basin. One such incursion is well documented by the presence of an intercalation of marine limestone (usually mm–cm thick) within the stromatolitic gypsum (Peryt 2001). This intercalation is regarded as an equivalent of the clay and clastic gypsum (layer h — see Kasprzyk 1993) occurring in the upper part of the autochthonous gypsum in nearly the entire margin of the basin (e.g. Bąbel 1999). During deposition of the upper, allochthonous part of gypsum section those incursions are marked by the occurrence of bivalves, foraminifers (mostly pelagic globigerinids), ostracods and pteropods, occasionally reported from clays intercalated within the gypsum in more basinward locations (Venglinskiy & Goretskiy 1966).

In this paper we focus on the significance of the evaporite/post-evaporite transition based on the micropaleontological, petrological and geochemical study of the Kudryntsi section in western Ukraine (Fig. 1). This transition reflects a major environmental change from hypersaline to marine conditions, although it should be mentioned that the geochemical modelling showed that the continental water was the main inflow source during the entire evaporite deposition in the Carpathian Foredeep Basin (cf. Petrichenko et al. 1997; Cendón et al. 2004). These brackish conditions apparently prevailed during gypsum precipitation and afterwards, when the basin became desiccated, forming gypsum microbialites, and then was rapidly reflooded by brackish water. This apparently concluded the Middle Miocene of eastern Crimea (Peryt et al. 2004a). A similar scenario in terms of mixed-water salinity was earlier proposed for the Messinian of the eastern Mediterranean where the oligohaline to mesohaline conditions typical of the Lago-Mare deposits already existed during deposition of the upper gypsum sub-unit (Rouchy et al. 2001).

Geological setting

The Carpathian Foredeep was initiated in the Early Miocene (Eggenburgian) and lasted at least until the end of the Middle Miocene (Oszczypko et al. 2006). In the outer part (up to 50 km wide) of the Ukrainian Carpathian Foredeep, called the

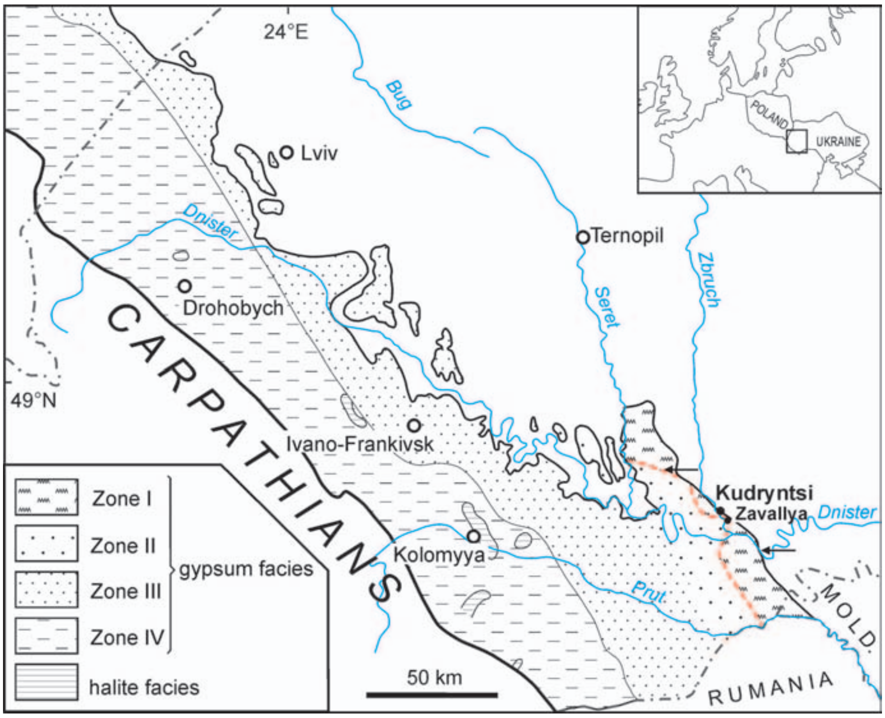

Fig. 1. Location of the Kudryntsi section. Facies zones of Badenian evaporites, present NE gypsum limit and the previously recorded siliciclastic facies (arrows) in the upper part of Badenian gypsum sequence are modified after Peryt et al. (2004b) and Peryt (2006). Arrows show the previously recorded occurrences of siliciclastic facies in the gypsum sections (Peryt et al. 2004b).

Bilche-Volytsa Zone, Badenian and Sarmatian marine deposits are a few hundreds of meters to more than 5 km thick. In the part of the Badenian basin located in the East European Platform, the Badenian gypsum of the Tyras Formation overlies Silurian, Devonian, Cretaceous and/or earlier Badenian deposits (Kudrin 1955), including the thin (up to 10 cm thick) Kryvchytsi (Ervilia) Bed (Andreyeva-Grigorovich et al. 1997). A nannoplankton study has shown that the Badenian gypsum corresponds to the lower part of the NN6 Zone (D. Peryt 1997, 1999).

The gypsum deposits (several tens of meters thick) form a wide (up to 100 km) marginal Ca-sulfate platform in the Ukrainian Carpathian Foredeep (Peryt 2006). The most marginal, facies zone I, consists entirely of stromatolitic gypsum and is characteristic of the area (>15 km wide) bordering the limits of the nearshore Ca-sulphate facies. Facies zone II (more than 40 km wide) is located basinward of the facies zone I and is characterized by the occurrence of stromatolitic gypsum in the lower part of the section and sabre gypsum (occasionally with a clastic gypsum unit above the sabre gypsum) in the upper part (Fig. 1; Peryt 2001; Peryt et al. 2004b; Bąbel 2007). The gypsum is overlain by the Ratyn Limestone (usually a few tens of centimeters thick) which is related to the Late Badenian marine transgression (Peryt & Peryt 1994). Commonly a clay layer (up to 30 cm thick) occurs below the Ratyn Limestone. The Tyras Formation (gypsum and the Ratyn Limestone) is overlain by the deep-marine Kosiv Formation in the Carpathian Foredeep and the adjacent part of the foreland and by various marine facies in more marginal parts of the basin (Andreyeva-Grigorovich et al. 1997). The thickness of the Kosiv Formation reaches a few tens of meters in the marginal part of the Carpathian Foredeep and increases rapidly towards the central part of the Carpathian Foredeep.

The Kudryntsi section is located within the gypsum facies zone I close to the boundary with the facies zone II present at Zavallya (Fig. 1). The gypsum sequence is 23 m thick in natural outcrops located along the Zbruch River valley, north of the quarry, and Dromashko (1955) reported the thickness of up to 30 m at Kudryntsi. At the base of the gypsum Lower Badenian biodetrital (usually coralline algal) limestones (2 m thick) occur, underlain by thin basal breccia lying on the Upper Cretaceous sandstones, as was recently recorded in the southern part of the quarry (N48°37.009′, E26°19.493′). In the quarry itself, above the stromatolitic gypsum (14 m thick), which, ca. 2.5 m below its top, contains an intercalation (up to 20 cm thick) of limestone with marine fauna (Peryt 2001), a unit of 4-m-thick fine siliciclastic deposits with intercalations of limestones and fine-grained sandstones (up to 15 cm thick) occurs (Figs. 2, 3). In the northern part of the gypsum quarry (N48°37.188′, E26°19.236′) this unit is pervasively gypsified in places and thus the main mineral is gypsum (cf. Fig. 8D–F). The lamination of gypsiferous fine siliciclastic rocks are rarely regularly planar, and erosional surfaces, wavy and lenticular lamination (Fig. 4), isolated cross-laminated lenses of coarser-grained material (Fig. 3) as well as deformational structures are present: convolutions and in situ brecciation of lamina sets are common, which have been interpreted as a development triggered by earthquakes (Peryt et al. 2008).

This siliciclastic unit is overlain by the Ratyn Limestone (1.3–1.4 m thick) composed of lithoclastic and fossiliferous limestones with minor intercalations of clays and marls (10–30 cm thick) (Figs. 3–5). The Ratyn Limestone is covered by the rhodoid limestones with minor intercalations of marls and claystones belonging to the Kosiv Suite (up to 6 m thick in the quarry) (Fig. 2).

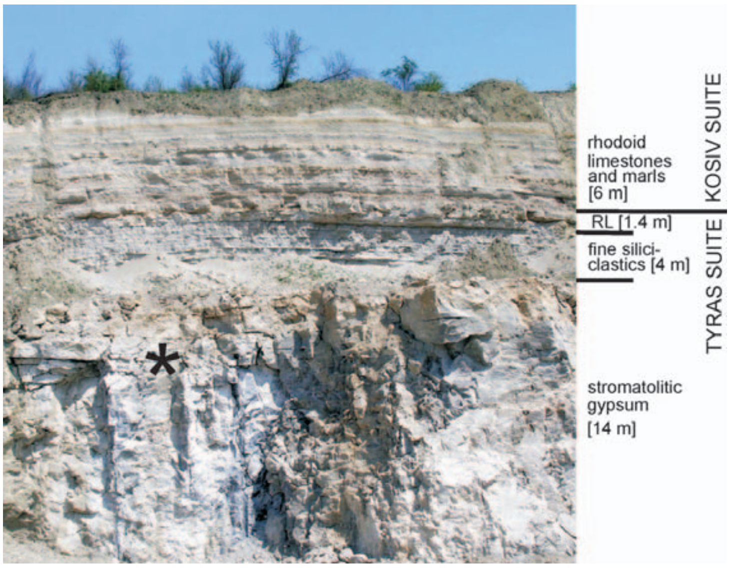

Fig. 2. The general section outcropped at Kudryntsi, northern part of the quarry (N48°37.262′, E26°19.108′). RL — Ratyn Limestone; asterisk shows the location of limestone intercalation within stromatolitic gypsum. Photo done in May 2009.

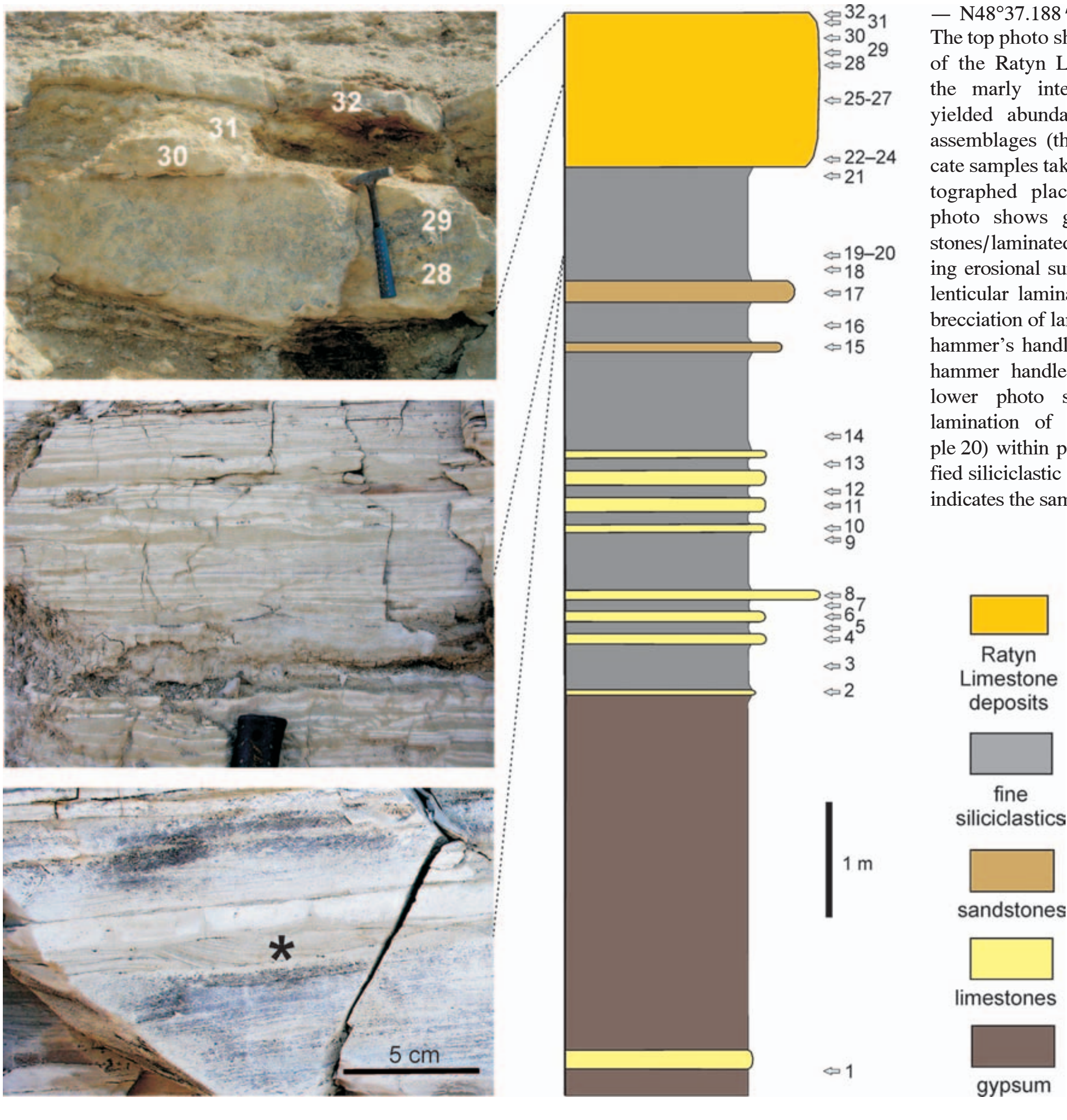

Fig. 3. The section of the upper part of the gypsum unit, siliciclastic unit and the Ratyn Limestone exposed at Kudryntsi at 1996 (approximate location of the section: N48°37.13′, E26°19.40′) showing the major lithologies and the sample locations and, to the left of the lithological column, some characteristic aspects of the rocks (photos from recent outcrop — N48°37.188′, E26°19.236′). The top photo shows the top part of the Ratyn Limestone, above the marly intercalation which yielded abundant foraminiferal assemblages (the numbers indicate samples taken from the photographed place). The middle photo shows gypsiferous siltstones/laminated gypsum showing erosional surfaces, wavy and lenticular lamination and in situ brecciation of lamina (right of the hammer's handle). The width of hammer handle is 3.7 cm. The lower photo shows lenticular lamination of limestone (sample 20) within pervasively gypsified siliciclastic deposits (asterisk indicates the sampling site).

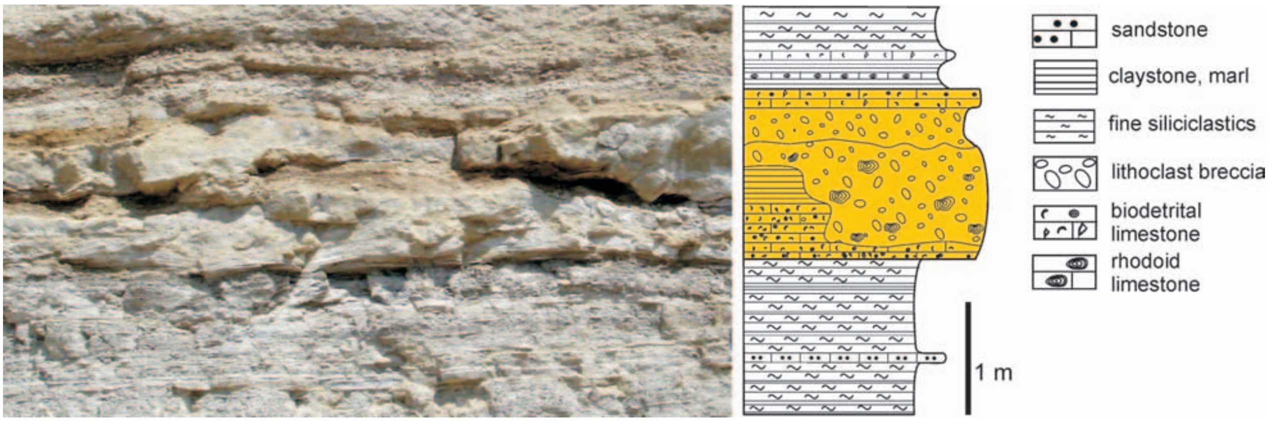

Fig. 4. Photo (done in May 2009) showing the Ratyn Limestone and adjacent strata (N48°37.185′, E26°19.261′) and the drawing showing the complex structure of the Ratyn Limestone (yellow).

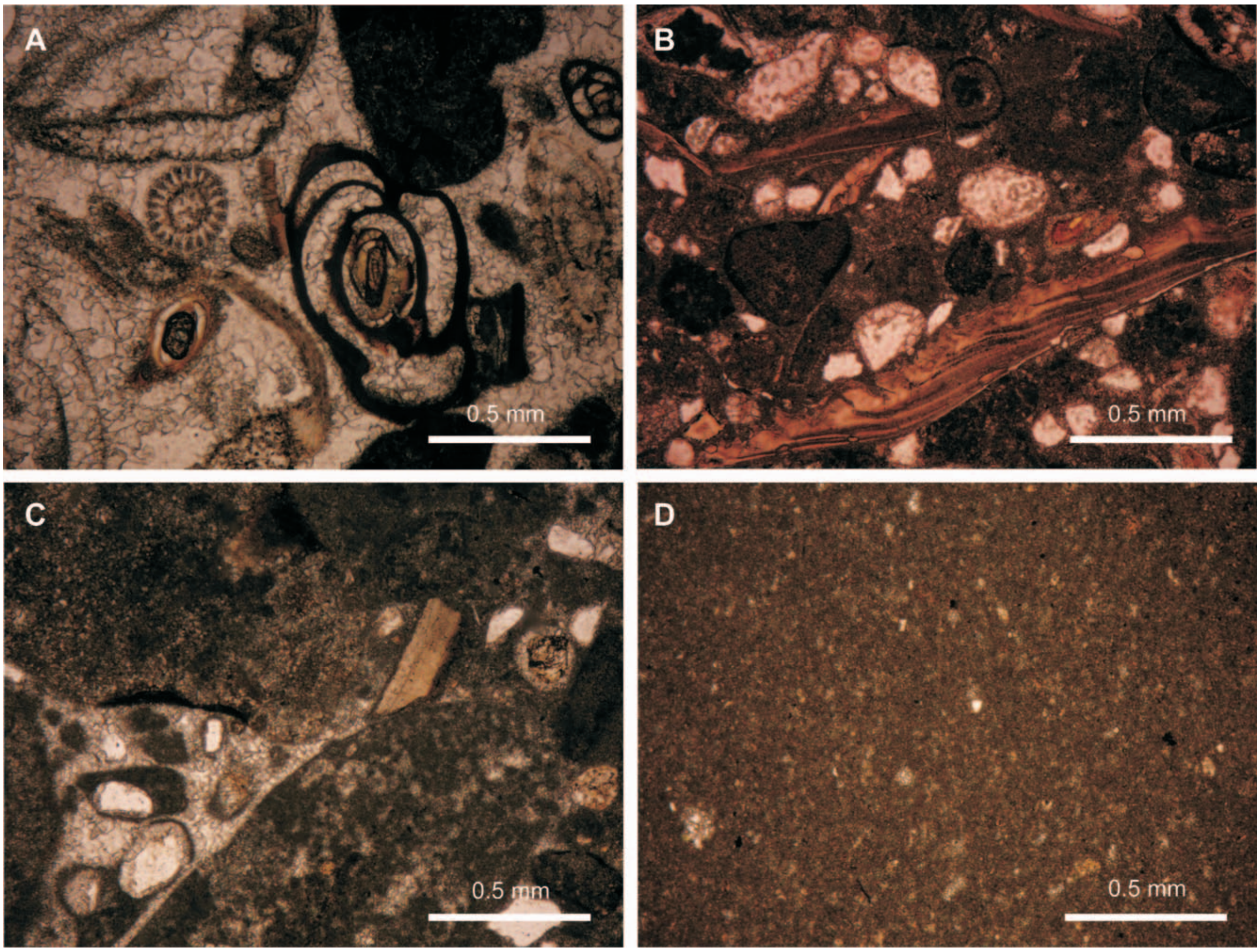

Fig. 5. Photomicrographs of the Ratyn Limestone. **A** — Mixed-fossil lithoclastic grainstone (sample 32); **B** — Mixed-fossil lithoclastic packstone (sample 24); **C** — Lithoclastic grainstone from the lower part of the limestone bed above the marly intercalation within the Ratyn Limestone (sample 28); **D** — Micritic lithoclast from sample 30.

Material and methods

Kudryntsi is an active gypsum quarry and the outcrops of the rocks overlying gypsum are only temporarily accessible. The composite section based on the previously measured sections is shown in Figure 3. For the purpose of this paper the previously collected samples have been renumbered and arranged in a stratigraphical order (Fig. 3).

The samples of those limestones which intercalate fine siliciclastic sediments and of the Ratyn Limestone were taken

Table 1: Results of isotopic analyses (C, O) of the samples of Ratyn Limestones (samples 22–32) and limestone intercalations in the siliciclastic unit (samples 2–20). The location of samples is shown in Fig. 3.

Sample number (Fig. 3)	Laboratory number	Sample description	$\delta^{13}C$ VPDB [‰]	$\delta^{18}O$ VPDB [‰]
32	10/2008 (x)	mixed-fossil lithoclastic grainstone	–4.92	–4.62
	10/2008 (o)		–15.42	–6.52
30	8a/2008	lithoclast: lime mudstone	–5.49	–4.62
29	9/2008 (x)	lithoclast grainstone with rare quartz grains	–5.15	–4.62
	9/2008 (o)		–7.59	–4.51
28	r.d./2008 (x)	lithoclast grainstone with rare bioclasts and common quartz grains	–6.61	–2.67
	r.d./2008 (o)		–13.75	–3.60
23	4/2008 (x)	pelletal mudstone with pseudomorphs after gypsum crystals	–6.53	–4.28
	4/2008 (o)		–6.41	–4.59
24	M-12/1996 (x)	mixed-fossil lithoclastic packstone–grainstone	–4.35	–3.24
	M-12/1996 (o)		–5.1	–2.85
22	b.n./2008 (x)	sparite with calcitized gypsum crystals showing relict laminated	–8.62	–5.44
	b.n./2008 (o)	pelletal packstone with common quartz grains	–9.12	–4.73
20	5/2008	pelletal-lithoclast grainstone with rare bioclasts (large lithoclasts of laminar microbialites)	–2.47	–2.83
19	3j/2008	laminated carbonate mudstone	–1.60	–0.15
17	M-11/1996 (x)	fine-grained sandstone and pelletal limestone	–6.31	–3.29
	M-11/1996 (o)		–11.60	–5.30
15	M-10/1996	fine-grained sandstone	–8.36	–4.39
13	12/2008	laminated carbonate mudstone, locally pelletal packstone	–7.98	–0.19
11	M-9/1996	pelletal wackestone	–7.52	–4.85
10	M-8/1996	pelletal wackestone	–8.66	–6.27
8	M-7/1996 (x)	pelletal wackestone	–13.19	–7.79
	M-7/1996 (o)		–13.76	–7.54
5	M-5/1996	sparite and microsparite	–17.10	–5.37
4	M-1/1996	sparite and microsparite	–18.21	–6.39
2	M-3/1996 (x)	sparite	–14.19	–9.41
	M-3/1996 (o)		–11.68	–9.26

for microfacies study (the location of samples is shown in Fig. 3). Eighteen samples of limestones were subjected to O and C isotope study at the Mass Spectroscopy Laboratory, Institute of Physics, Maria Curie-Sklodowska University, Lublin (analyst: S. Halas). For isotopic analyses of carbonates, CO_2 gas was extracted from the samples by reaction of calcite with H_3PO_4 at 25 °C in a vacuum line, following the standard practice (McCrea 1950). The gas was purified from H_2O on a P_2O_5 trap and collected on a cold finger. Isotopic compositions were analysed using a modified Russian MI1305 triple — collector mass spectrometer equipped with a gas ion source. Isobaric correction was applied. After subsequent normalization to measured certified reference materials, the isotopic composition was expressed in per mille (‰) relative to the VPDB (Vienna Pee Dee Belemnite) international standard and separately to PDB. The analytical precision of both $\delta^{13}C$ and $\delta^{18}O$ in a sample was ±0.08 ‰. In a number of cases, two different places were analysed (Table 1): those from the upper part of a sample are designated as (x) and from its lower part as (o).

Fourteen samples of marls (each weighing 200 g) and one sample of argillaceous limestone adjacent to sample 32 were taken for foraminiferal study. The location of samples is shown in Fig. 3. Micropaleontological samples were processed using Glauber's salt and washed and size sorted through a 63 μm and 100 μm mesh sieve. An aliquot of at least 300 specimens from the >100 μm size fraction was used for foraminiferal counts.

Eight samples of marly intervals (including one sample from the laminated gypsum occurring immediately below the intercalation of lenticular limestone within stromatolitic gypsum) were taken for the qualitative analysis of general phase composition (XRD study) (Table 2). The XRD study was done with the use of the X-ray Diffractometer X'Pert PW 3020 (Philips) at the Central Chemical Laboratory, Polish Geological Institute, Warsaw (analyst: W. Narkiewicz).

Table 2: Results of XRD analyses.

Sample number (Fig. 3)	Laboratory number	Qualitative composition of sample (XRD analysis)
31	7/2008	C++, Q, Ar, Sm, I
27	6/2008	C, Q, Zeo, Sm, I, Chl/K
26	2/2008	C, Q, Fel, Zeo, Sm, I
25	1/2008	C, Q, Fel, Zeo, Sm, I
21	M-18/1996	Q++, C, D, Sm, I
16	M-16/1996	C, Q, D, Cel, Sm, Chl/K
14	M-15/1996	C, Q, D, Cel, Sm, Chl/K
1	10/1994	G++, Q, Fel, Sm, I, Chl

++ — main mineral phase, **Ar** — aragonite, **C** — calcite, **Cel** — celestite, **Chl** — chlorite, **Ckl/K** — chlorite and/or kaolinite, **D** — dolomite, **F** — feldspar, **G** — gypsum, **I** — illite, **Sm** — smectite 15 Å, **Zeo** — zeolite.

Results

Foraminifers

The occurrence of foraminifers is very rare in all samples of the siliciclastic unit. In turn, samples of the Ratyn Limestone unit contain rare (samples 25 and 27) or abundant foraminifers (samples 26, 31 and 32) (Figs. 6, 7; Table 3).

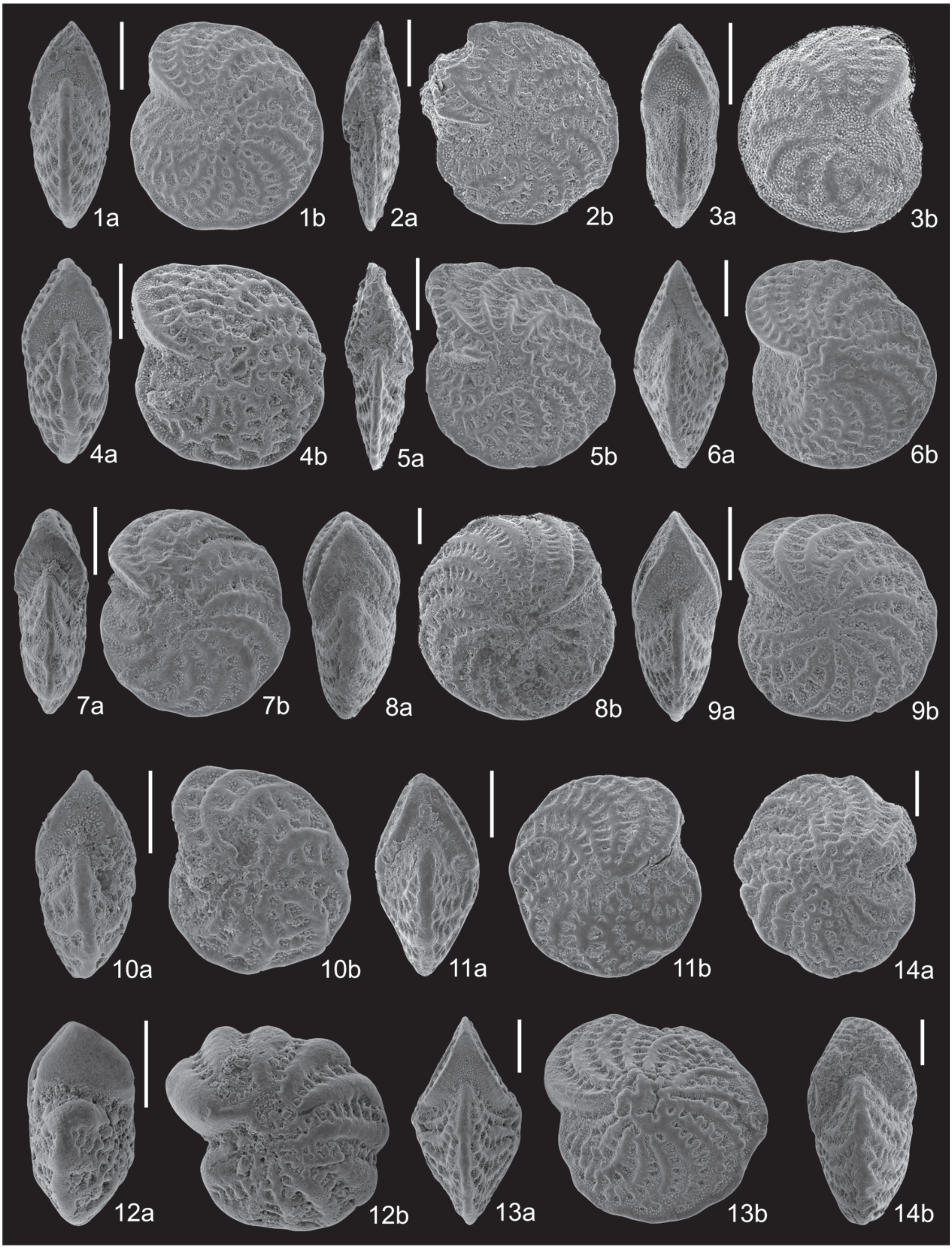

Fig. 6. *Elphidium* species. **1a–b** — *Elphidium macellum* (Fichtel & Moll), sample 32; **2a–b** — *Elphidium joukovi* Serova, sample 31; **3a–b** — *Elphidium argenteum* Parr, sample 26; **4a–b** — *Elphidium macellum converia* Venglinski, sample 32; **5a–b** — *Elphidium joukovi* Serova, sample 31; **6a–b** — *Elphidium crispum* (Linné), sample 32; **7a–b** — *Elphidium macellum* (Fichtel & Moll), sample 26; **8a–b** — *Elphidium macellum* (Fichtel & Moll), sample 26; **9a–b** — *Elphidium macellum* (Fichtel & Moll), sample 31; **10a–b** — *Elphidium macellum converia* Venglinski, sample 32; **11a–b** — *Elphidium macellum* (Fichtel & Moll), sample 26; **12a–b** — *Elphidium ungeri* Reuss, sample 32; **13a–b** — *Elphidium crispum* (Linné), sample 1; **14a–b** — *Elphidium macellum* (Fichtel & Moll), sample 31. Scale bars = 200 µm.

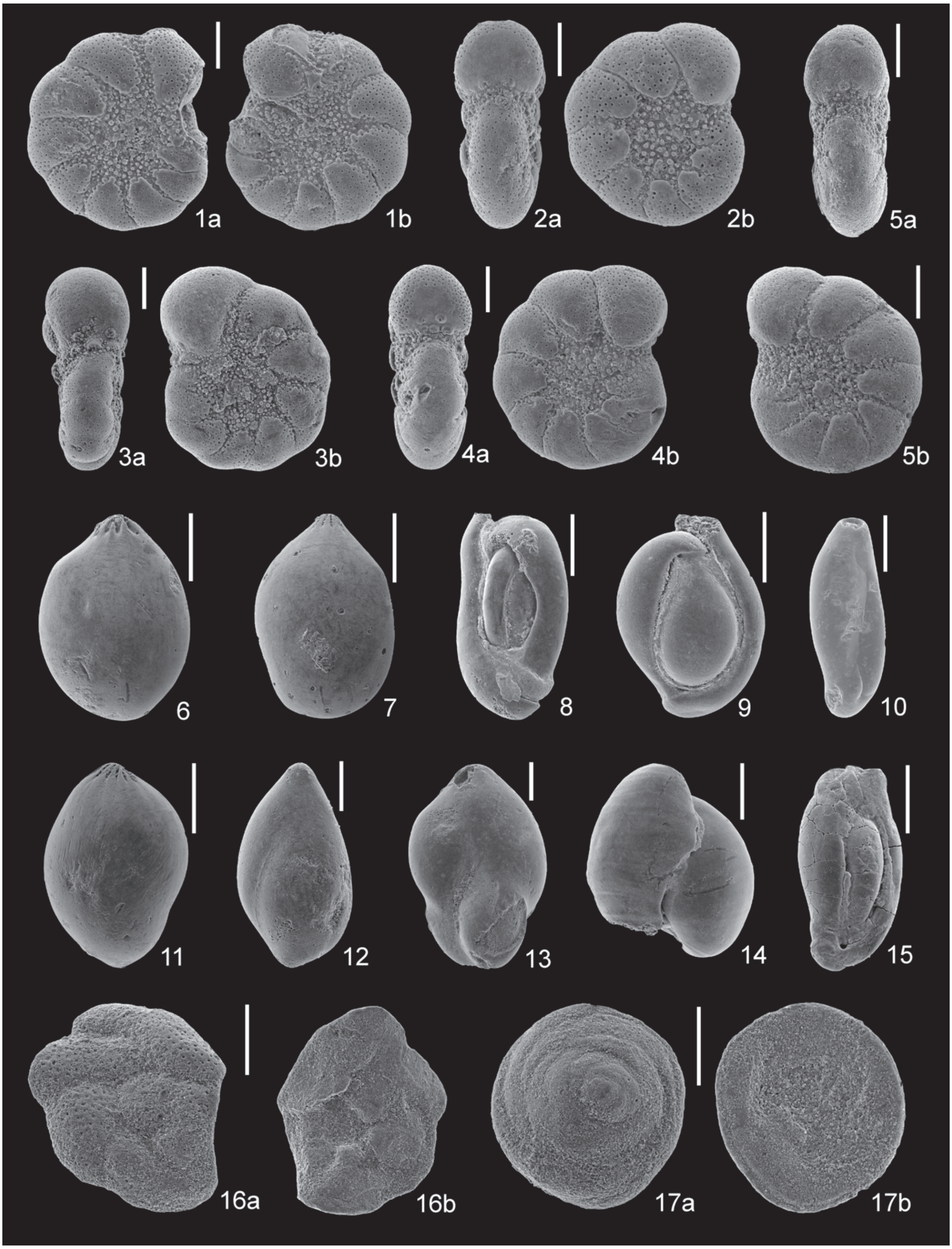

Fig. 7. Other foraminiferal taxa. **1–4** — *Porosononion martkobi* Bogdanowicz, sample 32; **5** — *Porosononion martkobi* Bogdanowicz, sample 31; **6** — *Glandulina* sp., sample 32; **7** — *Globulina gibba* d'Orbigny, sample 32; **8** — *Quinqueloculina akneriana* d'Orbigny, sample 32; **9** — *Triloculina* sp., sample 32; **10** — *Pseudotriloculina consobrina* (d'Orbigny), sample 32; **11** — *Glandulina* sp., sample 32; **12** — *Guttulina austriaca* d'Orbigny, sample 31; **13** — *Guttulina problema* (d'Orbigny), sample 31; **14** — *Pyrgo* sp., sample 32; **15** — *Quinqueloculina gracilis* Karrer, sample 31; **16** — *Rosalina* sp., sample 32; **17a–b** — *Asterigerinata planorbis* (d'Orbigny), sample 32. Scale bars 1–6 = 100 µm; 7–17 = 200 µm.

Table 3: Distribution of benthic foraminifers in samples of the Ratyn Limestone (their location is shown in Fig. 3).

Species \ Sample	25	26	27	31	32
Elphidium crispum (Linné)	2	140	8	160	145
Elphidium macellum (Fichtel & Moll)	1	121	2	102	97
Elphidium joukovi Serova	1	18	0	13	11
Elphidium ungeri (Reuss)	0	12	2	13	6
Elphidium argenteum Parr	0	11	0	9	7
E. macellum converia Venglinski	0	3	0	1	2
Elphidium spp.	2	41	2	34	29
Porosononion martkobi (Bogdanowicz)	1	61	1	1	11
Porosononion granosum (d'Orbigny)	1	27	0	1	14
Asterigerinata sp.	4	3	0	1	13
Pseudotriloculina consobrina (d'Orbigny)	0	34	1	3	9
Quinqueloculina spp.	0	3	0	8	34
Triloculina spp.	0	0	0	6	13
Guttulina spp.	0	3	0	3	5
Glandulina sp.	0	4	0	4	2
Globulina sp.	0	2	0	2	2
Lobatula lobatula (Walker & Jacob)	1	0	1	0	0
Rosalina sp.	0	0	0	0	1
Discorbis sp.	1	0	0	0	1
Nonion sp.	2	0	1	0	0
Anomalinoides certus Venglinski	1	0	0	0	0
Globigerina subcretacea Lomnicki	1	0	0	0	0
Textularia sp.	0	0	1	0	1
indet.	2	12	3	4	20
Total	20	495	22	365	423

Foraminiferal specimens in samples of the siliciclastic unit are usually very poorly preserved (sometimes undeterminable, as in sample 16) and/or recrystallized. Sample 3 yielded a few specimens of *Riminopsis boueanus* and *Lobatula lobatula*, and sample 7 had *Lobatula lobatula*, *Lenticulina* sp., *Globulina* sp. and ?*Anomalinoides* sp. in addition to several broken bryozoan specimens. Several small biserial planktonic foraminifers (?*Heterohelix* sp. or ?*Chiloguembelina* sp.) occur in sample 13. Sample 9 yielded ?*Porosononion* sp., *Elphidium joukovi*, *Quinqueloculina* sp. and ?*Asterigerinata* sp., and sample 14 did *Melonis pompilioides*, *Elphidium joukovi*, *Quinqueloculina* sp., ?*Asterigerinata* sp., *Lobatula lobatula*, *Bulimina* sp. and ?*Spiroloculina* sp.

Samples 25 and 27 yielded rare foraminifers: *Porosononion martkobi*, *Elphidium joukovi*, *E. crispum*, *Elphidium* sp., *Anomalinoides certus*, *Nonion* sp., ?*Asterigerinata* sp., *Lobatula lobatula*, *Bulimina* sp. A single specimen of planktonic *Globigerina subcretacea* has been recorded in sample 25.

Assemblages of samples 26, 31 and 32 (which as mentioned contain abundant foraminifers) are dominated by elphidiids. They form 70 to 90 % of foraminiferal assemblages. The most common are two species: *Elphidium crispum* and *E. macellum*. In addition, rare *E. joukovi*, *Elphidium* sp., *E.* cf. *argenteum, Asterigerinata* sp. and *Eponides* sp. as well as common *Porosononion martkobi* and *Pseudotriloculina consobrina*, occur in sample 26.

Samples 31 and 32 are characterized by large-sized elphidiids. *Elphidium crispum* is very often strongly biconvex and heavily ornamented, *E. macellum* exceeds 800 μm in diameter. Small *E.* cf. *argenteum* and *E. joukovi* are present in low numbers. *Glandulina*, *Guttulina*, *Pseudotriloculina* and *Quinqueloculina* are minor components of the assemblage. *Porosononion martkobi* occurs rarely in the samples.

Petrography and stable isotopes of carbonates

The results of microfacies and stable isotope study of the carbonates are summarized in Table 1. The rocks show relatively little petrographical variation. In the siliciclastic unit, limestones show various contribution of quartz grains — from subordinate to dominating in which carbonate occurs in the form of cement. There are three types of limestone: pelletal (either pelletal wackestone with pseudomorphs after gypsum crystals and relics of microbial lamination or pelletal packstone), sparitic with pseudomorphs after gypsum crystals and relics of microbial lamination, and intensively gypsified grainy rock containing clasts of microbially-laminated limestone (Fig. 8C) and rare shell fragments (Fig. 8E,F), ostracods (Fig. 8F), possibly foraminifers (Fig. 8D) and bryozoans. Sparitic limestone was also recorded in the 10-cm-thick limestone bed which covers the gypsum. Sparitic and microsparitic limestones occur in the lower intercalations, pelletal wackestones (sometimes becoming laminated — Fig. 8B) in the middle intercalations, and, in the upper part of the siliciclastic unit, pelletal limestone with relics of microbial texture (Fig. 8A) occur accompanied by fine-grained sandstones

The Ratyn Limestone is mixed-fossil lithoclastic packstone/grainstone with common quartz grains (Fig. 5B) and rare calcite pseudomorphs after discoidal gypsum crystals. The bioclasts are composed of bivalves, ostracods and gastropods. Usually the Ratyn Limestone unit contains a discontinuous marly bed (Figs. 3–4) and the limestone bed overlying the marly bed is characterized by lithoclast grainstone texture, with common quartz grains in the lower part (Fig. 5C). The bioclasts of bivalves and ostracods, similar to those recorded in lowest part of the Ratyn Limestone, were also recognized in the limestone bed. In its upper part quartz grain become rarer. Above the limestone, within a muddy matrix (Fig. 4), pebbles of various carbonate and gypsum rocks occur: lime mudstone (Fig. 5D), pelletal mudstone with ostracods, and mixed-fossil lithoclastic grainstone with foraminifers, ostracods and bivalves. This bed contains a very rich foraminiferal assemblage, as is characterized above. Higher up in the section, mixed-fossil lithoclastic grainstones occur. The fauna is very rich and contains foraminifers, brachiopods, bivalves, bryozoans, crinoids, echinoids, ostracods and rhodoids (Fig. 5A).

Stable isotope study of limestone samples showed that they are characterized by a large range of $\delta^{13}C$ and $\delta^{18}O$ values: the $\delta^{13}C$ values range from −1.6 ‰ to −18.2 ‰ (average 9.0 ‰), and the $\delta^{18}O$ values range from −0.2 ‰ to −9.4 ‰ (average −4.8 ‰) (Table 1, Fig. 9). The range and average $\delta^{13}C$ values from limestones in the siliciclastic complex are from −1.6 ‰ to −18.2 ‰ (average −10.2 ‰). Carbon isotope values from the Ratyn Limestone range from −4.6 ‰ to −15.4 ‰ (average −7.2 ‰). The range and average $\delta^{18}O$ values for limestones in the siliciclastic complex are from −0.2 ‰ to −9.4 ‰ (average −5.2 ‰) and for the Ratyn Limestone they are from −2.7 ‰ to −6.5 ‰ (average −4.3 ‰) (Fig. 9). Plot of data (after Peryt et al. 2008) characterizing marine limestone forming an intercalation within the stromatolitic gypsum is shown in Figure 9; the average $\delta^{13}C$ and $\delta^{18}O$ values are −7.1 ‰ and −1.8 ‰, respectively.

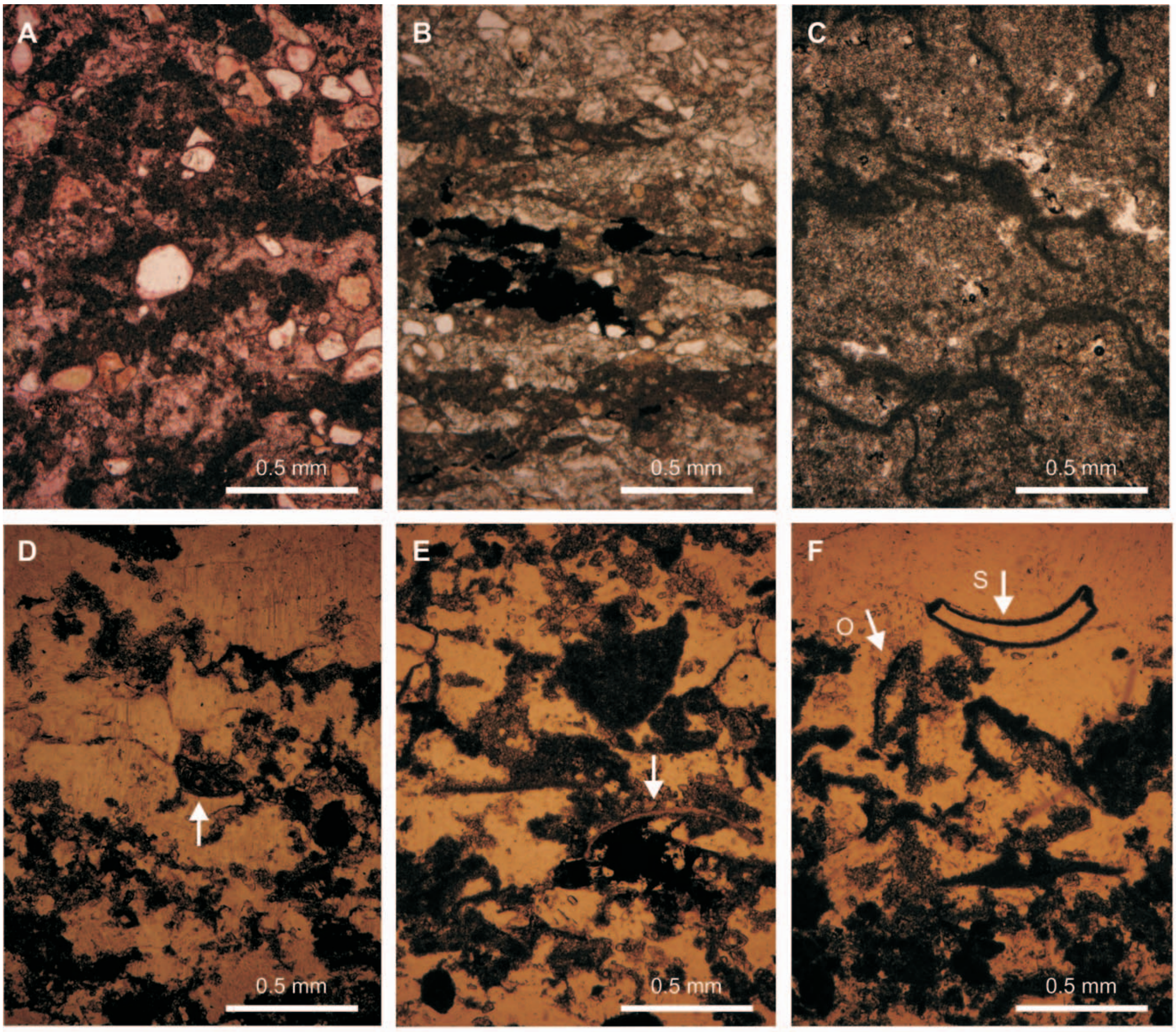

Fig. 8. A, B — Photomicrographs of limestones occurring in the siliciclastic series: A, B — pelletal limestones with quartz grains and relics of microbial texture (A — sample 10, B — sample 15). **C** — Microbial texture in clast within the lenticular gypsified grain-supported limestone (sample 20) shown in D–F. **D–F** — Bioclasts in gypsified grain-supported limestone (sample 20): D — foraminifer (?) (arrowed); E — shell fragment (arrowed); F — bivalve fragment (s) defined by micritic envelope and ostracod (o) (arrowed).

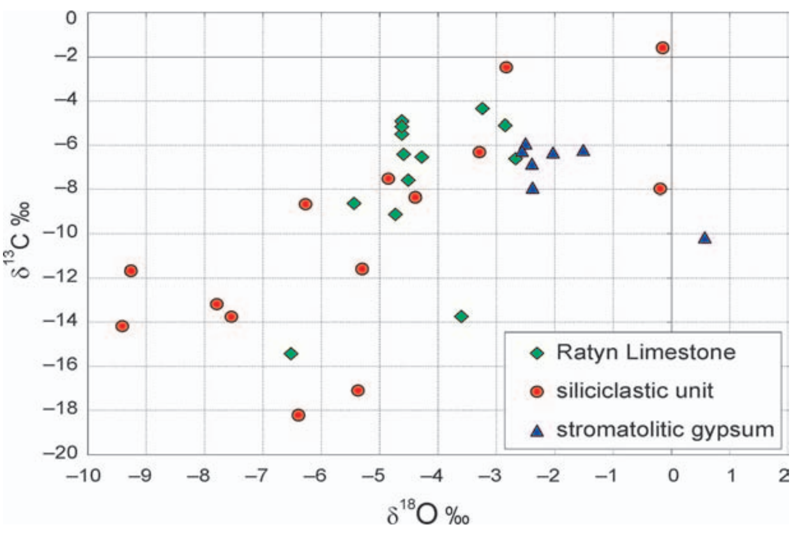

Fig. 9. Plot of isotope data (C, O) of various limestones of the Tyras Suite of the Kudryntsi: the Ratyn Limestone, limestones within siliciclastic unit and limestone intercalation within stromatolitic gypsum (after Peryt et al. 2008); samples of the Ratyn Limestone and limestones within the siliciclastic unit are characterized in Table 1.

Phase composition

The results of XRD study are summarized in Table 2. Two sets of samples: one taken from the Ratyn Limestone and the second one from the siliciclastic unit differ in minor constituents: dolomite and celestite occur only in the set from the siliciclastic unit, and feldspar and zeolite occur in the Ratyn Limestone.

Interpretation

Foraminifers

The environmental requirements of recent benthic foraminifers have been subject to many studies (e.g. Murray 1991, 2006; Hottinger et al. 1993; Hayward et al. 1997; Debeney et al. 2005; Abbene et al. 2006). Some Miocene foraminiferal species still live in recent seas. Assuming that they had similar ecological distribution and they were similar in trophic requirements to those of present foraminifers, we can interpret the paleoenvironment in which they lived.

The rarity of foraminifers and their generally very poor state of preservation as recorded in all samples from the siliciclastic unit suggest that they are probably reworked and redeposited. This conclusion is strongly supported by the occurrence of redeposited Cretaceous forms in the sample 13. In contrast, in the sample set from the Ratyn Limestone foraminifers are abundant and with no trace of redeposition. Assemblages are dominated by elphidiids which are opportunistic and generally live in sediment as epifaunal or infaunal dwellers (Murray 1991; Hayward et al. 1997). Elphidiids are herbivores but they may be sometimes detrivorous. Their main diet is usually pinnate diatoms (Murray 1991). They exhibit a variety of distribution patterns ranging from restricted to cosmopolitan. Cosmopolitan elphidiids may occur in different climate zones around the world; some live in warmer waters, some show a sporadic distribution in several widely separated areas and others are widely distributed in the tropics. Salinity and water depth are also important ecological controls for this group as well as water depth and the degree of exposure to high wave and current energy (Hayward et al. 1997) and various *Elphidium* species exhibit distinct environmental preferences. Elphidiids are characterized by two morphologies: some possess the peripheral keel, others have rounded peripheries. Keeled morphotypes are mostly herbivorous, epifaunal dwellers preferring sandy sediment, occurring in shallow marine environments (inner shelf) with warm to temperate and normal to hypersaline (35–70 ‰) waters (Murray 2006).

Foraminiferal assemblages in the Kudryntsi section are dominated by two keeled elphidiids: *Elphidium crispum* and *E. macellum*. The *E. crispum* association occurs in recent seas in shallow subtidal (0–20 m) environments of normal marine salinity (30–35 ‰) and temperate to warm waters (8–18 °C) (Murray 2006). The preferred substrate is muddy sand, and seaweed. Additional common species in this association are *E. macellum, Rosalina globularis* and *Lobatula lobatula*. The *E. crispum* association is described from the Atlantic seaboard of Europe (Murray 1991). *E. crispum* is one of the most common species of *Elphidium* along the east coast of Australia and around some of the south-east Pacific islands (Hayward et al. 1997).

Quinqueloculina and *Porosononion* are other common constituents of foraminiferal assemblages recorded in the Kudryntsi profile. *Quinqueloculina* is an epifaunal dweller, living free or clinging on plants or sediment, herbivorous, preferring shallow normal marine to hypersaline (32–65 ‰) environments. Similar ecological requirements are characteristic of *Triloculina*, commonly occurring in combination with *Elphidium* and *Quinqueloculina* (Murray 1991). *Porosononion* is not present in the recent seas.

Assuming that Miocene foraminifers had similar environmental requirements to recent foraminifers, we can infer shallow subtidal environment of normal marine salinity and temperate to warm waters for the Kudryntsi site.

Petrography and stable isotopes of carbonates

The bioclastic microfacies of limestones of the Ratyn Limestone indicate a marine provenance. In contrast, limestone within the siliciclastic complex are barren of marine fauna. The pelletal depositional textures in that part of the section apparently originated in restricted environments. Sparry limestones with pseudomorphs after gypsum crystals are interpreted as formed in a restricted deposit as well, and the former gypsum crystals at least in some cases grew displacively within a carbonate deposit.

The provenance of the rare bioclasts (Fig. 8D–F) in strongly gypsified deposits remains enigmatic. A possible source is Lower Badenian coralline algal limestones occurring beyond the limit of gypsum deposition east of Kudryntsi. On the other hand, clasts of microbially-laminated limestone (Fig. 8C) may derive from the more marginal parts of the Badenian evaporite basin which have been eroded during the deposition of the upper part of the gypsum section following the block tectonics.

The bulk samples of all limestones analysed show negative carbon and oxygen isotope values and both strongly suggest the presence of isotopically light, meteoric water rather than only seawater or concentrated, ^{18}O-rich seawater-derived brines. The limestones have microspar and equant sparry calcite cements, and pore spaces and vugs as well as fissure fillings are filled with sparry calcite cement. To explain the stable isotope data, the sparite cementation and some recrystallization, but with preservation of most microfabrics, had to take place in meteoric-water-dominated fluid. An alternative explanation (the influence of hydrothermal fluids) is not supported by field or petrographic evidence. It is remarkable that the average $\delta^{18}O$ values in limestones of Kudryntsi follow a restriction-controlled trend. The most positive field is the one characterizing the intercalation within the stromatolitic gypsum unit, and the most negative field is the one corresponding to the period of pre-Ratyn Limestone deposition (Fig. 9). The field of the Ratyn Limestone occupies an intermediate position between the most restricted (evaporitic) environment in which the stromatolitic gypsum was deposited and the evaporitic lagoon in which the siliciclastic deposits originated and which was influenced by large inflows of continental waters carrying the siliciclastic and other detrital material.

The $\delta^{13}C$ and $\delta^{18}O$ values for bulk carbonates of the Upper Badenian from the Vienna Basin are between 3 ‰ and −2.3 ‰ and between 0.1 ‰ and −5.1 ‰, respectively (Kováčová et al. 2009), and are interpreted as controlled by limited open-marine exchange — the more negative the more restricted. Kováčová et al. (2009) related the strong negative isotope ratio to the fresh water input of the paleo-Danube which affected the near-surface waters. We also relate the observed trend in the $\delta^{13}C$ and $\delta^{18}O$ values of Kudryntsi to restriction-controlled environment although a much more widespread data set is recorded in Kudryntsi, probably because of the more complex recystallization due to many episodes of dissolution and reprecipitation and thus changes in isotopic composition of the final precipitated carbonate.

Phase composition

It is remarkable that there is a strong similarity in the phase composition of the first deposits of the Late Badenian transgression and the laminated gypsum below the limestone intercalation within the stromatolitic gypsum unit (Table 2). This supports the earlier interpretation of the origin of that intercalation as due to influx of fresh seawater (cf. Peryt 2001).

Discussion

The Kudryntsi section documents the importance of the recycling of previously formed evaporites during deposition of the upper part of the Badenian gypsum sequence (cf. Peryt et al. 2002). Afterwards, in relation to the structural rebuilding of the Carpathian Foredeep, the gypsum deposits underwent partial erosion which was previously recorded in various parts of the basin (e.g. Aleksenko 1961; Bobrovnik 1966; Kubica 1992; Peryt & Peryt 1994). The erosion was related to subaerial exposure, although not the entire basin, even in its more marginal part, has desiccated, and in some local depressions thicker accumulations of clastic gypsum have formed (e.g. Peryt et al. 2004b). In such local depression, the siliciclastic deposits (with intercalations of limestones) overlying gypsum at Kudryntsi have been deposited.

The subsequent transgression which led to deposition of the Ratyn Limestone (and associated marls) was controlled by a general sea-level rise outside the Central Paratethys realm (Kováč et al. 2007). This change in the hydrology of the Central Paratethys implies the dilution of brines by inflowing marine water. This act terminated the Badenian salinity crisis, and the basin water returned to a normal salinity (Peryt 2006). In SE Poland, the pteropod-rich lower part of the Spirialis Clay Member is followed by the foraminifer-rich upper part of the Member. Planktonic fauna appear first followed by benthic foraminifers. Common occurrence of stenohaline pteropods is interpreted as due to mass extinction caused by mixing of the upper water bed that was of normal salinity and of moderate temperature, with the warmer, lower water bed of high salinity (Peryt 2006). The foraminiferal assemblages of the upper part of Spirialis Clay Member indicate an outer shelf setting where the water salinity was close to normal (Czepiec & Kotarba 1998). However, such a scenario assumed for a more basinward location is not necessarily correct for more peripheral zones of the basin as indicated by the Kudryntsi section.

First, the foraminiferal assemblages of the Kudryntsi section are dominated by *E. crispum* association indicating shallow-water environments of normal marine salinity (30–35 ‰). The first moderately diversified assemblage of benthic foraminifers, recorded in the marly bed below the limestone bed from which samples 28 and 29 derive, is followed by a low-diversified assemblage, almost entirely composed of elphidiids. This assemblage occurs in the marl bed contained between the first and second limestone beds (sample 32). In the close neighbourhood of the latter bed, another moderately diversified assemblage of benthic foraminifers occurs, and it is accompanied by a very varied macrofauna assemblage recorded in the limestone bed. This, in general, indicates general amelioration of environmental conditions.

Second, during the deposition of the siliciclastic unit, neighbouring calcareous deposits were being eroded and transported towards local depressions. In the Kudryntsi area, the gypsum is underlain by thin Upper Cretaceous and Badenian coralline algal limestones which rest upon Silurian deposits. The presence of dolomite as a minor component of marls indicates the Silurian source of carbonates whereas redeposited foraminifers suggest the Cretaceous and Badenian sources. These redeposited carbonates were the source of carbonate in the siliciclastic unit. Marls and limestone intercalations of the siliciclastic series are practically barren of fauna. It seems that the transporting agent of the carbonate as well as siliciclastic grains was the continental water, which anyway was the main inflow during evaporite deposition in the Carpathian Foredeep Basin as proved by Cendón et al. (2004).

As was mentioned earlier, sporadic occurrence of marine fauna in clay intercalations within the gypsum of the evaporite facies zone III indicates incursions of seawater (Venglinskiy & Goretskiy 1966). However, in most cases the anoxic conditions characteristic of evaporite deposition were accompanied by (very) incomplete dilution of the dense bottom brines so preventing the colonization of the bottom by marine fauna, but the dilution effect could have been sufficient to prevent the further deposition of gypsum (i.e. the salinity was below 150 ‰ — see Orti Cabo et al. 1984). In the case of the siliciclastic complex with limestone intercalations at Kudryntsi, the source of the waters which diluted the residual brines was probably the continent. When the oxic conditions prevailed over the shallower parts of the basin and the salinity dropped below 80 ‰, calcium carbonate pelletal mud could originate (Orti Cabo et al. 1984). The salinity finally dropped following the inflow of fresh seawater although very locally during the first phases of transgression, even in oxic conditions, the water salinity was high enough to allow for displacive growth of lenticular gypsum crystals.

Implications

A dramatic decrease in water salinity occurred during deposition of the studied interval — from ca. 150–300 ‰ during the Badenian gypsum precipitation (cf. Peryt 1996), to not more than 35 ‰ during the deposition of the bed which yielded the abundant foraminiferal assemblage dominated by *Elphidium crispum* and *E. macellum*. This implies that the inflowing seawater bed had a volume enabling, after mixing with the relict brines, salinity conditions suitable for the colonization of the sea bottom by fauna. At the same time, the magnitude of rise of sea level can be estimated as several tens of meters. At the end of evaporite-related deposition in the Kudryntsi area the depth was less than a dozen meters in the depressions. The local recrystallization of the uppermost part of gypsum as well as the scoured surface of gypsum suggest that in some places the gypsum deposits underwent subaerial exposure. The lack of planktonic foraminifers in the assemblage of the lowest part of the transgressive Upper Badenian strata supports the conclusion that the depth of deposition was less than 20 m. This suggestion is also based on the environmental requirements of *E. crispum* association (as discussed above).

Until now the first limestone overlying gypsum deposits in the Carpathian Foredeep seemed to be the Ratyn Limestone (see Peryt & Peryt 1994, with references therein). The present study proves that it is not correct as limestone beds occur within the siliciclastic series which is genetically related to the terminal stages of development of the Badenian evaporite basin. Therefore, the term "Ratyn Limestone" should be applied only to marine-derived limestone formed during the Late Badenian transgression.

Conclusions

Micropaleontological and geochemical study of the pelites of the siliciclastic series occurring above the Badenian gypsum deposits and below clearly marine deposits (limestones and intercalated marls with abundant faunal assemblage) of the Kudryntsi section (West Ukraine) showed that they formed from the redeposition of the material coming from the older Badenian rocks as well as from the substrate to the evaporite basin. However, this phase of reworking with substantially decreased salinity because of the inflow of great volume of continental water loaded with the eroded particles. The siliciclastic series contains rare redeposited microfauna, and limestone intercalations within the siliciclastic series are barren of fauna. The limestone intercalations within the siliciclastic series display a pelletal depositional texture and are apparently formed in restricted environments. The bulk samples of all limestones show negative carbon and oxygen isotope values. The limestones have microspar and equant sparry calcite cements, and pore spaces and vugs as well as fissure fillings are filled with sparry calcite cement. To explain the stable isotope data, the sparite cementation and recrystallization had to take place in meteoric-water-dominated fluid. The $\delta^{18}O$ values in limestones of Kudryntsi follow a restriction-controlled trend similar to that assumed for the Upper Badenian from the Vienna Basin (Kováčová et al. 2009). However, the much wider ranges of $\delta^{13}C$ and $\delta^{18}O$ values in Kudryntsi are probably result of considerably more complex recrystallization owing to many episodes of dissolution and reprecipitation. The faunal assemblage in the marine strata records a gradual improvement of environmental conditions — the first limestone contains bivalves, ostracods and gastropods, and the second limestone bed contains a very rich, diversified faunal assemblage. A similar (although more complex) pattern results from the study of benthic foraminiferal assemblages which are dominated by *E. crispum* association indicating shallow environments (0–20 m deep) with a normal marine salinity (30–35 ‰).

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