Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Sedimentary Geology 170 (2004) 21–36

Sedimentary Geology

www.elsevier.com/locate/sedgeo

Post-evaporitic restricted deposition in the Middle Miocene Chokrakian-Karaganian of East Crimea (Ukraine)

Tadeusz Marek Peryt[a,*], Danuta Peryt[b], Marek Jasionowski[a], Andriy V. Poberezhskyy[c], Tomasz Durakiewicz[d,e]

[a] Państwowy Instytut Geologiczny, Ul. Rakowiecka 4, 00-975 Warsaw, Poland
[b] Institute of Paleobiology, Polish Academy of Sciences, Twarda 51/55, 00-818 Warsaw, Poland
[c] Institute of Geology and Geochemistry of Combustible Minerals, National Academy of Sciences of Ukraine, Naukova 3A, 79053 Lviv, Ukraine
[d] Mass Spectrometry Laboratory, Institute of Physics, Maria Curie-Sklodowska University, 20-031, Lublin, Poland
[e] Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Received 16 December 2003; received in revised form 15 March 2004; accepted 7 April 2004

Abstract

In the Middle Miocene of East Crimea, gypsum evaporites formed in a shallow basin from mixed seawater–nonmarine waters are overlain by marl, siltstone and claystone which contain a few horizons of stromatolitic limestone. The thickness and abundance of the stromatolitic horizons increase up the section. In the siliciclastic portion of the section, a very poor and taxonomically impoverished assemblage of benthic foraminifers (*Jadammina*, *Nonion*, *Haynesina*, *Astrononion* and *Eponides*) is recorded. It is typical for a shallow water marsh or lagoon environment with a lowered salinity. Accordingly, the brackish conditions prevailing during gypsum precipitation in East Crimea continued afterwards, although at the end of evaporite deposition the basin became desiccated and then it was rapidly reflooded by brackish water.

The impoverished biota and the occurrence of microbialites in the Ptashkino section indicate extremely unfavourable conditions for most living organisms during the deposition of both the terrigenous and carbonate beds. The water salinity thus was probably not only lowered but also anomalous in composition if compared to normal marine water. The occurrence of carbonate stromatolitic horizons is probably related to the periodic shallowing of the basin caused by a drop of the lake water table driven by climatic factors. The resulted changes allowed for a growth of the bizarre microbial-serpulid communities that gave birth to most of the stromatolites.

In Karaganian time, the Eastern Paratethys was a huge lake isolated from the Tethys. This lake responded to any climatic fluctuation that in turn might lead to water level oscillations. In humid climate periods, the lake could be open with a surface outflow and, when it was drier, it could be a closed system without surface outflow. Gypsum evaporites and stromatolitic carbonates are clear evidence of strong evaporation in a dry climate that probably induced water level fall in the whole basin. However, all the time the environmental conditions were predominantly brackish, even during gypsum precipitation as suggested by the chemical composition of fluid inclusions in gypsum. Similar conditions may be expected in other evaporite-hosted, predominantly brackish basins, such as some Messinian basins of the eastern

---

* Corresponding author. Fax: +48-22-8495342.
E-mail address: tperyt@pgi.waw.pl (T.M. Peryt).

doi:10.1016/j.sedgeo.2004.04.003

Mediterranean, where some evaporites were deposited in the oligohaline to mesohaline conditions typical of the Lago Mare deposits.

Keywords: Stromatolites; Middle miocene; Palaeoenvironments; Foraminifers; Geochemistry; Evaporite basins

1. Introduction

The Middle Miocene in some Peri-Tethyan basins was characterised by the occurrence of evaporites. In the Central Paratethys, evaporites occur in the Karpatian and Badenian. Although the general picture of Badenian evaporites is well known, the precise series of events leading to the onset and then the termination of evaporite deposition are much debated (Babel, 1999; Peryt, 2002, with references therein). In the Carpathian Foredeep, Badenian evaporites are bounded by two maximum flooding surfaces and must represent a major transgressive–regressive–transgressive cycle. The calcareous nannoplankton indicates that Badenian evaporites represent the lower part of the NN6 zone (Peryt, 1997, 1999; Andreyeva-Grigorovich et al., 2003).

In the Middle Miocene of Eastern Paratethys, the transition from marine environments to brackish conditions was gradual (Rögl, 1998). In east Crimea, in the Middle Miocene Chokrakian, a marine transgression began after a long continental period. Starting from that time till the end of Pliocene, shallow seas existed in the area of Kerch Peninsula (Figs. 1 and 2) (Kropacheva, 1981). The development of Neogene deposits of the Kerch Peninsula was controlled by numerous small anticlines (with Maykopian clays in their nuclei) that originated due to clay diapirism during Tarkhanian-Chokrakian times, as indicated by the thicknesses of the Middle Miocene deposits within anticlines and adjacent synclines. At tops of the anticlines, the Chokrakian oolithic-bioclastic bars and bryozoan reefs developed that separated the shallow lagoons from the open sea. Gypsum was

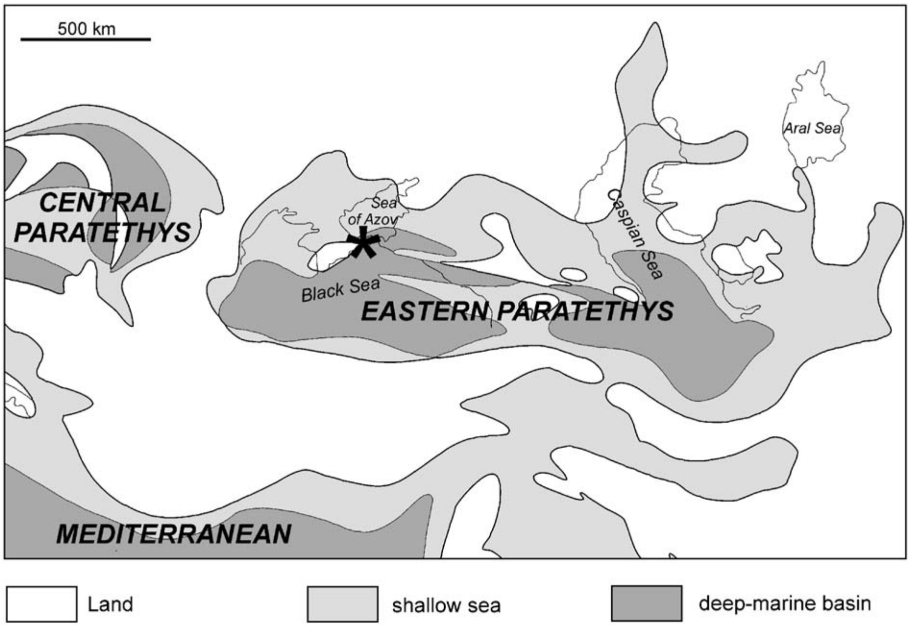

Fig. 1. Paleogeography of the Eastern Paratethys in the beginning of the Middle Miocene (Chokrakian–Early Badenian–Langhian) (after Goncharova, Shcherba and Khonkarian in Gontsharova, 2001, Fig. 1). Asterisk shows the location of Ptashkino section.

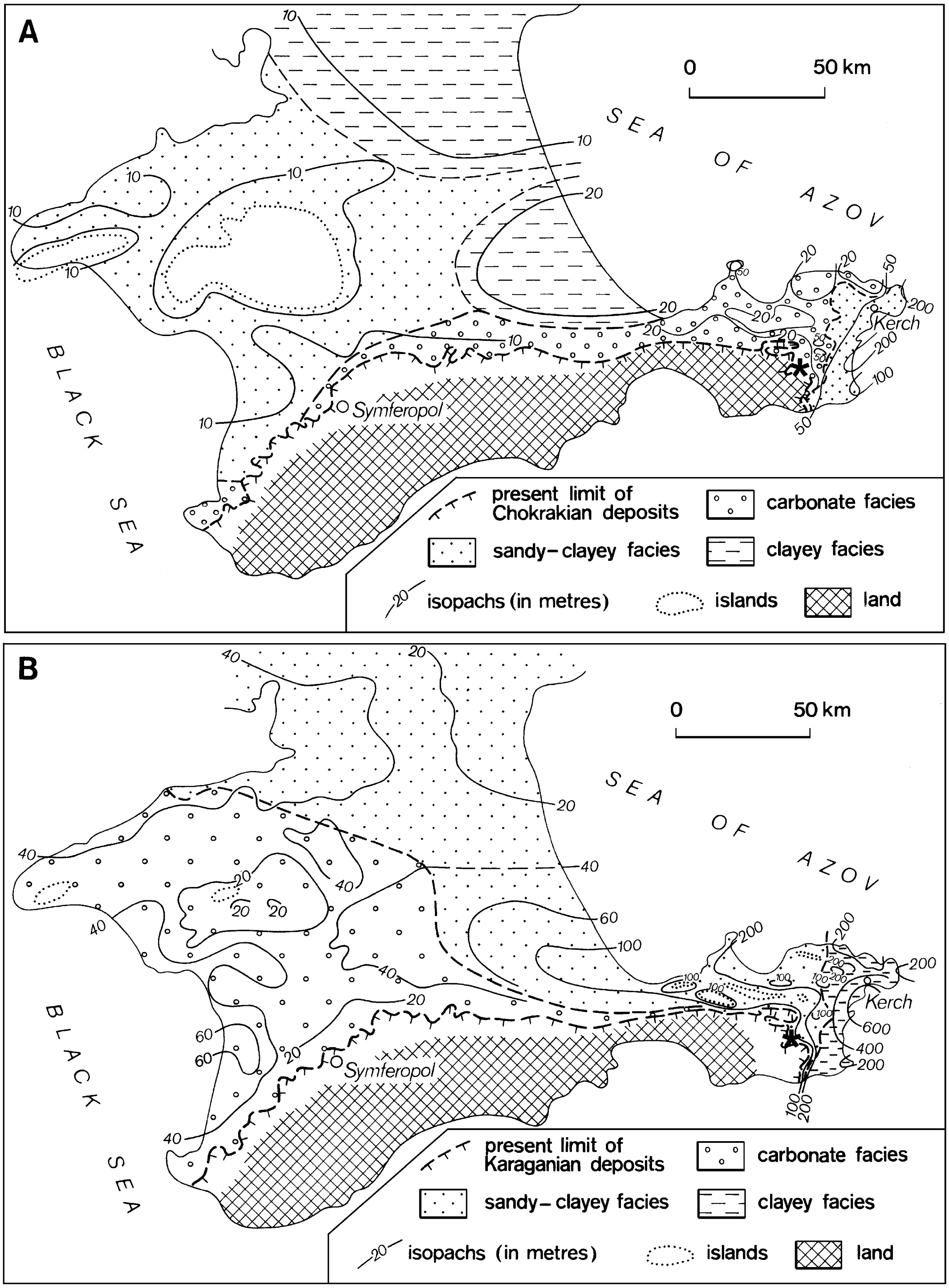

Fig. 2. Location of the Ptashkino section (asterisk) showing the lithofacies distribution during Chokrakian (A—after A.E. Kamenetskiy and V.E. Zheleznyak in Muratov, 1973) and Karaganian and Konkian times (B—after A.E. Kamenetskiy and V.E. Zheleznyak in Muratov, 1973).

deposited in the lagoons, but due to continual transgression, the gypsum deposition quickly ceased and was replaced by sedimentation of interbedded claystones and limestone (Kropacheva, 1981).

We have selected and studied one section located in eastern Crimea aiming to characterise the sedimentary environments during this major environmental change. Gypsum deposits in East Crimea are probably coeval with the Badenian evaporites of the Carpathian Foredeep and thus it is important to understand tectonic and climatic constraints leading to widespread, coeval evaporite deposition in Middle Miocene in the entire Paratethys basin system. These evaporites in the Paratethys are followed by brackish-water deposits, and thus the general sequence resembles the classical Messinian sequence where marine deposits are followed by evaporites and then brackish Lago Mare facies (e.g. Rouchy et al., 2001). New data illustrating the environmental changes, which occurred in the Crimean part of the Eastern Paratethys at the end of the evaporite deposition, may thus provide information helpful to interpret "Messinian Salinity Crisis" in the Mediterranean region.

2. Geological setting

The biostratigraphic calibration of the Middle Miocene of Eastern Paratethys is poor. The Tarkhanian, Chokrakian, Karaganian and Konkian stages have collectively been correlated with the Badenian of Central Paratethys. The Tarkhanian sections yielded calcareous nannoplankton characteristic for the NN5 Zone (Nosovskiy et al., 1976; Andreyeva-Grigorovich and Savytskaya, 2000) and the Mid-Miocene age of other stages is assumed on regional evidence as direct biostratigraphic evidence is lacking (see reviews by Jones and Simmons, 1996; Gontsharova, 2001).

The Chokrakian carbonate deposits with poor marine fauna and subordinate clay intercalations are followed by the Karaganian deposits that consist of interbedded carbonates and clays in the lower part (the Chekur-Koyash Beds) and of predominant clays (Karaganian Clay Series) in the upper part (Fig. 3). The Karaganian deposits are also characterized by very poor biota. For example, all the Karaganian bivalve fauna consist of 11 endemic species belonging to 3 genera only (Studencka et al., 1998, p. 330).

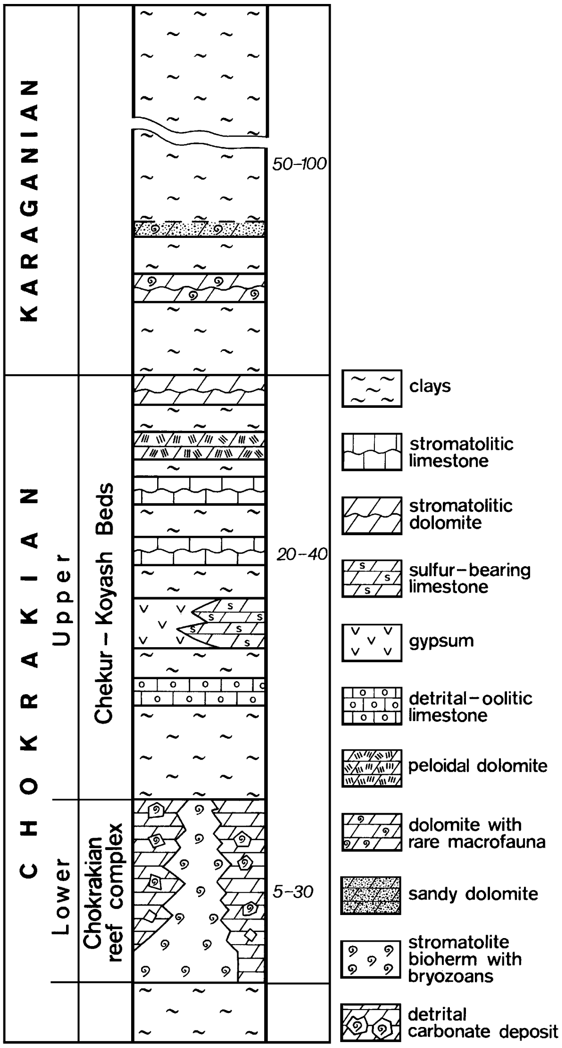

Fig. 3. Composite section of the Middle Miocene rocks on Crimea (after Kropacheva, 1981).

The age of the Chekur-Koyash Beds is unequivocal as their fauna consists of sparse specimens of long-lasting species and, hence, for example, the age of gypsum was regarded by some workers to be Chokrakian (e.g. Poltorakov et al., 1979). Other workers assume that the gypsum horizon occurs in the lower part of Karaganian deposits (e.g. Shnyukov et al., 1971; Nevesskaya et al., 1984). In places, the gypsum and post-gypsum limestone are host rocks for sulphur (e.g. Ishchenko and Kisilov, 1967; Pavlenko et al., 1974; Arkhipova and Mamchur, 1975) and hence they have been studied in detail. Laterally the Chekur-Koyash Beds can be replaced by thin (up to 7 m) stromatolitic limestones and dolomites that occur in the top of anticlines (Kropacheva, 1981).

During the exploration of sulphur deposits numerous boreholes have been drilled near Ptashkino and in other areas of eastern Crimea. The results have been summarised by Kropacheva (1976, pp. 68–70), who observed that carbonate rocks (most commonly dolomites) occur 20–30 m above the sulphur-bearing deposits, and are covered by clays. She recorded the presence of serpulids and fragments of *Spaniodontella* within the stromatolites and, in the "pockets" within stromatolites, occurrence of phosphatised fish bones, terrigenous grains and small (< 0.5 mm) ooids. In the Chokrakian deposits, coprolites are very common while in the Karaganian deposits they are rare or lacking.

We have studied the Ptashkino section located in the eastern part of the Kerch Peninsula in the eastern Crimea, 30 km SW of Kerch city and 7 km NW of Marievka village. In an abandoned quarry of the biggest gypsum deposit in Crimea-Elkedzhi-Eli (Polakova, 1974), ca. 25-m-thick deposits are exposed (Figs. 4 and 5).

The lower part of the Ptashkino section is composed of gypsum evaporites. Their thickness varies from 0.8 to 5.3 m (Polakova, 1974); at present ca. 5 m is exposed. There occurs the lower fine crystalline gypsum laminated with abundant admixture of limestone, sand, and clay and the upper coarsely crystalline (selenitic) gypsum. Kropacheva (1981) recorded nodular and chicken-wire facies as well as erosional features in the uppermost part of gypsum. Kulchetskaya (1987, p. 170) studied geochemistry of the gypsum and concluded that crystallization of gypsum occurred in the warm and shallow basin of relatively low salinity.

In the upper part of the section (ca. 20 m thick) marls, siltstones and claystones occur which contain, in the uppermost part of the section, thin (up to 8 cm thick) intercalations of cross-bedded sandstones. In addition, thin intercalations of stromatolitic limestone occur, and the thickness and frequency of the stromatolitic horizons increase up the section (Figs. 4 and 5).

The stromatolites form continuous horizons that can be traced several hundred meters along the quarry wall and are a few centimetres to ca. 1 m thick. In places within these stromatolitic layers, there occur slightly thicker and dome-shaped structures (Fig. 4).

Fig. 4. View of the upper part of Ptashkino section. Stromatolitic dome is seen above the man (1.7 m tall).

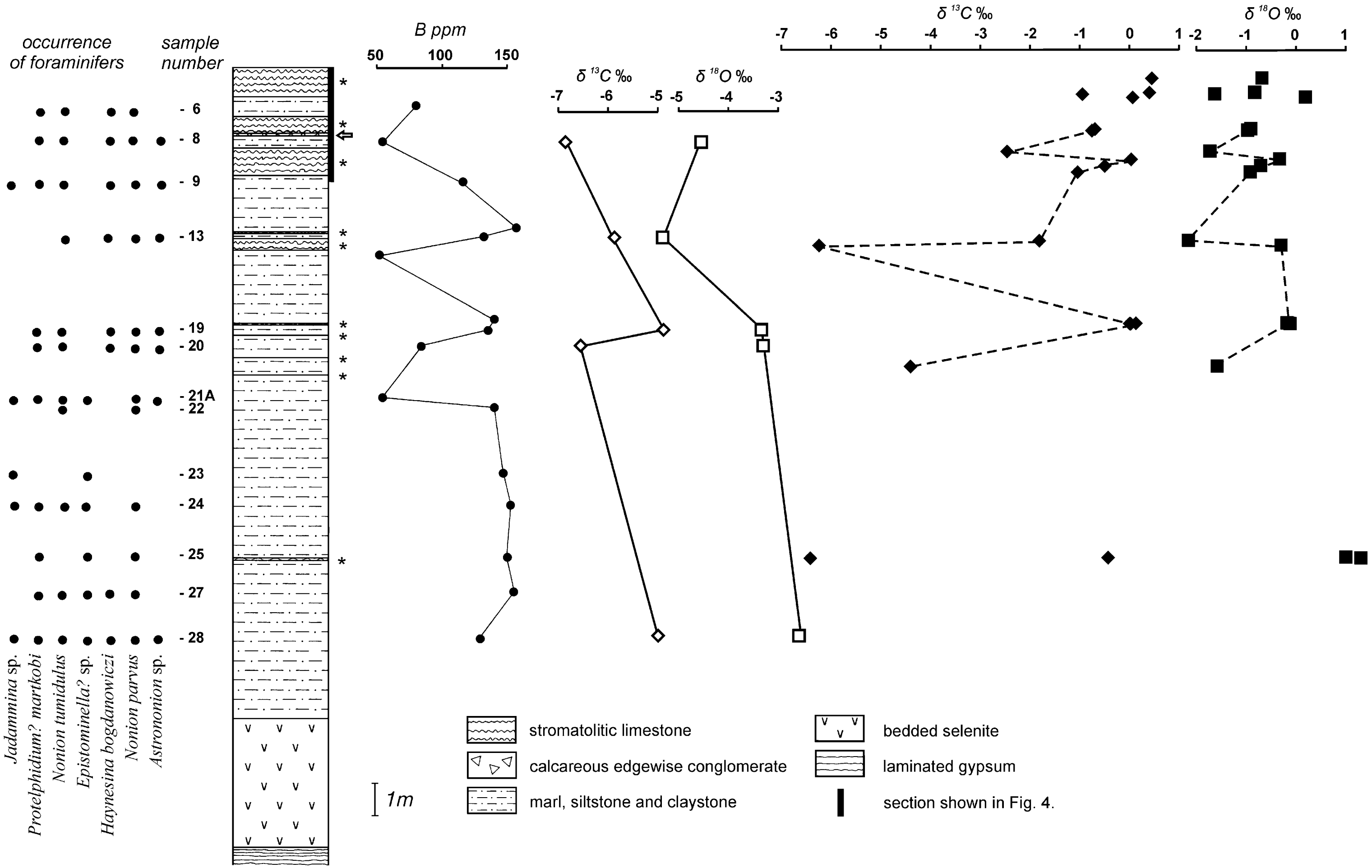

Fig. 5. Lithological log of the Ptashkino section, distribution of foraminifers, boron content in siliciclastic deposits, and carbon and oxygen isotopic data on foraminifers (open symbols) and limestone samples (black symbols). Asterisks indicate intercalations of stromatolitic limestone, and arrow shows the occurrence of calcareous edgewise conglomerate.

The stromatolites contain intercalations of oolitic grainstones with rip-up mudstone clasts. In marls, siltstones and claystones gypsum satin spar veins commonly occur.

3. Methods

A stratigraphic section was measured and 16 samples were taken from each individual layer for micropalaeontological studies in order to establish the presence of foraminifers, calcareous nannoplankton and dinocysts. However, only foraminifers have been found.

In the same samples, clay minerals and boron content have been determined at the Central Chemical Laboratory of the Polish Geological Institute (Warsaw, Poland). The boron content was measured using a Philips PV8060 Spectrometer; the error of determination is 3–5%.

To establish the mineralogical composition, analyses were made using the X-ray diffraction method. The Philips X-ray Diffractometer System PW1840 with Cu-tube and solid state detector provided with an automatic computerized powder identification system APD 1877 was used. Diffractometer measurements were made on raw samples in the 3–60° 2θ range of angles on pressed specimens, and on clayey fraction (<0.002 mm) samples in the 3–60° 2θ range on oriented and heated specimens.

In addition, petrological and geochemical investigation of limestone was carried out. Thirty-three

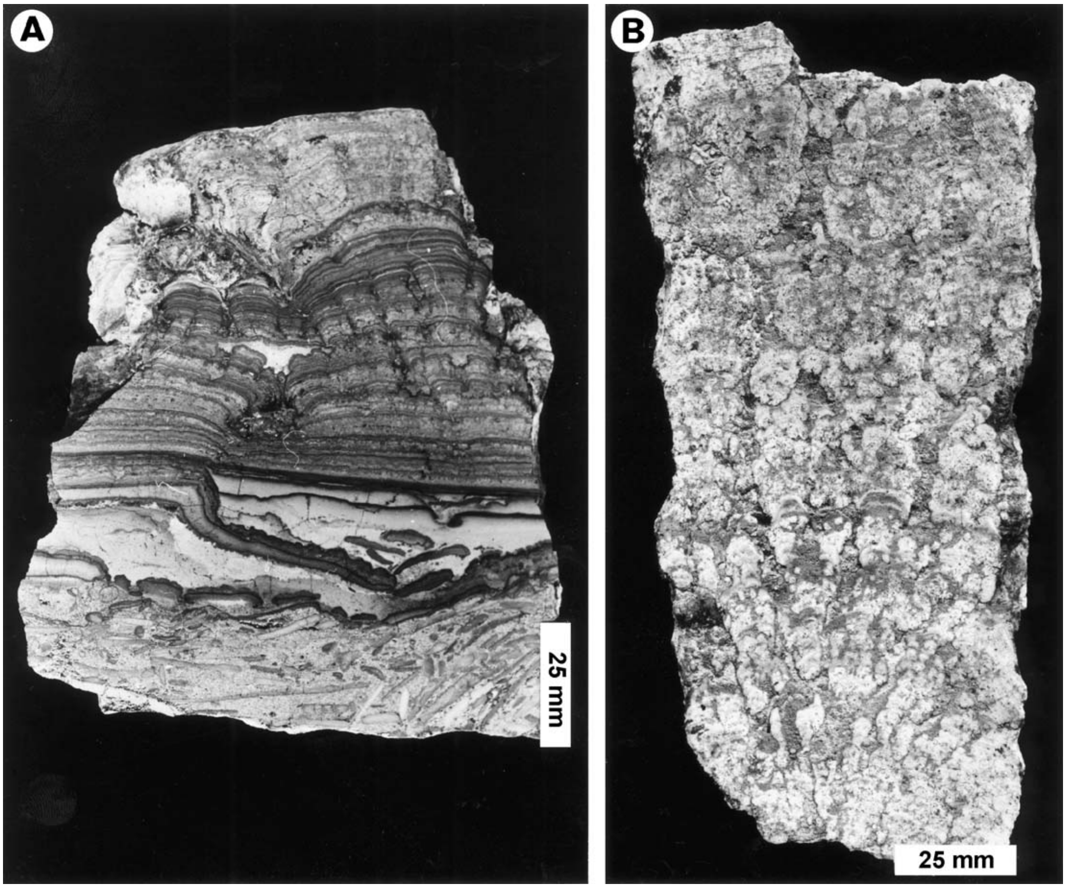

Fig. 6. Polished slabs of stromatolites. (A) Laminated planar and columnar stromatolites (upper part of the photo) growing on the edgewise conglomerate due to reworking of desiccation polygons (lower part). (B) Thrombolitic stromatolites: centimetre-scale light-colour branching columnar stromatolitic clots are separated by spaces filled up with darker micritc and terrigenous material.

oxygen and carbon isotopic analyses (5 samples of isolated foraminifers from marly layers and 28 selected places in limestone samples) were done at the Institute of Physics, University Maria Curie-Sklodowska, Lublin, Poland. For isotopic analyses of limestone, CO_2 gas was extracted from the samples by reaction of calcite with H_3PO_4 (McCrea, 1950) at 25 °C in a vacuum line, following the standard. The gas was purified of 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 (Durakiewicz, 1996) equipped with a gas ion source. Isobaric correction was applied. After subsequent normalisation to measured certified reference materials, the isotopic composition was expressed in per mill (‰) relative to the VPDB international standard and separately to PDB. Analytical precision of both $\delta^{13}C$ and $\delta^{18}O$ in a sample was ± 0.08‰.

A total of 41 thin sections was studied. Thin sections were stained with Alizarin Red S and potassium ferricyanide to assist the identification of dolomite and to assess the Fe content of the carbonates.

4. Results

Stromatolites exhibit variable morphologies and microstructures that can be included into two main types.

In some parts of the section occur stromatolitic horizons (see Fig. 6A) made up of laminated columnar or hemispherical bodies up to few or more centimeters in size and more or less planar or wavy

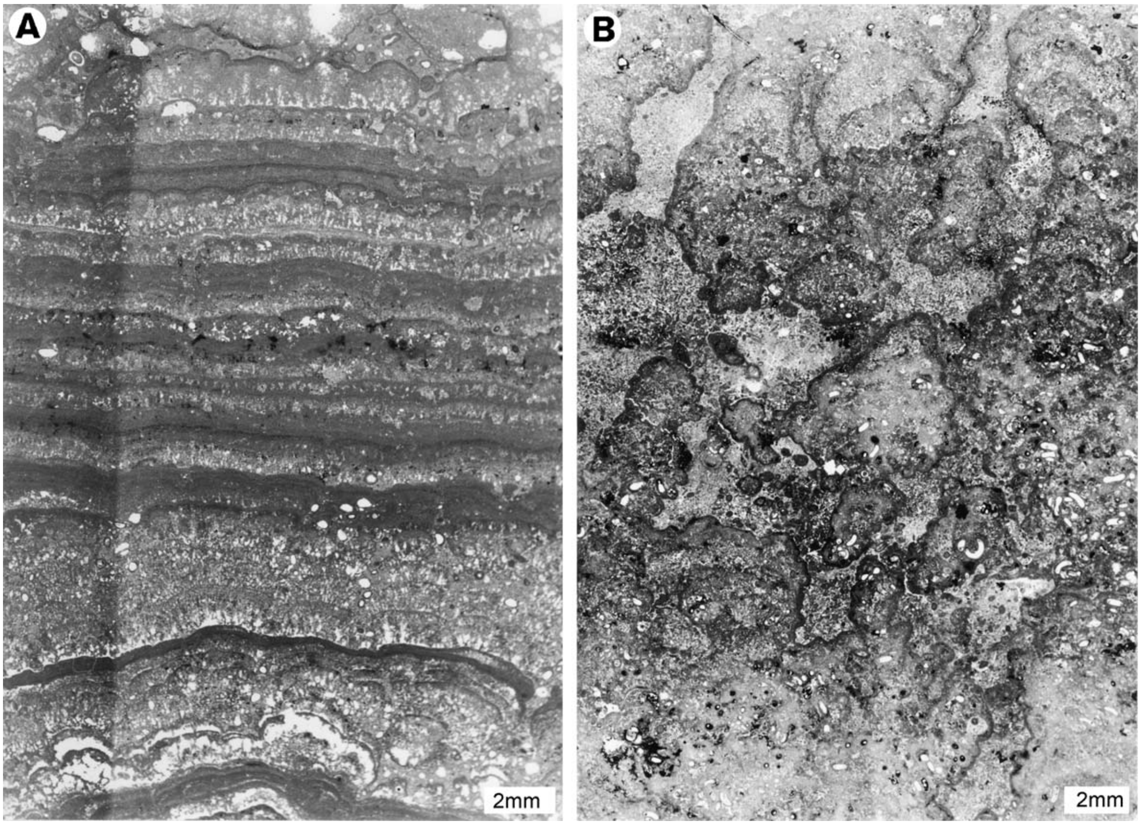

Fig. 7. Thin section microphotographs of stromatolites. (A) Laminations within columnar stromatolites. Thinner dark dense micritic laminae are alternated with thicker and porous micrite laminae. The latter ones exhibit bushy microstructures that are probably moulds left by cyanobacterial filaments. (B) Small branching columns that form thrombolitic stromatolites are made-up of faintly laminated or dense micrite and coiled tubes of a tiny serpulid warm (?*Spirorbis*). The spaces between columns are packed with pellets, ooids, silty quartz grains, bioclasts and micrite.

laminated layers. The stromatolites consist of millimetric or submillimetric couplets of dark dense micritic laminae alternated with much thicker and more porous micrite laminae (Fig. 7A). The latter ones often exhibit bushy microstructures that are probably moulds left by cyanobacterial filaments (Fig. 8A). The moulds are empty or occluded with microspar. In other cases, the stromatolites show faint microlaminations only (Fig. 9A). The large interstices between domes and columns are packed with relatively coarse material dominated by rounded carbonate grains of unclear origin (probably faecal pellets) with bioclasts as well quartz or lithoclast grains. Fine terrigenous material and micrite occur also within stromatolites filling up small interstices (that cut few laminations) as well spaces between millimetre-scale knobs and columns that constitute the larger scale stromatolite domes and columns (Fig. 9A). In places, thin intercalations of limy mudstones occur within the stromatolitic laminations indicating periods of more active sedimentation.

The second stromatolite type that forms mainly the upper horizons in the section, consist of a kind of thrombolitic fabrics (Fig. 6B). It is composed of small (1 cm across, few centimetres high) branching columns that are made-up of faintly laminated or dense micrite and coiled tubes of a tiny serpulid warm (?*Spirorbis*) (Fig. 7B). The serpulid tubes constitute

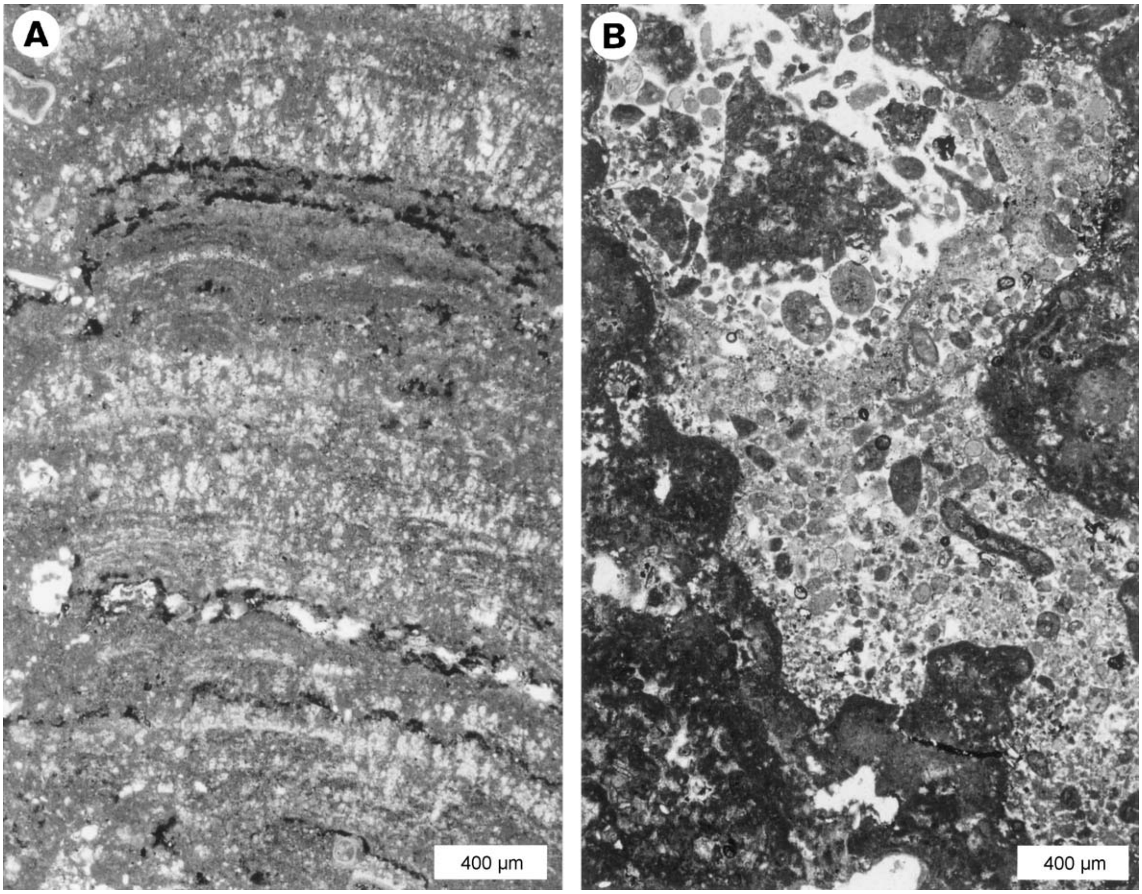

Fig. 8. Thin section microphotographs of stromatolites. (A) Faint laminations with bushy fabrics. The erect pores occluded with microspar are probably moulds left by cyanobacterial filaments. (B) Fine material filling up the spaces between thrombolitic bodies is mainly composed of pellets together with some ooids, quartz grains and stromatolitic lithoclasts.

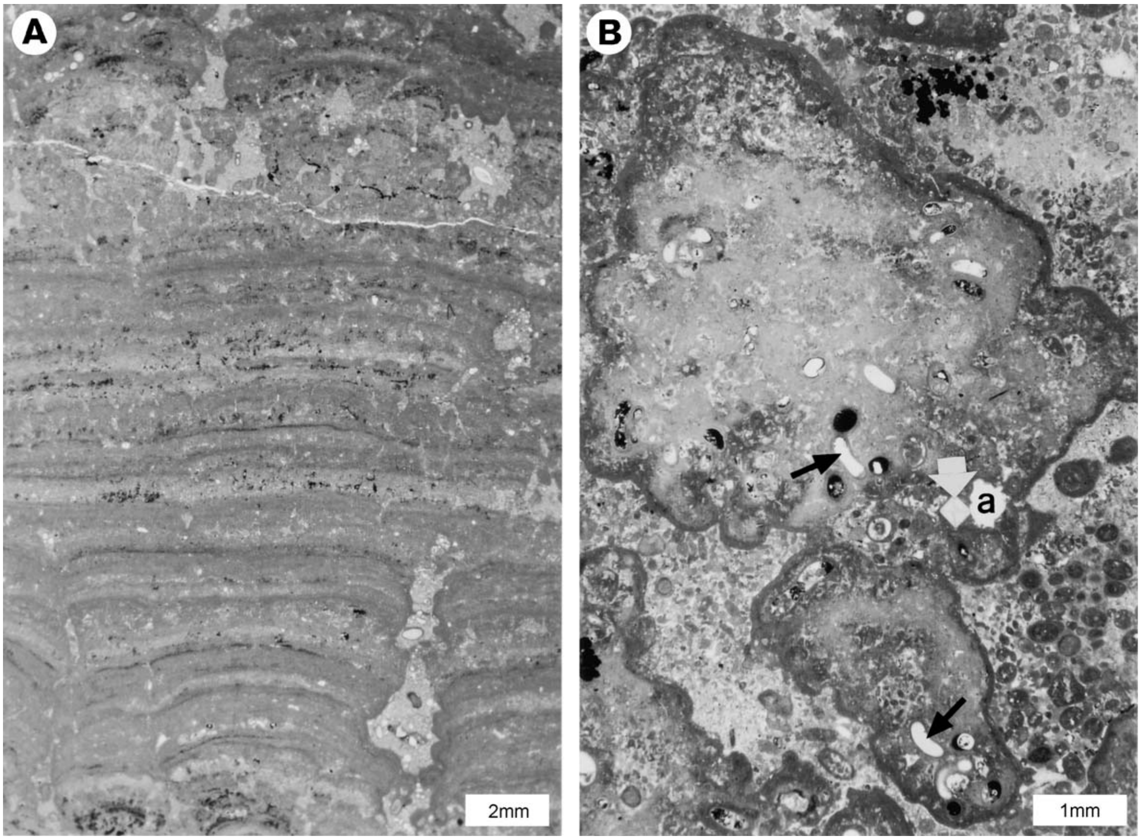

Fig. 9. Thin section microphotographs of stromatolites. (A) Faintly laminated columnar stromatolite. Fine terrigenous material and micrite fill up small interstices cutting laminations and spaces between millimetre-scale knobs and columns that constitute this large stromatolitic column. (B) A single column within thrombolitic stromatolite with coiled serpulid tubes (black arrows) constituting a foundation for the column, and square pore (white arrow) which is interpreted as mould after dissolved halite crystal; a—artefact (pore formed during thin section preparation).

a foundation for the microbialites (Fig. 9B). In places pellets, ooids and quartz grains are involved into the microbialite fabrics. Additionally, within some microbialitic columns very rare, single, square pores occur (Fig. 9B). They are few tens of micrometers in size, empty or filled with sparite. Kropacheva (1981) interpreted the pores as moulds after dissolved halite crystals.

The interstices between columns are packed with pellets, ooids, silty quartz grains, bioclasts and micrite (Fig. 8B). The thrombolites are rich in brownish iron oxides that are dispersed within laminations or often coat the outer surfaces of stromatolitic bodies.

Fossils and bioclastic grains within the stromatolitic horizons are extremely rare. Except for the serpulid tubes there occur additionally some small thin-shelled bivalves and, in the highest stromatolitic horizon, gastropods. Absence of any microfossils is striking.

In the siliciclastic portion of the section studied samples contain sparse to moderately abundant benthic foraminiferal assemblages consisting of seven species belonging to six genera. Calcareous taxa include *Astrononion* sp., *Nonion parvus*, *Nonion tumidulus*, *Haynesina bogdanowiczi*, *Protelphidium*? *martkobi* and *Epistominella*? sp. (Fig. 10). *Jadammina* sp. (Fig. 10) is the only agglutinant. In several samples (nos. 8, 13, 19, 20 and 28), the abundances are high, in some they are considerably lower (Nos. 6, 24, 27) and in the other foraminifers occur only very rarely. Distribution of the recorded species in the Ptashkino section is presented on Fig. 5.

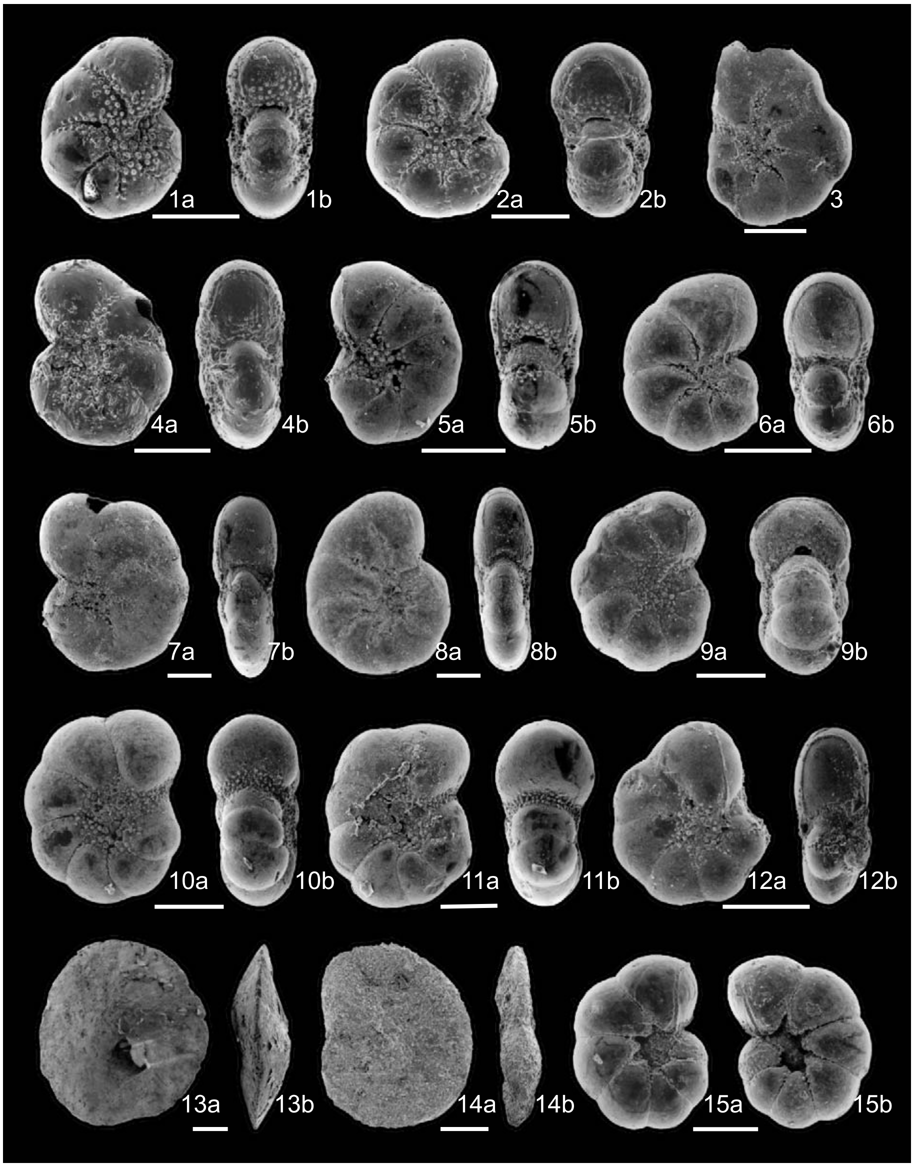

Fig. 10. SEM photographs of foraminiferal taxa from Ptashkino (1, 6—sample 27; 2, 4—sample 9; 3, 5, 7, 9, 10, 12, 14, 15—sample 28; 8, 13—sample 24; 11—sample 19). Scale bars represent 100 μm. (1) *N. parvus* Bogdanowicz, 1950 (a—lateral view, b—apertural view); (2) *N. parvus* Bogdanowicz, 1950 (a—lateral view, b—apertural view); (3) *H. bogdanowiczi* (Voloshinova, 1952), lateral view; (4) *N. tumidulus* Pishvanova, 1960 (a—lateral view, b—apertural view); (5) *N. tumidulus* Pishvanova, 1960 (a—lateral view, b—apertural view); (6) *N. parvus* Bogdanowicz, 1950 (a—lateral view, b—apertural view); (7) *H. bogdanowiczi* (Voloshinova, 1952) (a—lateral view, b—apertural view); (8) *H. bogdanowiczi* (Voloshinova, 1952) (a—lateral view, b—apertural view); (9) *N. parvus* Bogdanowicz, 1950 (a—lateral view, b—apertural view); (10) *P.*? *martkobi* Bogdanowicz, 1947 (a—lateral view, b—apertural view); (11) *Nonion martkobi* Bogdanowicz, 1947 (a—lateral view, b—apertural view); (12) *N. tumidulus* Pishvanova, 1960 (a—lateral view, b—apertural view); (13) *Epistominella*? sp. (a—umbilical view, b—edge view); (14) *Jadammina* sp. (a—trochospiral view, b—edge view); (15) *Astrononion* sp., lateral views.

The mineralogical studies showed that the main constituents are quartz, calcite, feldspars and muscovite, and in the lower part, in addition, also gypsum. The following clay minerals have been identified: illite, kaolinite and chlorite.

The boron content measured are from 53 to 156 ppm (average is 117 ppm) (Fig. 5).

Fig. 5 and Table 1 show the results of isotopic analyses of limestone samples and foraminifers in the studied section, and Fig. 11 shows the plot of isotopic results. It should be mentioned that in Fig. 5 the results of isotopic study are shown only for samples taken from the quarry wall. Table 1 and Fig. 11 include all results. δ^{18}O values range form −4.5‰ to +1.3‰ PDB but most samples fall in the interval −2‰ to 0‰ PDB. δ^{13}C values are more variable (from −9.6‰ to +0.5‰ PDB, with most samples close to 0‰ PDB). C and O stable isotope analyses of foraminifer tests from the terrigenous parts of the section reveal very low values of δ^{18}O (−6.5‰ to −2.5‰ PDB, average −3.81‰ PDB) and δ^{13}C (−7‰ to −5‰ PDB, average −5.89‰ PDB).

Table 1
Results of the carbon and oxygen stable isotopes studies (Ptashkino section)

Sample number	Location in the section (above the gypsum, in meters)	δ^{18}O ‰ [PDB]	δ^{13}C ‰ [PDB]	Sample description
2	20.00	−0.67	0.48	stromatolite
3/2	19.55	−1.62	−0.92	thrombolite
3/1	19.55	−0.81	0.43	thrombolite
4/1	19.50	−0.27	0.30	stromatolite
4/2	19.50	−0.32	0.18	stromatolite
5	19.40	0.21	0.09	stromatolite
7/2	18.50	−0.89	−0.67	thrombolite
7/1	18.45	−0.96	−0.73	thrombolite
B/6	18.30	0.30	0.22	stromatolite
B/5	18.25	−0.20	−0.24	stromatolite
B/1	18.24	−2.53	−9.59	mud
B/4	18.23	−0.68	−1.00	stromatolite
B/2	18.21	−3.29	−5.55	ooids
B/3	18.20	−1.17	−4.51	rip-up clast
10C	17.70	−1.72	−2.44	thrombolite
10B/2	17.45	−0.31	0.06	stromatolite
10B/1	17.25	−0.69	−0.47	thrombolite
10A	17.05	−0.90	−1.02	thrombolite
12	15.20	−1.18	−3.01	mud
14B	14.90	−2.15	−1.79	thrombolite
14A	14.75	−0.28	−6.24	ooids
18/3	12.31	−0.16	0.16	stromatolite
18/1	12.30	−0.13	0.03	stromatolite
18/2	12.29	−0.10	0.05	stromatolite
21	10.95	−1.57	−4.39	mud
26/2	4.95	1.03	−0.40	thrombolite
26/1	4.93	1.33	−6.41	mud

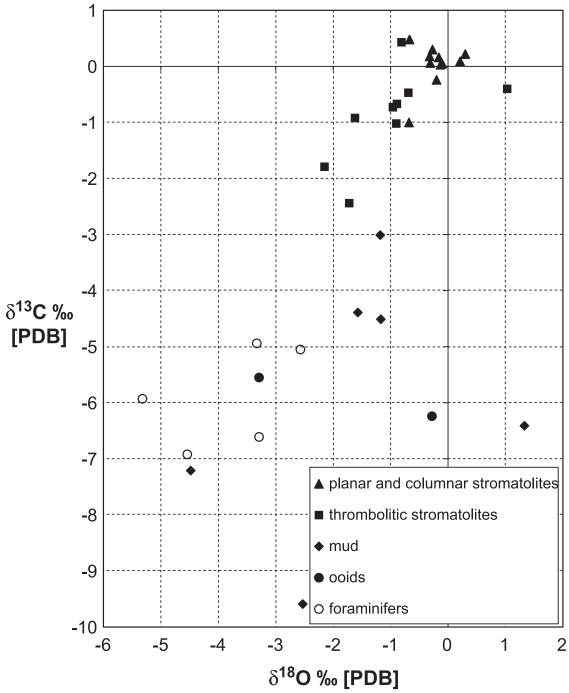

Fig. 11. Plot of carbon and oxygen isotopic data.

5. Interpretation

The composition of fluid inclusions in selenitic gypsum of Ptashkino indicates that the gypsum has formed from relatively dilute (2–6% mass equiv. NaCl according to Kulchetskaya, 1987, p. 170), mixed seawater–nonmarine waters.

Environmental requirements of Recent representatives of foraminifers which were recorded in the marls occurring above the gypsum are as follows (after Boltovskoy and Wright, 1976; Murray, 1991).

Nonion is infaunal form preferring muddy or clayey deposit, occurring in different marine environments (from brackish to hypersaline and from warm to cold water), at the depth 0–180 m.

Haynesina is infaunal form preferring muddy or clayey deposit, occurring in shallow marine environments of low salinity (0–30‰) and warm to cold water.

Astrononion is infaunal or epifaunal form preferring cold waters. The genus is known both from shelf as well as bathyal environments.

Jadammina is epifaunal form tolerant for salinity (it occurs in environments of low to high salinity, mainly in marshes of tidal zone) and temperature (0–30 °C).

Epistominella is epifaunal, semi-infaunal form preferring muddy deposits, preferring moderate and cold waters from shelf to bathyal depths.

Foraminiferal assemblages from the Ptashkino section are sparse to moderately abundant, poorly diversified (Fig. 5), composed mainly of nonionids of very small and tiny tests. They are dominated by infaunal forms preferring muddy or clayey sediments as the substrate in which they are living (*Nonion*, *Haynesina*), brackish environments (*Haynesina*, *Jadammina*) or are tolerant for salinity (as *Nonion*); they are also tolerant for temperature changes. Foraminiferal assemblages taxonomically impoverished, dominated by a few species with very small sizes indicate adverse environmental conditions (e.g. Boltovskoy and Wright, 1976; Bernard, 1986; Koutsoukos et al., 1990).

Assuming that Miocene foraminifers were similar in environmental requirements to those of present foraminifera we can infer brackish, nearshore marine environments such as marshes and lagoons for the Ptashkino site (Boltovskoy and Wright, 1976; Banner and Culver, 1978; Murray, 1991).

Stromatolitic horizons made up of laminated columnar or hemispherical bodies and more or less planar or wavy laminated layers resemble some lacustrine stromatolites encountered in many sub-recent and fossil lakes (e.g. Casanova, 1994; Ramos et al., 2001). Serpulid-microbialite assemblages, although of quite different facies development, are known in other Miocene stratigraphic horizons in the Paratethys and stressed environment conditions (see Pisera, 1996). Other serpulid-microbialite associations occur also in some recent saline lakes or lagoons with variable salinities (e.g. Davaud et al., 1994; Bone and Waas, 1990).

C and O stable isotope studies of the stromatolites show δ^{18}O and δ^{13}C values rather beyond the marine realm. δ^{18}O values are from -2‰ to $+1$‰ PDB but most samples fall in the interval from -2‰ to 0‰ PDB (Table 1, Fig. 11). δ^{13}C values are more variable (from ca -2.5‰ to slightly above 0‰ PDB, with most samples close to 0‰ PDB). The stromatolitic deposits containing serpulids (thrombolites) are generally slightly depleted in heavier C and O isotopes (average $\delta^{18}O = -0.99$‰ PDB and $\delta^{13}C = +1.06$‰ PDB) in comparison to the laminated stromatolites lacking serpulids ($\delta^{18}O = -0.26$‰ PDB and $\delta^{13}C = +0.06$‰ PDB). The micritic sediments within stromatolitic horizons are much more depleted in heavy carbon isotope (δ^{13}C is from -3‰ to -10‰ PDB) and exhibit more dispersed δ^{18}O values (-4.5‰ to $+1$‰ PDB) if compared to stromatolites (Fig. 11).

The δ^{18}O in the carbonate precipitates depends on the oxygen isotopic composition of the water in which they were formed and the temperature of precipitation. In the case of any biological mediation in precipitation, so-called vital effects may play some role. The isotopic composition of the closed basin water body is determined by the water composition of inflow (what depends directly on the precipitation composition in the catchment area) and evaporation (Gonfiantini, 1986).

The stromatolites in the section studied formed in water much more enriched in heavy oxygen isotope than the foraminifers did. Even in comparison to normal marine water, the water had slightly increased content of the heavier oxygen isotope (δ^{18}O close to or somewhat higher than 0‰ VSMOW if assume precipitation temperature 20 °C). Such δ^{18}O values provide evidence for quite strong evaporation reaching at least few per mill as is indicated by the divergence between isotopic compositions of the foraminifers and the stromatolites (Fig. 11). Relatively high δ^{13}C values indicate only minor contribution of organic carbon or quite long residence time (no complete equilibration with atmospheric CO_2-in closed lakes, δ^{13}C values of sub-recent microbialitic calcites are usually close to $+2$‰ to $+5$‰ PDB) (see e.g. Talbot, 1990). The distinct difference in oxygen isotope composition between laminated stromatolites and thrombolites with serpulid tubes may be indicative of water of slightly different origins or temperatures of precipitation. The observed difference (average 0.73‰) needs temperature change of ca 4 °C what seems quite realistic. On the other hand, however, such a shift may be explained by a larger contribution of fresh (?meteoric) water containing carbonate organic origin. Such a scenario is supported by the generally much higher drop of δ^{13}C as well as by the fact that both δ^{18}O and δ^{13}C are much more scattered in the thrombolites with serpulid tubes than in the laminated stromatolites.

The stable isotope values measured in foraminiferal tests, if primary (which is supported by the lack of recrystallisation or cementation of the tests), are indicative of water with δ^{18}O reaching from -6‰ to -3‰ SMOW (assuming precipitation at the fixed temperature of 15 °C). Water with such isotopic composition must be of meteoric origin or must have a major meteoric input. The measured δ^{18}O values are in a good agreement with palaeontological data as well as with the general geological situation showing that in the Chokrakian-Karaganian time the basin was isolated or closed and consequently brackish. δ^{13}C indicates that the foraminiferal tests originated in waters with a great contribution of organic CO_2 what is typical of such brackish bottom environments in closed basin. The non-marine depositional environment is supported also by a relatively low boron content (from 52 to 158 ppm) of the clay minerals.

The clear distinction in δ^{18}O values measured in foraminifer tests and stromatolites (Fig. 11) provides evidence for complete change of hydrological regime in the basin between the periods of terrigenous and carbonate (stromatolitic) deposition. The basin changed periodically probably from the more open system when the terrigenous deposition took place to the closed one during stromatolitic carbonate sedimentation.

6. Discussion and conclusions

In Karaganian time, the Eastern Paratethys was a huge lake isolated from the Tethys (e.g. Rögl, 1998). This lake responded to any climatic fluctuation that in turn might lead to water level oscillations. In humid climate periods, the lake could be open with a surface outflow and, when it was drier, it could be a closed system without surface outflow. Gypsum evaporites and stromatolitic carbonates are clear evidence of strong evaporation in a dry climate that probably induced water level fall in the whole basin. Biotic data indicate that in the Chokrakian-Karaganian time the climate in the Eastern Paratethys area was warm (subtropical), and in the Karaganian it was much drier, probably with dry summers, than in the Chokrakian (Goncharova et al., 2001, p. 102).

In recent environments, selenitic gypsum forms by subaqueous growth of crystals nucleated on the bottom of hypersaline pools (e.g. Orti Cabo et al., 1984). The composition of fluid inclusions in selenitic gypsum of Ptashkino indicates brackish environment. Gypsum evaporites with marine isotopic signature formed in a brackish environment are not unique: they were earlier recorded in the Middle Miocene Badenian of Carpathian Foredeep (Petrichenko et al., 1997) and the Messinian of the southern Cyprus basin (Rouchy et al., 2001).

The geochemical data suggest that the youngest Middle Miocene Badenian sulphate deposits of the Carpathian Foredeep basin precipitated from brines that derived from waters being a mixture of relic seawater (depleted in NaCl), ground water (enriched in calcium sulphate) and surface run-off (see discussion in Peryt, 2001). These waters were very similar in composition to the water of the Aral Sea that is enriched in calcium sulphate (up to 1.5–1.6 g/l), and its density at the beginning of gypsum precipitation is 1.015 (Lepeshkov and Bodaleva, 1952), i.e. it is lower than the density of normal seawater (1.0257). In the central part of the Polish Carpathian Foredeep Basin, a regional angular unconformity developed between Badenian evaporites and overlying siliciclastics as is observed on all the seismic lines from this part of the basin, and in the eastern part a gentle onlapping of evaporites by siliciclastics is recorded (Krzywiec, 2001). The change of sedimentary conditions after the gypsum deposition was associated with the extension and then the intensive subsidence (cf. Dziadzio, 2000; Krzywiec, 2001), and the inflow of marine water terminated the Badenian salinity crisis. The pteropod-bearing claystones and marlstones that contain, in SE Poland, thin intercalations of sandstones and mudstones originated in outer shelf environment, and the water salinity was close to normal (Czepiec and Kotarba, 1998).

In the Messinian of the southern Cyprus basin, the onset of brackish conditions was recorded during the sedimentation of the uppermost gypsum (Rouchy et al., 2001). Typical brackish and freshwater fossil assemblages occur there in the last two gypsum layers and intergypsum beds. Accordingly, the oligohaline to mesohaline conditions typical of the Lago-Mare deposits in the eastern Mediterranean existed during deposition of the upper gypsum sub-unit (Rouchy et al., 2001). The isotopic composition of the gypsum proves the marine origin of the sulphate of the brines where gypsum precipitated, but these brines were diluted by massive inputs of meteoric water. Although the environmental conditions were predominantly brackish, there occurred some recurrences of evaporitic conditions (Rouchy et al., 2001).

The recorded assemblage of benthic foraminifers in the siliciclastic deposits of Ptashkino section is typical for a shallow water marsh or lagoon environment with a decreased salinity. This conclusion is supported by very low δ^{18}O and δ^{13}C values of foraminiferal tests. Accordingly, the brackish conditions prevailing during gypsum precipitation in Ptashkino, as indicated by study of fluid inclusions in gypsum, continued afterwards. However, as noticed by Kropacheva (1981), the characteristics of the uppermost part of gypsum suggest that desiccation of the basin took place at the end of evaporite deposition. The overlying deposits in turn indicate a rapid reflooding of the basin with brackish water, which was filling the entire East Paratethys basin.

The impoverished biota and the occurrence of microbialites in the Ptashkino section indicate extremely unfavourable conditions for most living organisms during the deposition both of terrigenous and carbonate beds. The water salinity thus was probably not only lowered but also anomalous in composition compared to normal marine water. The occurrence of carbonate stromatolitic horizons is probably related to the periodic shallowing of the basin caused by a drop of the lake water table driven by climatic factors. That in turn caused changes in the water chemistry, allowing a growth of the bizarre microbial-serpulid communities that gave birth to the most stromatolites.

Acknowledgements

O.I. Petrychenko organised the field expedition to Crimea in 1995. W. Narkiewicz studied mineralogical composition of claystones, J. Kucharzyk did boron analyses, P. Gedl examined the samples for dinocysts occurrence, and E. Davaud, F. Surlyk and M.R. Walter read and criticized the first draft of the paper. We are grateful to all of them.

References

Andreyeva-Grigorovich, A.S., Savytskaya, N.A., 2000. Nannoplankton of the Tarkhanian deposits of the Kerch Peninsula (Crimea). Geol. Carpath. 51, 399–406.

Andreyeva-Grigorovich, A.S., Oszczypko, N., Slaczka, A., Savitskaya, N.A., Trofimovich, N.A., 2003. Correlation of Late Badenian salts of the Wieliczka, Bochnia and Kalush areas (Polish and Ukrainian Carpathian Foredeep). Ann. Soc. Geol. Pol. 73, 67–89.

Arkhipova, L.D., Mamchur, G.P., 1975. Petrograficheskiye issledovaniya i izotopiya ugleroda C13 sernykh rud Kryma. Litol. Polezn. Iskop. (3), 121–127.

Babel, M., 1999. History of sedimentation of the Nida Gypsum deposits (Middle Miocene, Carpathian Foredeep, southern Poland). Geol. Q. 43, 429–447.

Banner, F.T., Culver, S.J., 1978. Quaternary Haynesina n. gen. and Paleogene Protelphidium Haynes; their morphology, affinities and distribution. J. Foraminiferal Res. 8, 177–207.

Bernard, J.M., 1986. Characteristic assemblages and morphologies of benthic foraminifera from anoxic, organic-rich deposits: Jurassic through Holocene. J. Foraminiferal Res. 16, 207–215.

Boltovskoy, E., Wright, R., 1976. Recent Foraminifera. Dr. W. Junk, The Hague. 15 pp.

Bone, Y., Waas, R.E., 1990. Sub-recent bryozoan-serpulid buildups in the Coorong lagoon, South Australia. Aust. J. Earth Sci. 37, 207–214.

Casanova, J., 1994. Stromatolites from the East African Rift: a synopsis. In: Bertrand-Sarfati, J., Monty, C. (Eds.), Phanerozoic Stromatolites, vol. II, pp. 193–226.

Czepiec, I., Kotarba, M.J., 1998. Paleoecology and organic matter in the Late Badenian and Early Sarmatian marine basin of the Polish part of the Carpathian Foredeep. Przegl. Geol. 46, 732–736.

Davaud, E., Strasser, A., Jedoui, Y., 1994. Stromatolite and serpulid bioherms in a Holocene restricted lagoon (Sabkha El Melah, southeastern Tunisia). In: Bertrand-Sarfati, J., Monty, C. (Eds.), Phanerozoic Stromatolites, vol. II, pp. 131–151.

Durakiewicz, T., 1996. Electron emission controller with pulsed heating of filament. Int. J. Mass Spectrom. 156, 31–40.

Dziadzio, P., 2000. Sekwencje depozycyjne w utworach badenu i sarmatu w SE części zapadliska przedkarpackiego. Przegl. Geol. 48, 1124–1138.

Goncharova, I.A., Khondkarian, S.O, Shcherba, I.G., 2001. The Tarkhanian-Karaganian stage in development of the Euxinian-Caspian Basin (Eastern Paratethys): Part 1. Tarkhanian. Stratigr. Geol. Correl. 9, 508–522.

Gonfiantini, R., 1986. Environmental isotopes in lake studies. In: Fritz, P., Fontes, J.C. (Eds.), Handbook of the Environmental

Isotope Geochemistry. The Terrestrial Environment, vol. 2, pp. 113–168.

Gontsharova, I.A., 2001. Tarkhanian and Chokrakian of the Eastern Paratethys: state of knowledge and correlation. Ber. Inst. Geol. Paläontol. Karl-Franzens Univ. Graz 4, 14–22.

Ishchenko, D.I., Kisilov, M.V., 1967. Do pytannya pro geologichnu budovu ta utvorennya gipsovykh rodovyshch Krymu. Geol. Zh. 27 (1), 68–76.

Jones, R.W., Simmons, M.D., 1996. A review of the stratigraphy of Eastern Paratethys (Oligocene–Holocene). Bull. Nat. Hist. Mus., Geol. Lond. 52 (1), 25–49.

Koutsoukos, E.A.M., Leary, P.N., Hart, M.B., 1990. Latest Cenomanian–earliest Turonian low-oxygen tolerant benthonic foraminifera: a case study from the Sergipe Basin (N.E. Brazil) and the western Anglo-Paris Basin (southern England). Palaeogeogr. Palaeoclimatol. Palaeoecol. 77, 145–177.

Kropacheva, S.K., 1976. Mineralogo-petrograficheskiye issledovaniya karbonatnykh otlozheniy miotsena Kerchenskogo poluostrova s tselu vyyavleniya litologo-fatsiyalnykh zon, blogopriyatnykh dla protsessov seroobrazovaniya. Unpublished report. Min. Geol. USSR, Institut mineralnykh resursov, Simferopol, p. 154.

Kropacheva, S.K., 1981. Sravnitelnyy analiz stroyeniya seronosnykh galogennykh formatsiy. Nedra, Moskva, p. 121.

Krzywiec, P., 2001. Contrasting tectonic and sedimentary history of the central and eastern parts of the Polish Carpathian foredeep basin-results of seismic data interpretation. Mar. Pet. Geol. 18, 13–38.

Kulchetskaya, A.A., 1987. Genezis gipsa i angidrita iz osadochnykh porod Ukrainy (po dannym izucheniya vklucheniy mineraloobrazuyushchey sredy). Diss. Institut Geohkimii i Fiziki Mineralov, Kiev, p. 244.

Lepeshkov, I.N., Bodaleva, N.V., 1952. O poryadke kristallizatsii soley pri isparenii vody Aralskogo morya. Dokl. Akad. Nauk SSSR 83, 583–584.

McCrea, J.M., 1950. On the isotopic geochemistry of carbonates and a paleotemperature scale. J. Chem. Phys. 18, 849–857.

Muratov, M.V., 1973. Rukovodstvo po uchebnoy geologicheskoy praktikie v Krymu. Geologia Krymskogo poluostrova, vol. 2. Nedra, Moskva, p. 192.

Murray, J.W., 1991. Ecology and Palaeoecology of Benthic Foraminifera. Longman, Avon, p. 398.

Nevesskaya, L.A., Goncharova, I.A., Ilina, L.B., Paramonova, N.P., Popov, S.V., Bogdanovich, A.K., Gabuniya, L.K., Nosovskiy, M.F., 1984. Regionalnaya stratigraficheskaya shkala neogena Vostochnogo Paratetisa. Sov. Geol. (9), 37–49.

Nosovskiy, M.F., Barg, I.M., Pishvanova, L.S., Andreyeva-Grigorovich, A.S., 1976. Ob obyome tarkhanskogo yarusa na yuge SSSR. In: Nosovskiy, M.F., Barg, I.M., Korallova, V.V. (Eds.), Stratigrafia kaynozoya Severnogo Prichernomoya i Kryma. Dnepropetrovskiy gosudarstvennyi universitet, Dnepropetrovsk, pp. 22–31.

Orti Cabo, F., Pueyo Mur, J.J., Geisler-Cussey, D., Dulau, N., 1984. Evaporitic sedimentation in the coastal salinas of Santa Pola (Alicante, Spain). Rev. Inst. Invest. Geol. Diput. Barc. 38/39, 169–220.

Pavlenko, V.V., Kropacheva, S.K., Poltorakov, G.I., 1974. Zakonomernosti proyavleniya samorodnoy sery na Kerchenskom poluostrove. Sov. Geol. (8), 149–152.

Peryt, D., 1997. Calcareous nannoplankton stratigraphy of the Middle Miocene in the Gliwice area (Upper Silesia, Poland). Bull. Pol. Acad., Earth Sci. 45, 119–131.

Peryt, D., 1999. Calcareous nannoplankton assemblages of the Badenian evaporites in the Carpathian Foredeep. Biul. Państw. Inst. Geol. 387, 158–161.

Peryt, T.M., 2001. Gypsum facies transitions in basin-marginal evaporites: middle Miocene (Badenian) of West Ukraine. Sedimentology 48, 1103–1119.

Peryt, T.M., 2002. The onset and the termination of Middle Miocene Badenian salinity crisis in Central Paratethys: the state of the art. Geol. Carpath. 53 (spec. issue), 32–33.

Petrichenko, O.I., Peryt, T.M., Poberegsky, A.V., 1997. Pecularities of gypsum sedimentation in the Middle Miocene Badenian evaporite basin of Carpathian Foredeep. Slovak Geol. Mag. 3, 91–104.

Pisera, A., 1996. Miocene reefs of the Paratethys: a review. In: Franseen, E.K., Esteban, M., Ward, W.C., Rochy, J.-M. (Eds.), Models for Carbonate Stratigraphy From Miocene Reef Complexes of Mediterranean Regions. SEMP Concepts in Sedimentology and Paleontology, vol. 5, pp. 97–104.

Polakova, M.M., 1974. Gips. In: Muratov, M.V. (Ed.), Krym. Poleznyye iskopayemyye. Geologia SSSR, vol. VIII. Nedra, Moskva, pp. 163–164.

Poltorakov, G.I., Kropacheva, S.K., Goryainov, E.P., Pavlenko, V.V., 1979. Krymskaya perspektivnaya seronosnaya oblast. In: Kityk, V.I. (Ed.), Stroyenie i zakonomernosti razmeshchenia sernykh mestorozhdeniy SSSR. Naukova Dumka, Kiev, pp. 223–230.

Ramos, E., Cabrera, L., Hagemann, H.W., Pickel, W., Zamarreño, I., 2001. Palaeogene lacustrine record in Mallorca (NW Mediterranean, Spain): depositional, palaeogeographic and palaeoclimatic implications for the ancient southeastern Iberian margin. Palaeogeogr. Palaeoclimatol. Palaeoecol. 172, 1–37.

Rögl, F., 1998. Palaeogeographic considerations for Mediterranean and Paratethys seaways (Oligocene to Miocene). Ann. Naturhist. Mus. Wien 99A, 279–310.

Rouchy, J.M., Orszag-Sperber, F., Blanc-Valleron, M.-M., Pierre, C., Rivière, M., Combourieu-Nebout, N., Panayides, I., 2001. Paleoenvironmental changes at the Messinian–Pliocene boundary in the eastern Mediterranean (southern Cyprus basins): significance of the Messinian Lago-Mare. Sediment. Geol. 145, 93–117.

Shnyukov, E.F., Naumenko, P.I., Lebedev, Y.S., Usenko, V.P., Gordiyevich, V.A., Yukhanov, I.S., Shchiritsa, I.S., 1971. Gryazevoy vulkanizm i rudoobrazovanie Naukova Dumka, Kiev. 332 pp.

Studencka, B., Gontsharova, I.A., Popov, S.V., 1998. The bivalve faunas as a basis for reconstruction of the Middle Miocene of the Paratethys. Acta Geol. Pol. 48, 285–342.

Talbot, M.R., 1990. A review of the palaeohydrological interpretation of carbon and oxygen isotopic ratios in primary lacustrine carbonates. Chem. Geol. 80, 261–279.