GEOLOGICA CARPATHICA, FEBRUARY 2011, 62, 1, 77–90 doi: 10.2478/v10096-011-0007-x

Upper Maeotian–Lower Pontian “Transitional Strata” in the Taman Peninsula: stratigraphic position and paleogeographic interpretation

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(Manuscript received June 10, 2010; accepted in revised form January 11, 2011)

Abstract: Three sections (Taman, Popov Kamen, and Zheleznyi Rog) of the Upper Maeotian–Lower Pontian sediments of the Taman Peninsula (Eastern Paratethys) have been studied. The sequences represent continuous successions of the Maeotian and Pontian sediments. The transitional Upper Maeotian–Lower Pontian relatively deep-water sediments were formed at the time when Eastern Paratethys was connected with other marine basins. The facies are represented by thin clay layers interbedded with laminated diatomites and contain unusual diatom and nannofossil associations. The small size of coccoliths and the absence of zonal markers indicate that the influx of marine waters took place in the stressed conditions of a restricted basin. Diatom assemblages are more diverse and include the open-marine species *Azpeitia* aff. *komurae* and *Thalassiosira maruyamica* and marine endemics *Actinocyclus* aff. *paradoxus*, *Rhizosolenia bezrukovii*, *Hemiaulus* sp., *Nitzschia miocenica* of the tropical *Nitzschia miocenica* Zone and — the index species of next *Thalassiosira convexa* Zone appear in these part of the sections. Three stages of the Mediterranean marine invasion are distinguished; during the first one the connection between basins was rather permanent, for the two others its character became pulsing and not stable. The possible duration of the invasion is estimated from 6.4 to 6.1 Ma and belongs to the Early Messinian — to pre-evaporate deposits and lower part of lower evaporate deposits.

Key words: Upper Miocene, Eastern Paratethys, biostratigraphy, diatoms, nannofossils.

Introduction

During the Middle and Late Miocene the Eastern Paratethys became a semi-isolated basin with endemic biota, restrictedly connected to both Central Paratethys and the Mediterranean. The history of its development is manifested in the sections of the Taman Peninsula that together with the Kerch Peninsula in the Crimea is a stratotype area of Neogene deposits of the Eastern Paratethys. The key Neogene sections of the Taman Peninsula were first described by Andrusov (1903) and were accepted as reference ones when the Middle–Upper Miocene and Pliocene regional stages of the Eastern Paratethys were recognized (Menner et al. 1976). Subsequently the Taman Peninsula outcrops were proposed as reference sections for the Sarmatian–Kimmerian regional stages when evolving the unified scheme of the regional Neogene deposits in the southern European part of Russia (Nevesskaya et al. 2004).

The regional stratigraphy up to now was based on mollusc fauna; studies of foraminifers and ostracods were carried out only sporadically (Nevesskaya et al. 1984; Popov et al. 1996). Diatom stratigraphy was considered to be of regional significance and was mainly used as a climatostratigraphic instrument though its potential in the Eastern Paratethys is very high (Makarova & Kozyrenko 1966; Kozyrenko & Temnishkova-Topalova 1990; Kozyrenko & Radionova 2002; Olshtynska 2001). The use of nannoplankton for direct correlation between stages of the Eastern Paratethys and Tethys seems to be questionable (Semenenko & Luljeva 1982; Semenenko 1987).

Beginning in 2000, comprehensive lithological and biostratigraphic investigations of key sections in the Taman Peninsula have been carried out by a group of specialists including the authors of this paper. The paleontological study involved molluscs and ostracods (Popov et al. 2009; Rostovtseva & Tesakova 2009). The new data on dinocysts, spores and pollen, foraminifers, diatoms, and nannofossils are available (Filippova 2002, 2008). The reference sections in the Taman Peninsula were subdivided using the regional diatom scale elaborated for the Eastern Paratethys (Kozyrenko & Radionova 2002; Radionova & Golovina 2004, 2008, 2009). High-resolution lithological studies of the Taman Peninsula sections were obtained for the first time (Rostovtseva 2009; Rostovtseva & Goncharova 2006) and paleomagnetic investigation is in progress (Filippova & Trubikhin 2009; Trubikhin & Pilipenko 2009).

One of the results of the continuous layer-by-layer study of microbiota was the distinction of stratigraphic intervals with increased abundance and diversity of marine microplankton. Specifically, such intervals were found at the base and top of the Maeotian (Radionova & Golovina 2004; Rostovtseva et al. 2006). The proposed investigation deals with the study of the transitional beds of the Upper Maeotian–Lower Pontian, in which a specific marine diatom, nannoplankton and dinocyst association was found (Radionova & Golovina 2008; Filippova 2008), with the micropaleontological analysis and paleogeographic interpretation of the interval, and with the determination of the Maeotian-Pontian boundary in the Zheleznyi Rog reference section according to micropaleontological data.

We emphasize that the integration of the uppermost Upper Maeotian and the Lower Pontian sediments into a particular sequence called here the "Transitional Strata" is based primarily on micropaleontological records, namely, on the appearance and occurrence of calcareous nannoplankton and marine diatoms. Despite the fact that the "Transitional Strata" are represented by lithologically different sediments and belong to two regional stages, their accumulation corresponds to a single important step of the Eastern Paratethys evolution, the period of connection with the Mediterranean Basin, which was characterized by peculiar bionomic conditions.

Geological setting

Shoreface outcrops of the Taman Peninsula display a continuous sequence of six regional stages of the Middle Miocene to Pliocene (Karaganian–Konkian–Sarmatian–Maeotian–Pontian–Kimmerian) in the system of synclinal and anticlinal folds (Figs. 1, 2). The Upper Maeotian–Lower Pontian sediments were studied in three key sections, the Taman (Kerch Strait coast), Popov Kamen and Zheleznyi Rog (Black Sea coast). The Taman and Popov Kamen sections are relatively shallow-water ones where the Maeotian-Pontian boundary is marked by a stratigraphic gap, while the Zheleznyi Rog section contains an uninterrupted sequence of relatively deep-water Maeotian-Pontian sediments (Figs. 2, 3, 4).

The Neogene regional stratigraphic scheme of the Eastern Paratethys is based on mollusc associations. In the Zheleznyi Rog section, which is suggested as a reference section for the Pontian regional stage of the southern Russia Neogene (Nevesskaya et al. 2004), the lower boundary of the Pontian is recorded on the first findings of *Paradacna abichi* (Andrusov 1903). The objectives of our research was stratigraphic subdivision of the sequences (Taman, Popov Kamen, and Zheleznyi Rog) of the Upper Maeotian–Lower Pontian of the Taman Peninsula by microplankton. And therefore we accept that the stratigraphic range of the Upper Maeotian according to the regional diatom scale (Jouse 1949; Kozyrenko & Radionova 2002) corresponds to the Beds with the *Cymatosira savtchenkoi* of the *Thalassiosira maeotica* Zone. The Lower Pontian corresponds to Beds with the *Actinocyclus octonarius.* In the Zheleznyi Rog section this boundary is determined at the top of **Unit I** (Figs. 2, 3, 4).

Fig. 1. Location map of the studied area. **1** — Zheleznyi Rog sequence; **2** — Taman sequence; **3** — Popov Kamen sequence.

The lower part of the Upper Maeotian in the Zheleznyi Rog section (about 35 m thick) is composed of light clay, calcareous, non-calcareous, diatomaceous, bearing brackish-water ostracods, molluscs, and diatoms (Popov & Zastrozhnov 1998; Rostovtseva 2009). These sediments are not discussed in the proposed paper.

The "Transitional Strata" from the upper part of the Upper Maeotian in the Zheleznyi Rog section (about 38 m thick) are represented by dark grey carbonate clays and is considered in this paper as **Unit I** (Figs. 2, 3, 4).

The sediments of **Unit II** and **Unit III** correspond to the Lower Pontian and are composed of interbedded laminated diatomites and thin-bedded clays. The thickness of the laminated diatomites varies from few centimeters to several meters; they can be easily traced in the section and are used as lithostratigraphic markers. The most important and noticeable is a thick (up to 5 m) bed of diatomite that was first described by N.I. Andrusov ("Andrusov diatomite" — **"A"**) (Figs. 2, 3). Other markers described later by Popov & Zastrozhnov (1998), in this article are called **"J"**, **"L"**, **"SP"**, **"Ch"** and **"N"** marker beds (Figs. 2, 3).

The upper part of the Lower Pontian in the Zheleznyi Rog section is represented by non-calcareous and calcareous clays, up to 20 m thick, bearing brackish-water mollusc and ostracod fauna; diatoms and nannofossils are missing. These sediments are not included in the "Transitional beds" interval and are not discussed in the paper.

Material and methods

The detailed sampling of the boundary Maeotian–Pontian interval has been carried out during several field seasons. Three sections were litho- and biostratigraphically studied in detail. The lithological column and location of samples are shown in Figs. 3, 4. In total, over 80 samples were collected and investigated. Diatoms and nannofossils were studied from the same samples. To retain the original sample composition, smear slides were prepared directly from the untreated samples. At the same time, clay material was removed from a sample and smear slides were prepared for additional study. The calcareous nannofloral analyses were performed using a light polarizing microscope at ×1600 magnification. Part of the samples were studied using a scanning microscope. The nannofossil taxonomic identification follows Perch-Nielsen (1985) and Young (1998).

Diatoms were extracted from samples using the standard methods of Russian diatomologists (Proshkina-Lavrenko 1974).

Almost all the samples studied contain diatoms in amounts varying from single specimens to abundant.

Results

The most complete transitional sequence of the Upper Maeotian–Lower Pontian sediments is exposed in the rela-

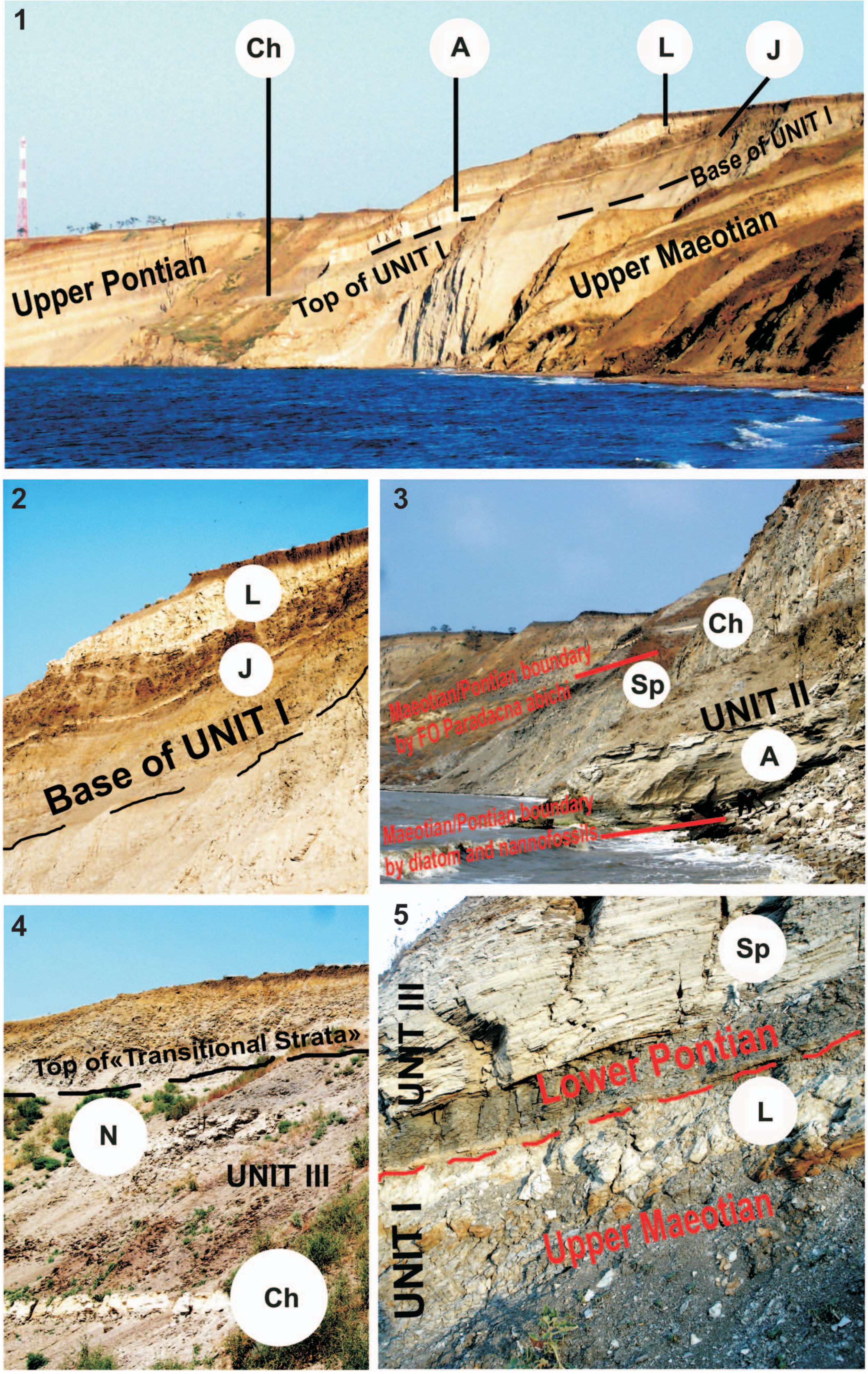

Fig. 2. 1 — View of the "Transitional Strata" in the Zheleznyi Rog sequence; **J, L, A, Ch** — marker diatomites; **2** — Base of the **Unit I** of the "Transitional Strata" in the Zheleznyi Rog sequence; **3** — Base of the **Unit II** of the "Transitional Strata" in the Zheleznyi Rog sequence; **4** — **Unit III** of the "Transitional Strata" in the Zheleznyi Rog sequence; **5** — Maeotian/Pontian boundary in the Taman sequence.

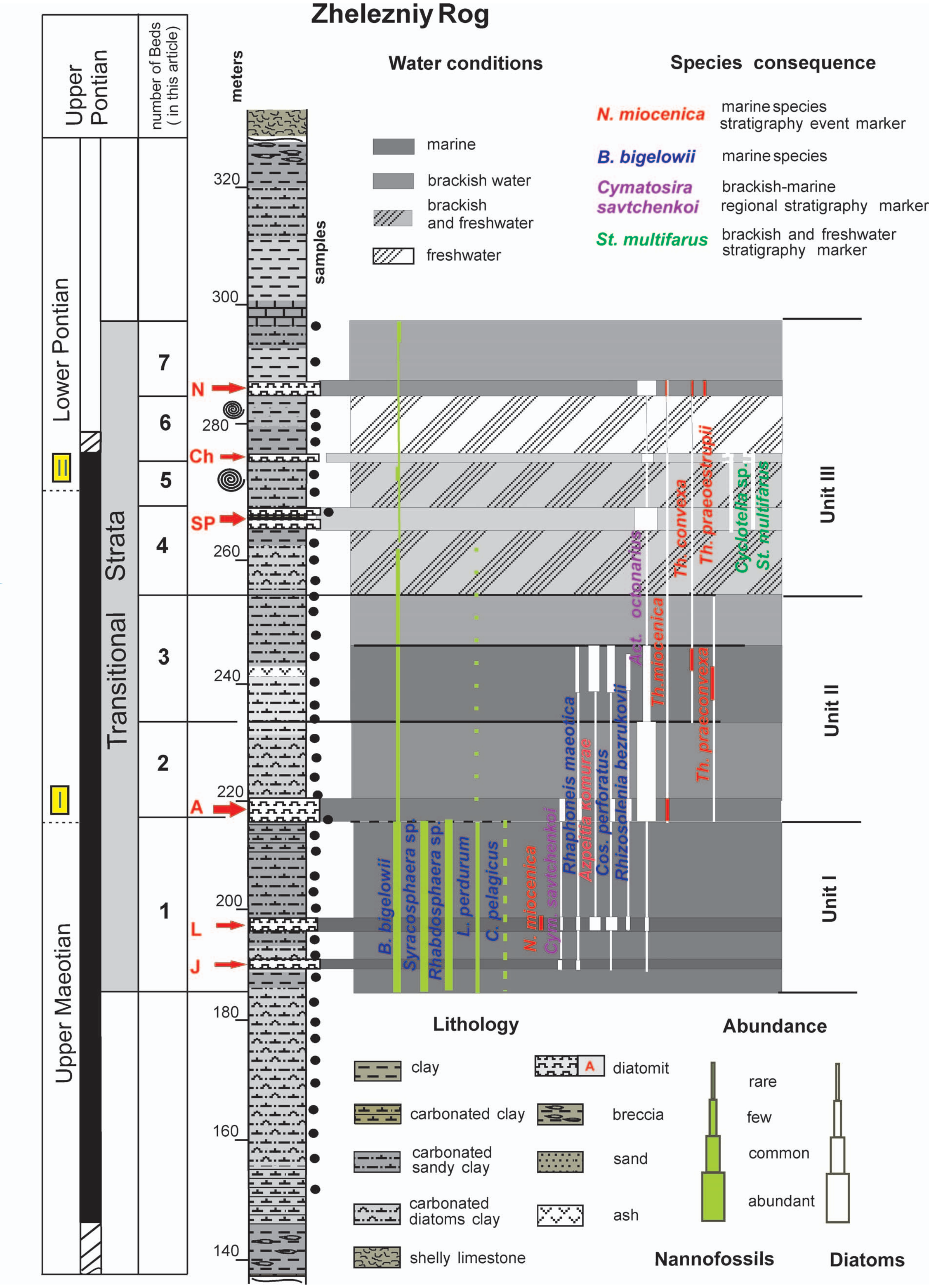

Fig. 3. The "Transitional Strata" in the Zheleznyi Rog sequence: lithology, stratigraphy, diatom and nannofossil distribution, interpretation of salinity conditions. Polarity according to Filippova & Trubikhin (2009). *B. — Braarudosphaera, L. — Lithostromation, C. — Coccolithus, N. — Nitzschia, Cym. — Cymatosira, Cos. — Coscinodiscus, Act. — Actinocyclus, Th. — Thalassiosira, St. — Stephanodiscus.*

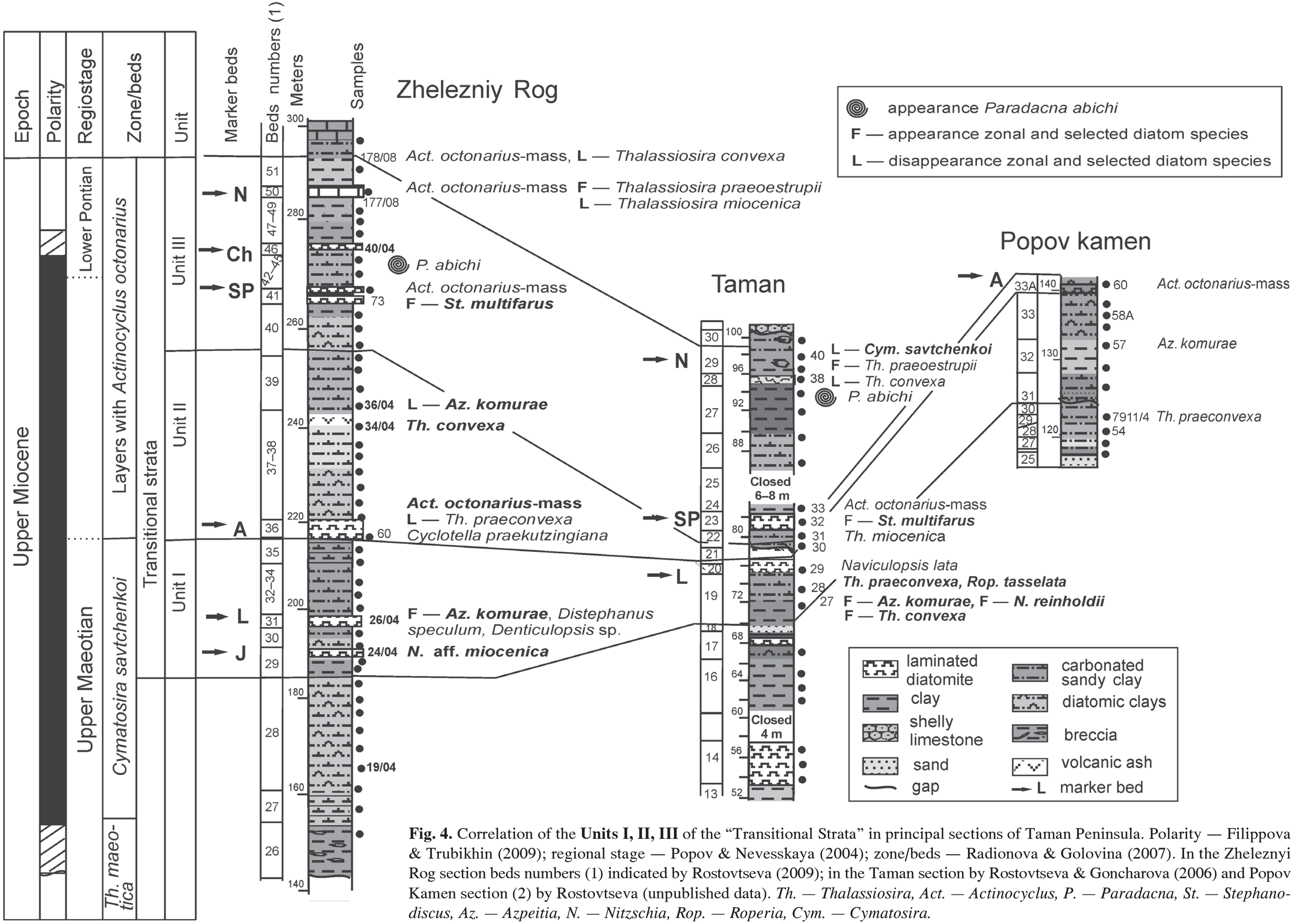

Fig. 4. Correlation of the **Units I, II, III** of the “Transitional Strata” in principal sections of Taman Peninsula. Polarity — Filippova & Trubikhin (2009); regional stage — Popov & Nevesskaya (2004); zone/beds — Radionova & Golovina (2007). In the Zheleznyi Rog section beds numbers (1) indicated by Rostovtseva (2009); in the Taman section by Rostovtseva & Goncharova (2006) and Popov Kamen section (2) by Rostovtseva (unpublished data). *Th. — Thalassiosira, Act. — Actinocyclus, P. — Paradacna, St. — Stephanodiscus, Az. — Azpeitia, N. — Nitzschia, Rop. — Roperia, Cym. — Cymatosira.*

tively deep-water Zheleznyi Rog section. In the Taman and Popov Kamen sections the same interval is represented by shallow deposits of less thickness with hiatuses (Fig. 4).

Unit I

Zheleznyi Rog Section

Unit I includes Beds 29–35 (Figs. 3, 4). In the marker diatoms siltstones **"J"** and **"L"** an abundant nannoplankton assemblage with *Braarudosphaera bigelowii*, *Syracosphaera pulchra*, *Syracosphaera* sp. and rare *Coccolithus pelagicus*, *Lithostromation perdurum*, *Reticulofenestra* spp., and *Rhabdosphaera* sp. was found (Fig. 3 and Fig. 5). Both the absence of zonal species and very small size of coccoliths point to a restricted or indirect connection of the environment with a marine basin of normal salinity.

The marker siltstone "**J**" contains *Cymatosira savtchenkoi*, *Rhaphoneis maeotica*, common benthic *Endyctia oceanica* and *Thalassiosira gravida*.

The diatom association of siltstone **"L"** yields only marine species dominated by oceanic *Azpeitia* aff. *komurae.* It also includes *Coscinodiscus perforatus*, *Podosira lozcii*, *Actinoptychus undulatus*, *Actinocyclus octonarius*, *Actinocyclus* aff. *paradoxus* (described from modern sediments of the Caspian Sea), and *Rhizosolenia bezrukovii* first described from the Pliocene of the Black Sea (Jouse & Mukhina 1978). It makes its first appearance there (Figs. 3 and Fig. 6). Rather scarce silicoflagellates *Distephanus speculum* and *Naviculopsis lata* indicate close to normal salinity conditions. Among characteristic Maeotian species, few *Rhaphoneis maeotica*, *Cymatosira savtchenkoi* are found, and benthic forms are represented by sporadic *Diploneis bomboides.*

The sediments of **Unit I** contain *Cymatosira savtchenkoi*, the index species of the regional *Cymatosira savtchenkoi* Zone and a singular *Nitzschia miocenica*, an index species of the *Nitzschia miocenica* Zone of the tropical diatom scheme. The diatom association in both **"J"** and **"L"** marker siltstones is considerably more diverse then that in the overlying clays. In siltstone **"L"**, both oceanic and Eastern Paratethys endemic species appear for the first time in the basin.

In the upper part of Unit 1 the diatom abundance considerably drops and only the dinocyst assemblage with *Batiacasphaera* sp. dominates in microplankton (Filippova & Trubikhin 2009).

Popov Kamen section

The Upper Maeotian sediments are of small thickness there and are characterized by hiatuses (Fig. 4). **Unit I** includes Beds 32–33 (about 12 m thick) deposited on a wavy surface, with pockets and pebbles, and composed of dark grey, slightly calcareous, pyritized clay, lacking malacofauna but bearing diverse, mainly planktonic microflora. The planktonic diatom assemblage of Bed 32 includes *Coscinodiscus radiatus*, *Paralia sulcata*, *P.* sp., and *Pseudopodosira hyalina.* It is characterized by complete absence of brackish-water plankton. Benthic species are scarce and represented by *Biddulphia toomey*, *Diploneis bomboides*, *Lirella lira*, together with *Endyctia oceanica*, *Psammodiscus nitidus*, *Amphytetras antideluvianum*, *Hyalodiscus* sp., and *Cocconeis scutellum.*

The *Coscinodiscus* representatives, are dominated in Bed 33, namely, by *C. radiatus*, *C. asteromphalus*, and by *Azpeitia* aff. *komurae*. *Actinocyclus paradoxus*, *A. octonarius*, and *Thalassiosira miocenica* occur as well. Among the pennate taxa *Rhabdonema adriaticum*, *R. forellii*, *Grammatophora marinae*, *Nitzschia tryonella* var. *hantzschia*, and *Achnantes hauckiana* appear.

Nannofossils were encountered in the upper part of Bed 32 and in the lowermost Bed 33. *Braarudosphaera bigelowii* comprises 90 % of the total assemblage. Other species present are *Coccolithus pelagicus*, *Syracosphaera pulchra*, *Syracosphaera* sp., *Lithostromation perdurum*, *Reticulofenestra* sp., and *Rhabdosphaera* sp. In Bed 33 *Braarudosphaera bigelowii* is not numerous; other species are scarce. The nannofossil assemblage of **Unit I** in the Popov Kamen section is analogous to that of the Zheleznyi Rog section, though it is slightly richer and better preserved (Fig. 5). It can probably be explained by lesser amount of terrigenous component.

Taman section

The sediments of **Unit I** (Beds 19–20) overlie the shallow Upper Maeotian deposits and are marked by hiatuses (Figs. 2, 4).

Bed 19 (5 m thick) is composed of dark grey clays, slightly or non-calcareous, slightly siliceous, thin-bedded. Diatoms are not numerous and are represented by an open-sea assemblage bearing *Coscinodiscus perforatus*, *Azpeitia* aff. *komurae*, *Actinocyclus* aff. *paradoxus*, *Endyctia oceanica*, *Amphytetras antideluvianum*, and *Hyalodiscus* sp. A single specimen of *Thalassiosira convexa* was found (Sample 66). Nannofossils are missing.

Bed 20 (0.3 m thick) is made up of light grey, thin-bedded diatom clay and clayey diatomite, with a deformation at the top (Fig. 4). The siliceous plankton assemblage includes silicoflagellate *Naviculopsis lata* and single oceanic diatoms *Thalassiosira praeconvexa*, *Nitzschia cylindricus*, and *N. reinholdii.* Composition and diversity of the siliceous plankton permits the correlation of this bed with marker siltstone **"L"** in the Zheleznyi Rog section.

Nannofossils are abundant and well-preserved, with dominant *Braarudosphaera bigelowii* and very rare *Lithostromation perdurum.*

Unit II

Zheleznyi Rog section

Unit II (Beds 2–3, Fig. 3) is composed of interbedded laminated diatomite strata and thick clay beds. Thinly laminated diatomites are characterized by a great abundance of both mass diatom and calcareous nannofossils, but mainly represented by monoassociations bearing *Actinocyclus octonarius* and *Braarudosphaera bigelowii.*

In Bed 2, which begins with thick laminated diatomite sediments **"A"**, nannofossils are represented by just one taxon *Braarudosphaera bigelowii*, whereas *Lithostromation*

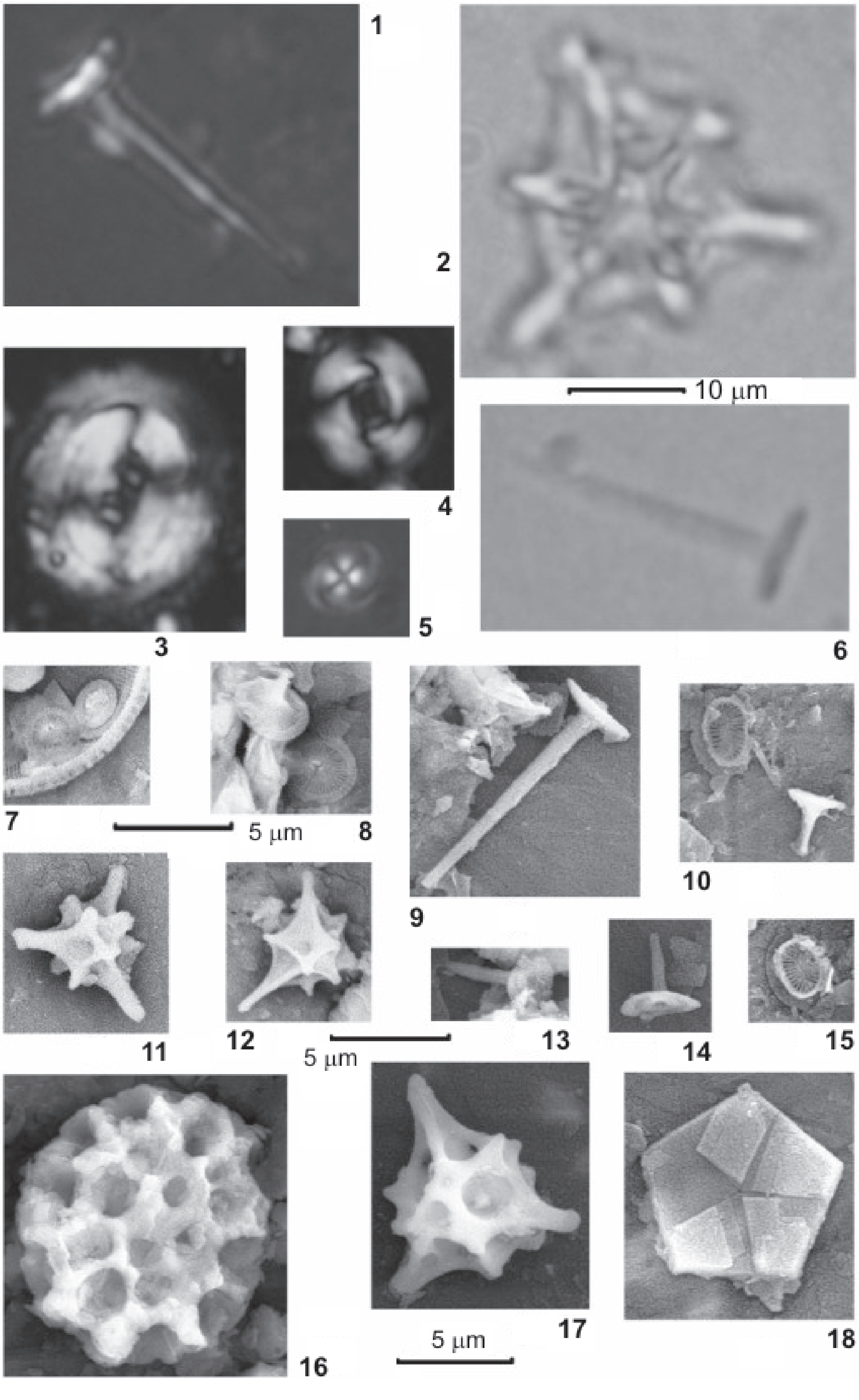

Fig. 5. 1, 6, 7, 8, 9, 13, 14 — *Rhabdosphaera* sp. 1 — crossed polarized light; Zheleznyi Rog sequence, sample 28/04; 6 — parallel light, Popov Kamen sequence, sample 57a; 9, 13 — Popov Kamen sequence, sample 57a; 14 — Zheleznyi Rog sequence, sample 28/04; 7, 8 — distal view of non spine-bearing coccolith; 7 — Zheleznyi Rog sequence, diatomite N; 8 — Popov Kamen sequence, sample 57a; **2, 11, 12, 17** — *Lithostromation perdurum* Deflandre, 1942; 2 — parallel light; Popov Kamen sequence, sample 57a; 11, 12, — Zheleznyi Rog sequence, diatomite N; 17 — Popov Kamen sequence, sample 57a; 3 — *Coccolithus pelagicus* (Wallich, 1871) Schiller, 1930, crossed polarized light; Taman sequence, sample 50; **4** — *Reticulofenestra pseudoumbilica* (Gartner, 1967) Gartner 1969, crossed polarized light; Taman sequence, sample 50; **5, 10, 15** — *Syracosphaera pulchra* Lohmann 1902, 5 — crossed polarized light; Zheleznyi Rog sequence, sample 29/04; 10 — Popov Kamen sequence, sample 57a; 15 — Popov Kamen sequence, sample 12; **16** — *Lacunolithus menneri* Luljeva, 1978; **18** — *Braarudosphaera bigelowii* (Gran & Braarud), sequence, Zheleznyi Rog sample 28/04.

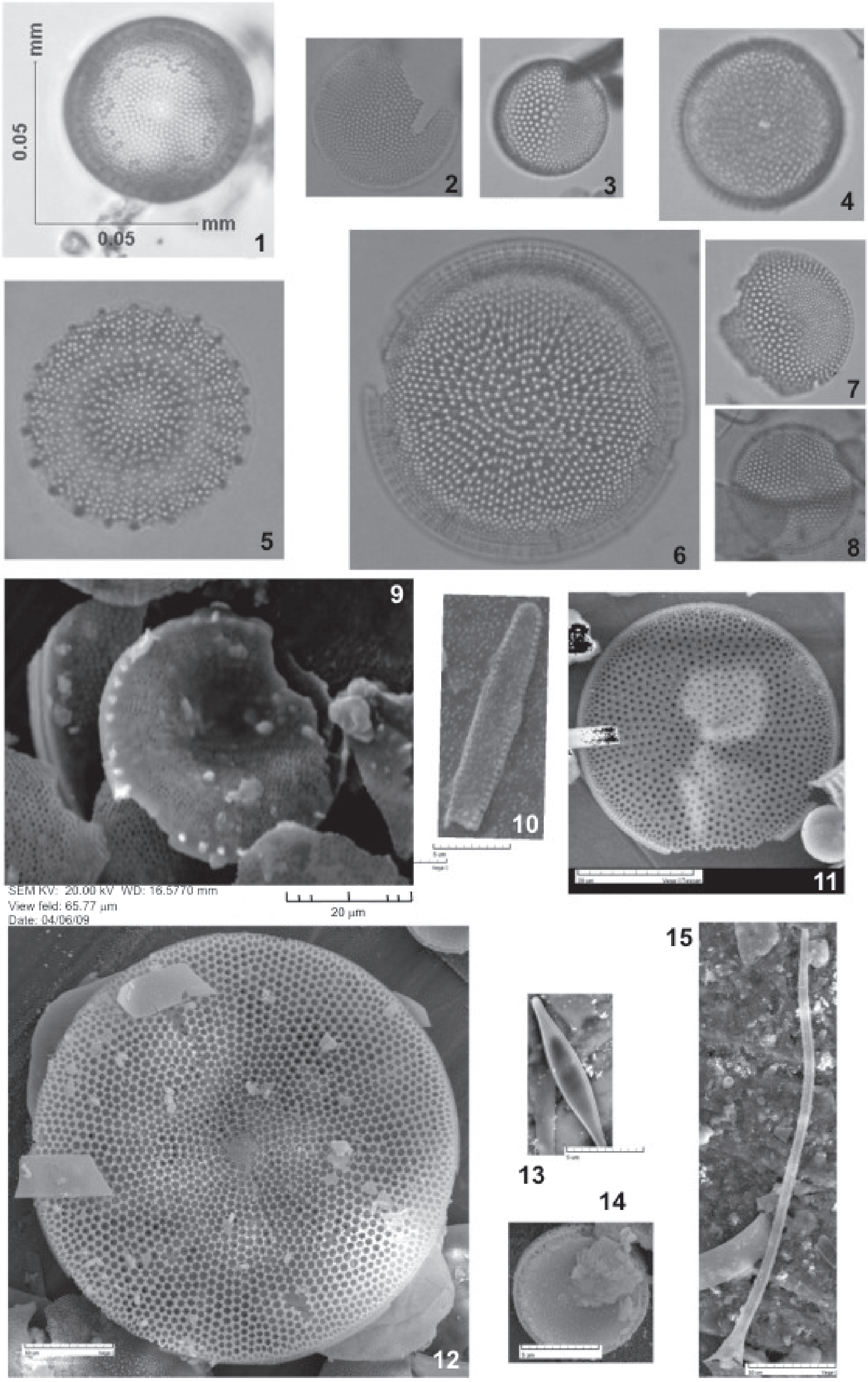

Fig. 6. 1 — *Thalassiosira convexa* var. *aspinosa* Schrader; Taman sequence, sample 44; **2** — *Thalassiosira praeconvexa* Burckle; **3** — *Thalassiosira* aff. *oestrupii*; **4** — *Cyclotella praekutzingiana* Mukhina; **5** — *Stephanodiscus digitatus* Chursevich & Mukhina; **6** — *Actinocyclus octonarius* Ehrenberg; **7** — *Thalassiosira miocenica* Schrader; **8** — *Thalassiosira antiqua* (Grunow) A. Cleve. 2–8 — Zheleznyi Rog sequence, diatomites **"N"** and **"Ch"** (light microscope, magnification see Fig. 6.1). Scanning: **9** — *Stephanodiscus multifarus* Chursevich & Mukhina; Zheleznyi Rog sequence, diatomite **"Ch"**; **10** — *Thalassionema nitzschioides* Grunow; Zheleznyi Rog sequence, diatomite **Ch**; **11** — *Azpeitia komurae* Akiba, Taman sequence, sample 28; **12** — *Coscinodiscus asteromphalus* Ehrenberg. Zheleznyi Rog sequence, sample 24/04; **13** — *Cymatosira savtchenkoi* Proshkina-Lavrenko. Taman sequence, sample 18; **14** — *Distephanosira* aff. *architecturalis* (Brun) Gleser; Zheleznyi Rog sequence, diatomite **"Ch"**; **15** — *Rhizosolenia bezrukovii* Jouse, Zheleznyi Rog sequence, diatomite **"Ch"**.

perdurum and *Reticulofenestra* sp. are found very rarely. Among diatoms *Actinocyclus octonarius* constitutes up to 95 % of the whole assemblage. However, typical Maeotian marine and brackish-water species *Chaetoceras danicus*, *Coscinodiscus perforatus*, *Rhaphoneis maeotica*, *Cymatosira savtchenkoi*, *Thalassiosira baltica*, and *Nitzschia punctata* make up the main part of the diatom association. Benthic species include *Surirella fastuosa*, *Biddulphia toomey*, *Navicula zichii*, *Diploneis demplitensis*, and *Grammatophora* sp. The structure of the association remains the same up the section in diatom clays (samples 61–64/2000) that overlap diatomite **“A”**.

Bed 3 shows a coarser intercalation of carbonate and diatomite clays (samples 66–69/2000, 33–04, 36–04). There is a 3-cm-thick ash horizon in the middle of this bed, with the age determined at 8.4 Ma (Chumakov et al. 1996). In the diatom association, *Actinocyclus octonarius* together with *Azpeitia* aff. *komurae*, *Coscinodiscus perforatus*, and *Paralia sulcata* typical for Unit 1, dominate. As in diatomite **“L”**, *Rhizosolenia bezrukovii* and *Rhaphoneis maeotica* appear there again. The occurrence of *Thalassiosira praeconvexa* and *T. convexa* var. *aspinosa* is considered as evidence for increased marine conditions. Brackish-freshwater diatoms *Cyclotella praekutzingiana*, *C. proshkinae*, *Stephanodiscus speciosus* appear here. Nannofossils are represented mainly by rare *Braarudosphaera bigelowii*.

Beds 2–3 are characterized by the presence of dinocyst assemblages with the dominance of euryhaline marine species *Batiacasphaera* spp., *Operculodinium* spp. (including *O. israelianum*) and *Lingulodinium machaerophorum* (Filippova & Trubikhin 2009).

Popov Kamen section

The boundary between **Unit I** and **Unit II** passes within the sequence of dark non-carbonate clay. It is defined by a change in the diatom assemblage (Fig. 4). Clays of **Unit II** (Bed 33a) are strongly dominated by *Actinocyclus octonarius* and contain rare *Paralia sulcata* and a single *Cocconeis scutellum.* Nannofossils are missing. The visual thickness of the sediments is 4 m.

Taman section

In the Taman section the sediments of **Unit II** are absent.

Unit III

Zheleznyi Rog section

The sediments of **Unit III** are represented by Beds 4–7. In Bed 4, in diatomite **“SP”** *Actinocyclus octonarius* again dominates. The corresponding association of species is similar to that described from diatomite **“A”**; freshwater diatoms were not found.

In the lower part of Bed 5, composed of non-carbonate sandy clays, nannofossils and diatoms are absent and only reworked Paleogene species were found. Up the section, rare specimens of *Actinocyclus octonarius* appear. In the overlying clays freshwater diatoms *Stephanodiscus hantzschii* and *S. digitatus* are found again. At the base of diatomite **“Ch”** only freshwater diatoms are present, *Stephanodiscus multifarus*, *S. digitatus*, *Cyclotella praekutzingiana*, *C. proshkinae* among them. The upper part of diatomite **“Ch”** is characterized by the presence of freshwater species and monoassociation of *Actinocyclus octonarius,* while the latter association predominates.

In the middle of Bed 5 (between diatomites **“SP”** and **“Ch”**) the first specimens of mollusc *Paradacna abichi* are encountered. Its appearance defines the Lower Pontian boundary (Andrusov 1903).

In the same interval the first occurrence of dinocyst *Galeacysta etrusca* was recorded, together with a paleomagnetic reversal (Filippova & Trubikhin 2009). Up the section from diatomite **“Ch”** in dark garbage clays of Bed 6 nannoplankton was not found.

At the base of Bed 7 diatomaceous marl **“N”** composed of interbedding siliceous and carbonate microlayers occurs. In the diatom assemblage *Actinocyclus octonarius* dominate, as well as thalassiosiras, including rare *Thalassiosira convexa* and diverse *T. praeoestrupii*, *T. baltica*, and *T. miocenica*. Up the section, carbonate clays, 3.5 m thick, with rare *Braarudosphaera bigelowii* and *Lithostromation perdurum* are bedded. This interval corresponds to the final phase of marine invasion. The overlying terrigenous-carbonate Lower Pontian facies are barren of both diatoms and nannofossils (Fig. 3).

Taman section

The sediments of **Unit III** include Beds 21–29 (Fig. 4) marked by hiatuses. A single diatomite horizon (Bed 23) contains dominating *Actinocyclus octonarius* represented by all varieties. The normally marine species *Thalassiosira excentrica*, *T. decipiens*, *Azpeitia komurae*, and *Cymatosira savtchenkoi* are scarce. Freshwater *Stephanodiscus multifarus* is few. The bed is marked by the first brackish-water dinocyst endemics *Impagidinium* ex gr. *globosum-spongianum* and *Galeacysta etrusca* (Filippova 2008).

The diatom association of this bed is similar to that of the thin-bedded diatomite “**SP”** in the Zheleznyi Rog section.

Braarudosphaera bigelowii is extremely abundant in Beds 21–25. *Lithostromation perdurum* occurs as single specimens. In Bed 26 *B. bigelowii* becomes less numerous.

Up the section, the up to 10-m-thick member of dark brown clays enriched with organic material overlies the diatomites. The clays yield *Actinocyclus octonarius*, *Cymatosira savtchenkoi*, brackish-water *Stephanodiscus multifarus*, *S. digitatus*, and rare *Braarudosphaera bigelowii. Paradacna abichi* appears in the upper part of Bed 27.

In Bed 28 (0.4 m thick), composed of clayey limestone with *Paradacna abichi* and scarce *Congeria*, the species *Actinocyclus octonarius* and *Cymatosira savtchenkoi* again occur, together with brackish-water *Stephanodiscus multifarus*, *S. digitatus*, benthic marine *Endyctia oceanica*, *Amphytetras antideluvianum*, and planktonic marine *Thalassiosira convexa* var. *aspinosa*, *T. maruyamica*, and *T. praeoestrupii*. This assemblage is similar to that of diatomaceous marl **“N”** in the Zheleznyi Rog section.

Stratigraphic interpretation of results

The age determination of the Pontian base was carried out indirectly by paleomagnetic investigations. Under the base of the Pontian a paleomagnetic inversion from normally to reversely magnetized sediments is recorded. In the Zheleznyi Rog section this event is associated with Bed 5 (Fig. 3). According to V.M. Trubikhin, it is dated to 5.9 Ma, according to M.A. Pevzner, the Pontian base is dated to 7.5 Ma (Nevesskaya et al. 2004).

Popov et al. (2006) correlated the Maeotian with Tortonian–Early Messinian, and the Pontian, with the Late Messinian on the basis of the paleomagnetic record and on the history of the Aegean molluscan migrations. According to the authors, the repeated penetration of Mediterranean molluscs into the Black Sea and Caspian regions finished in the Early Pontian, when brackish mollusc of Aegean origin inhabited the Euxine-Caspian Basin. The base of the Pontian is dated to 6.1 Ma. However, these paleontological data were not enough for a precise age estimate of the Pontian base.

One more attempt to combine paleomagnetic and paleontological records for the Dacian Basin and Taman Peninsula was made (Krijgsman et al. 2010). The authors studied paleomagnetically and paleontologically the Zheleznyi Rog section and also recorded a paleomagnetic inversion, which they dated as the base of the Pontian (6.04 ± 0.01 Ma). They indicated that the “Maeotian–Pontian boundary interval was marked by a short influx of calcareous benthic foraminifera *Porosononion* ex gr. *subgranosus* (Egger), *Ammonia* ex gr. *beccarii* (Linné), agglutinated foraminifera *Ammotium* sp., and planktonic foraminifera comprising *Streptochilus* sp.” (Krijgsman et al. 2010). From these findings the authors inferred a synchronous marine transgression in the Dacian and Black Sea Basins. Unfortunately, the plankton find (only genus reported) cannot serve as a strong biostratigraphic argument for age determination of the Pontian base.

The occurrence of foraminifers in the interval interpreted as the Maeotian–Pontian transition was regarded by the researchers as a “marine environment in the Eastern Paratethys, which was only a short-lived feature of at most 10 kyr”. Unfortunately, the precise attribution of benthic and planktonic microfaunal finds to the section is not indicated; so we cannot correlate them with our available micropaleontological records.

Our studies of nannofossils and diatoms permit the exact definition of boundaries and range of the sediments accumulated during penetration of marine water into the Eastern Paratethys in the Late Maeotian–Early Pontian.

The diatom records became fundamental for age estimation of this event and definition of peculiar hydrological phases.

Among calcareous nannofossils zonal species are missing and they are represented by several forms with dominating *Braarudosphaera bigelowii.* However, the presence of nannoplankton in the “Transitional Strata” is important for elucidation of bionomic conditions in the basin. Mass occurrence of *Braarudosphaera bigelowii* together with *Lithostromation perdurum* and *Reticulofenestra pseudoumbilica* in this part of the Zheleznyi Rog section was initially described by S.A. Luljeva, who pointed to the gradual impoverishment of coccolith composition in the sediments (Semenenko & Luljeva 1982). The acme of *B. bigelowii* is usually interpreted as an indicator of decreased salinity that results in almost complete disappearance of other nannofossil species. However, the combined study of nannoplankton and diatoms showed that in this case the mass development of *B. bigelowii* corresponded to the most marine conditions, since in the intervals rich in brackish- and freshwater diatoms nannofossils are absent.

Our research did not confirm the data by S.A. Luljeva on the presence of *Amaurolithus primus*, *A. delicatus*, and *A. tricorniculatus* at the top of the Maeotian, in the Pontian, and Lower Kimmerian in the sections of the Taman Peninsula (Semenenko & Luljeva 2006). This can result from both a strong terrigenous dilution of the rocks and different methods of investigation. In our opinion the sampling of **Unit I** should be more high-resolution in order to reveal the beds with the most abundant nannofossils. It is known that the most diverse nannofossil assemblages (NN11b, 11c, 11d Subzones) from the Dardanelles region were described in sections of small thickness and found in thin clayey beds (Melinte et al. 2009). In the Taman Peninsula the “Transitional Strata” in the Zheleznyi Rog section are about 80 m thick. The question of correlation of our results with nannofossil records from the Dacian Basin is of major interest. Previously a short calcareous nannofossil influx in the Maeotian–Pontian boundary interval was recorded (Papaianopol & Marunteanu 1993). In the Dacian Basin the transitional Maeotian–Pontian sediments were also studied (the Bizdidel valley and the Valea Vacii section) (Snel et al. 2006). The occurrence of the *Amaurolithus* sp. and *Discoaster* sp. members indicates stronger marine conditions in the Dacian Basin compared with the Taman Peninsula; so the former is characterized by a more diverse nannofossil assemblage. In the Bizdidel section nannofossil assemblage includes *Calcidiscus leptoporus*, *Calcidiscus macintyrei*, *Coccolithus pelagicus*, *Discoaster challengeri*, *Discoaster variabilis*, *Helicosphaera kamptneri*, *Reticulofenestra doronicoides*, *R. minuta*, *R. pseudoumbilicus*, *Sphenolithus abies*, and *Amaurolithus primus* and *Discoaster quinqueramus*, which are characteristic of the NN11b Subzone (Snel et al. 2006). The FO of *Amaurolithus* spp. is equivalent to the base of Subzone MNN11b, at 7.42 Ma, and the FO of *Nicklithus amplificus* is equivalent to the base of Subzone MNN11c, at 6.69 Ma. Further more detailed investigation of nannofossils from the “Transitional Strata” will probably reveal a richer assemblage bearing zonal taxa.

The corresponding local diatom scheme (Kozyrenko & Radionova 2002) (Fig. 3) is based on the changes of assemblages depending on ecological factors, such as salinity fluctuations. Findings of open marine diatoms including zonal species with a short stratigraphic range allow us to correlate the Upper Maeotian with the Mediterranean stratotype sections directly. The detailed micropaleontological study of the “Transitional Strata” resulted in discovery of stratigraphically important species of the tropical diatom schemes, namely:

— FO *Nitzschia miocenica* corresponds to Chron C3b;

— FO *Nitzschia reinholdii* in Chron C4 and LO in Chron C3a;

— FO *Thalassiosira convexa* var. *aspinosa* and *T. miocenica*

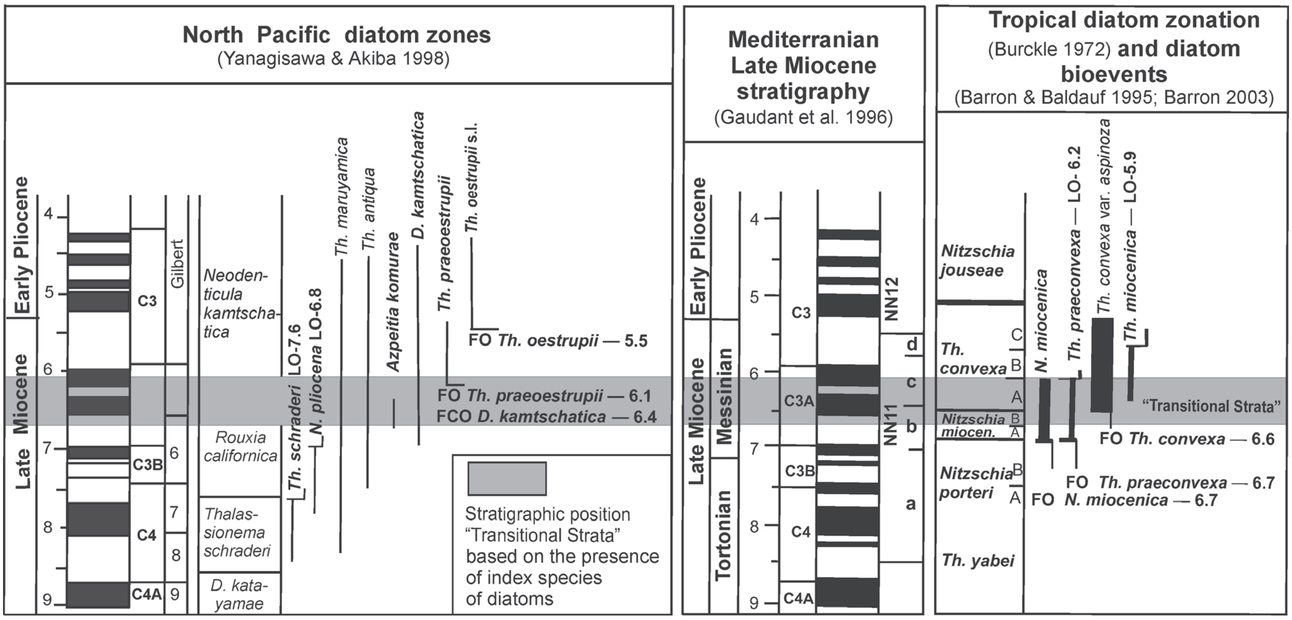

Fig. 7. Stratigraphic range of most important diatom species was found in the “Transitional Strata”: in boreal and tropical diatom zonal scales; Late Miocene Mediterranean scheme and the stratigraphic position “Transitional Strata” on the basis of their presence. *D. — Denticulopsis*, *Th. — Thalassiosira*, *N. — Nitzschia.*

in Chron C3a, FO *T. praeconvexa* and LO in Chron C3a (Burckle 1972) (**Fig. 7**).

The stratigraphic distribution of these species was established at numerous oceanic sites in the Pacific, directly correlated to paleomagnetic data and repeatedly verified (Barron 1992, 2003; Barron & Baldauf 1995). Their datum levels are synchronous in tropical and temperate zones. Having no possibility to assess the range of oceanic zones, we can, however, judge the position of the boundaries of certain zones in the discussed sections (Fig. 7). *Nitzschia miocenica* last occurred near the *Nitzschia miocenica–Thalassiosira convexa* Zones boundary (Burckle 1972). The lower boundary of the *Thalassiosira convexa* Zone is marked by the first occurrence of the index species (C3A, 6.2 Ma) (Barron 2003). In our material *Nitzschia miocenica* was found only in sediments of Unit I. *Thalassiosira convexa* var. *aspinosa* appeared in mid-**Unit II** (Figs. 3, 4). Consequently, the accumulation of sediments of **Unit I** took place up to 6.2 Ma. **Units II** and **III** were deposited later.

The occurrence of some stratigraphic key taxa of the boreal oceanic scale permits a more precise age determination of the “Transitional Strata”. These species are *Azpeitia komurae*, *Thalassiosira maruyamica*, *T. antiqua*, and *T. praeoestrupii* (Figs. 4, 7). The presence of *Azpeitia komurae* (FO at 6.7 Ma, LO at 6.4 Ma) (Yanagisawa & Akiba 1998) in **Unit I** indicates that the sequence is at least not younger than 6.4 Ma.

The FO of *Thalassiosira praeoestrupii* was defined at 6.1 Ma (Fig. 7). The species appeared at that time in both the temperate Pacific and North Atlantic together with other members of the group *Thalassiosira oestrupii* (Boden 1992).

According to the simultaneous presence of all marker species (Fig. 7), the time of “Transitional Strata” accumulation can be estimated in a wide range from 6.4 to 6.1 Ma. This provides an opportunity to correlate this part of Zheleznyi Rog with pre-evaporate sediments and possibly with the basal part of the Messinian lower-evaporate sediments.

It should be noted that the age estimate of the Messinian sediments in the stratotype section was carried out based on the same marker species (Burckle 1978; Gersonde 1980), and correlation of the Capodarso section with the paleomagnetic scale was initially done indirectly from the diatom zonation (Ryan et al. 1974). All siliceous deposits of the Mediterranean Lower Messinian are dated by diatoms to the upper *Nitzschia miocenica* Zone and Subzone A of the *Thalassiosira convexa* Zone (Gersonde & Schrader 1984).

An important event for the level discussed is the first appearance of a few brackish-water species *Stephanodiscus multifarus*, *S. digitatus*, and *Cyclotella praekutzingiana*, associated with **Unit III** and described earlier from freshwater Pliocene sediments of the Black Sea (Jouse & Mukhina 1978; Hursevich & Mukhina 1995).

The occurrence of silicoflagellates including *Distephanus speculum*, etc. in **Unit I** of the Zheleznyi Rog section became an additional supporting factor for the proposed correlation. Our data are very well correlated with the results of study of laminated diatomites of the Gavdos Formation described in northwestern Gavdos Island, South Crete (Frydas 2006). The diatomite of the Gavdos Formation is characterized by the presence of diatoms of the *Nitzschia miocenica* Zone and the lower part of *Thalassiosira convexa* Zone and is correlated to the Messinian stage.

D. Frydas notes that the abundant silicoflagellate association of *Distephanus speculum minutus* local Biozone approximately corresponds to C9bA (*Amaurolithus primus*) and C9bB (*Amaurolithus amplificus*) Zones of the nannoplankton scheme.

Dynamics of basin development

The studies of calcareous nannofossil and diatom assemblages suggest that accumulation of the "Transitional Strata" in the Upper Maeotian–Lower Pontian interval occurred in three stages.

The first stage (**Unit I**) corresponded to the beginning of the marine water invasion and signifies the short-term connection with the Eastern Mediterranean possibly through the Dacian and Aegean Basins.

It is known that the beginning of the Messinian was marked by a short-term transgression (Meulenkamp et al. 2000), rapidly acquiring a pulsing character, resulting from periodical closing of the connection with the Atlantic. The same discontinuous pulsing rhythm is typical for the next stages of the cycle (Beds 2–8) (**Unit II** and **Unit III**).

A short-term increase of marine waters invasion into the brackish-water basin together with a considerable river influx led to initiation of narrow frontal zones with sharp gradients of water density. Periodical outbreaks of microflora bioproductivity led to the formation of thick monodominant diatomite and nannofossil deposits.

A considerable impoverishment of monospecific nannoplankton association during the accumulation of sediments in the second and third stages makes the analysis of diatoms a priority. Formation of an assemblage with dominant *Actinocyclus ehrenbergii* (*A. octonarius)* is well known in modern epicontinental seas in big river delta areas and is usually interpreted as a hydrological front zone or as a convergence zone that forms at dumped depths of a brackish-water epicontinental basin. This type of diatom ooze bearing dominant *Actinocyclus ehrenbergii* was recorded in Quaternary sediments of the Caspian Basin (Sval'nov & Kazarina 2008). A seasonal bloom of dominant species produces billions of diatom shells per gram of sediment. Seaward from this zone a marine diatom association is being formed, while the brackish-water or freshwater one occurs coastward.

Unit II (Beds 2–3). The accumulation of Bed 2 (**"A"** diatomite and overlying diatom clays, Zheleznyi Rog) took place in the environment of mixed marine and brackish-water masses. The structure of the diatom assemblages shows that sedimentation occurred in the inner part of a frontal zone, because besides *Actinocyclus ehrenbergii*, the association contains numerous marine brackish-water Maeotian species. In Bed 3 (Fig. 3), in a diatom association containing *Actinocyclus ehrenbergii*, marine diatoms dominate and among them species of *Coscinodiscus* are abundant, as well as *Azpeitia* aff. *komurae*, *Rhizosolenia bezrukovii* and other species typical for the most marine conditions observed in Bed 1. *Thalassiosira convexa* var. *aspinosa* first appeared in this association, which may point to a new transgressive event and widening of the marine water mass influence.

Unit III (Beds 4–7) shows a growing regression process and connection with the marine basin coming to the end. Marine diatom species and nannoplankton are absent. Shallow-water conditions are developing, and numerous brackish-water molluscs appear in carbonate clays, the Early Pontian species *Paradacna abichi* among them. Diatoms of *Stephanodiscus* and *Cyclotella* genera are found in clays, and the first appearances of a few species later becoming widespread in freshwater Pleistocene sediments of the Black Sea are observed. Diatomite **"SP"** in Bed 4 may point to a short transgressive impulse against the background of a regressive environment; its diatom association is similar to that of diatomite **"A"**, but among marine species only local ones remaining from the time of the Maeotian basin continue to occur.

In diatomite **"Ch"** (Bed 6) intercalation of layers with freshwater species and monoassociation with *Actinocyclus octonarius* is observed. This shows the environment of a shoreface zone which is characterized by freshwater diatoms. Widening of the freshwater zone corresponds to a regression development. The upper part of Bed 6 is composed of sandy clay with abundant *Paradacna* and ostracods.

A short final impulse of marine invasion is reflected in diatomaceous marl **"N"** containing *Actinocyclus octonarius* together with few oceanic *Thalassiosira* species and *Braarudosphaera bigelowii* nannoplankton (Fig. 3).

Conclusion

Micropaleontological study of the "Transitional Strata" resulted in refinement of the age and in estimation of the ecological character of the sediments. The stratigraphic range of the strata of our data is defined as 6.4–6.1 Ma, which agrees well with the currently available paleomagnetic records that determined the base of the Pontian in the Zheleznyi Rog section at 6.1 Ma (Popov et al. 2006; Filippova & Trubikhin 2009; Krijgsman et al. 2010). The subdivision of the "Transitional Strata" into **Units I–III** corresponds to certain hydrological stages of the basin. **Unit I** records the maximum marine conditions. **Unit II** is fully represented only in the Zheleznyi Rog section and reflects a gradual transition from marine to brackish-water environment. **Unit III** indicates the predominance of brackish-water conditions. The Zheleznyi Rog section is a unique geological object. Only its thick and uninterrupted succession of sediments displays in detail all stages of the ecological evolution of the basin in the Late Maeotian–Early Pontian. In the closely located Taman and Popov Kamen' sections the sediments of **Unit II** are missing or are strongly reduced, and the Maeotian-Pontian boundary actually corresponds to that between **Unit I** and **Unit III**. According to the diatom and nannofossil record, the top of **Unit I** marks the termination of a relatively free communication with the Mediterranean and corresponds to the top of the *Cymatosira savtchenkoi* Beds of the *Thalassiosira maeotica* Zone (Jouse 1949; Kozyrenko & Radionova 2002). In the Zheleznyi Rog section this boundary occurs beneath the thick diatomite **"A"**. It was suggested as the Maeotian-Pontian boundary by siliceous plankton paleontologists and lithologists who used this group of biota (Jouse 1949; Kozyrenko & Radionova 2002; Rostovtseva 2009). However, a high-resolution research revealed this level to be located considerably below the boundary proposed by Andrusov (1903), which was based on the appearance of brackish-water endemics characteristic of the Pontian. The boundary after N. Andrusov (FO *Paradacna abichi*) approximately corresponds to that between **Units II** and **III** and is accepted by many subsequent researchers (Popov & Zastrozhnov 1998; Filippova & Trubikhin 2009; Krijgsman et al. 2010). The complicated and comprehensive character of changes at this level requires further research and achievement of an agreement concerning its position among specialists in different groups of fossil biota. The Upper Maeotian–Lower Pontian “Transitional Strata” in the Taman Peninsula sections corresponds to the period of indirect Mediterranean water invasion into the Eastern Paratethys basin. During the first stage an indirect connection between these two basins was relatively free, and at the second and third stages it was of a pulsing intermittent character. The estimated duration of the invasion event is from 6.4 to 6.1 Ma and corresponds to the Early Messinian, to the upper part of pre-evaporate deposits and lower part of lower evaporate deposits.

Acknowledgments: We thank Sergey Popov, Naci Görür and an anonymous reviewer for their comments, which improved the clarity of this manuscript. We are grateful to Nina Gorkova for SCAN photos and Marina Bylinskaya for translation. We express our gratitude to all our colleagues from the Geological Institute RAS, Paleontological Institute RAS, and Moscow State University for discussion, and especially to Nataly Filippova for field work cooperation. This work was supported by the Russian Foundation for Basic Research (Projects Nos. 09-05-00307-a and 10-05-01102-a).

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