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A Late Maeotian age (6.7–6.3 Ma) for the enigmatic “Pebbly Breccia” unit in DSDP Hole 380A of the Black Sea

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ABSTRACT

Various hypotheses exist on the age and origin of the so-called “Pebbly Breccia” unit in the deep-sea record of DSDP Hole 380A of the Euxinian (Black Sea) Basin. Here, we present a detailed study of diatom and nannofossil assemblages of Hole 380A. Our diatom records show a characteristic sequence of appearance of markers species, which we can correlate to the recently established bio-magnetostratigraphic time frame of the Zheleznyi Rog section on the Black Sea coast of the Taman Peninsula (Russia). It shows that the Pebbly Breccia is sandwiched between Upper Maeotian deposits, and must have been deposited at an age between 6.7 and 6.3 Ma. The appearance of nannoplankton and the marine diatom association at above the Pebbly breccia (Unit IVc) suggests a short-term incursion of marine conditions. The age of Unit IVc, based on diatom data, is 6.3–6.1 Ma. The nannoplankton record is mainly represented by species that do not have stratigraphic value. The previously reported presence of *Ceratolithus acutus* in the Black Sea is explained by misinterpretation of destructed elements of ascidian spicules. We conclude that the Pebbly Breccia is not related to a desiccated Black Sea at Messinian Salinity Crisis times, but it corresponds to a late Maeotian episode of gravitational instability in the SW Black Sea region.

1. Introduction

The only Mio-Pliocene stratigraphic archives (for scientific use) of the deep parts of the Euxinian (Black Sea) Basin have been obtained by the Deep Sea Drilling Project (DSDP) Leg 42B, which drilled three locations (379, 380/380A, 381) in the southwestern and central part of the basin (Fig. 1; Ross et al., 1978). The integrated studies from these wells have played a significant role in scientific discussions on the paleoenvironmental history of the Euxinian Basin and its connectivity with the Mediterranean Sea. Especially the age, significance and depositional environment of the anomalous Unit IVd of Hole 380A, the so-called “Pebbly Breccia”, has resulted in many and widely different interpretations (Hsü and Giovanoli, 1979; Kojumdgieva, 1983; Golovina et al., 1987; Grothe et al., 2014; Tari et al., 2015).

The Pebbly Breccia is a peculiar sedimentary unit of Late Miocene age. The interpretation of its limestone clasts as being indicative for shallow, supratidal and intertidal environments within an otherwise deep water sequence was suggested after the drilling (Hsü and Giovanoli, 1979), despite alternative interpretations indicating it may have formed as a slump breccia and/or cemented slump blocks (Shipboard Scientific Staff, 1978). The interpretation by Hsü and Giovanoli (1979), led to the hypothesis that the Black Sea water level dropped by more than ~1600 m in concert with the Mediterranean Sea during the Messinian Salinity Crisis (MSC). Later, seismic profiles of the Black Sea margins provided evidence of several major erosional surfaces, refuelling the hypothesis of a largely desiccated Black Sea Basin during MSC times (Dinu et al., 2005; Gillet et al., 2007; Munteanu et al., 2012). The alternative interpretation, that the Pebbly Breccia is caused by gravitational mass transport, without any relation to the MSC, has also recently revived (Grothe et al., 2014; Tari et al., 2015, 2016). The poor biostratigraphic control and the lack of reliable marine marker species in the deep Euxinian (Black Sea) basin so far prevented a direct age determination of this enigmatic interval.

Especially the changes in diatom assemblages have long been underestimated but indicate basin wide changes in hydrological regime (Radionova and Golovina, 2010, 2011). Here, we focus on new diatom

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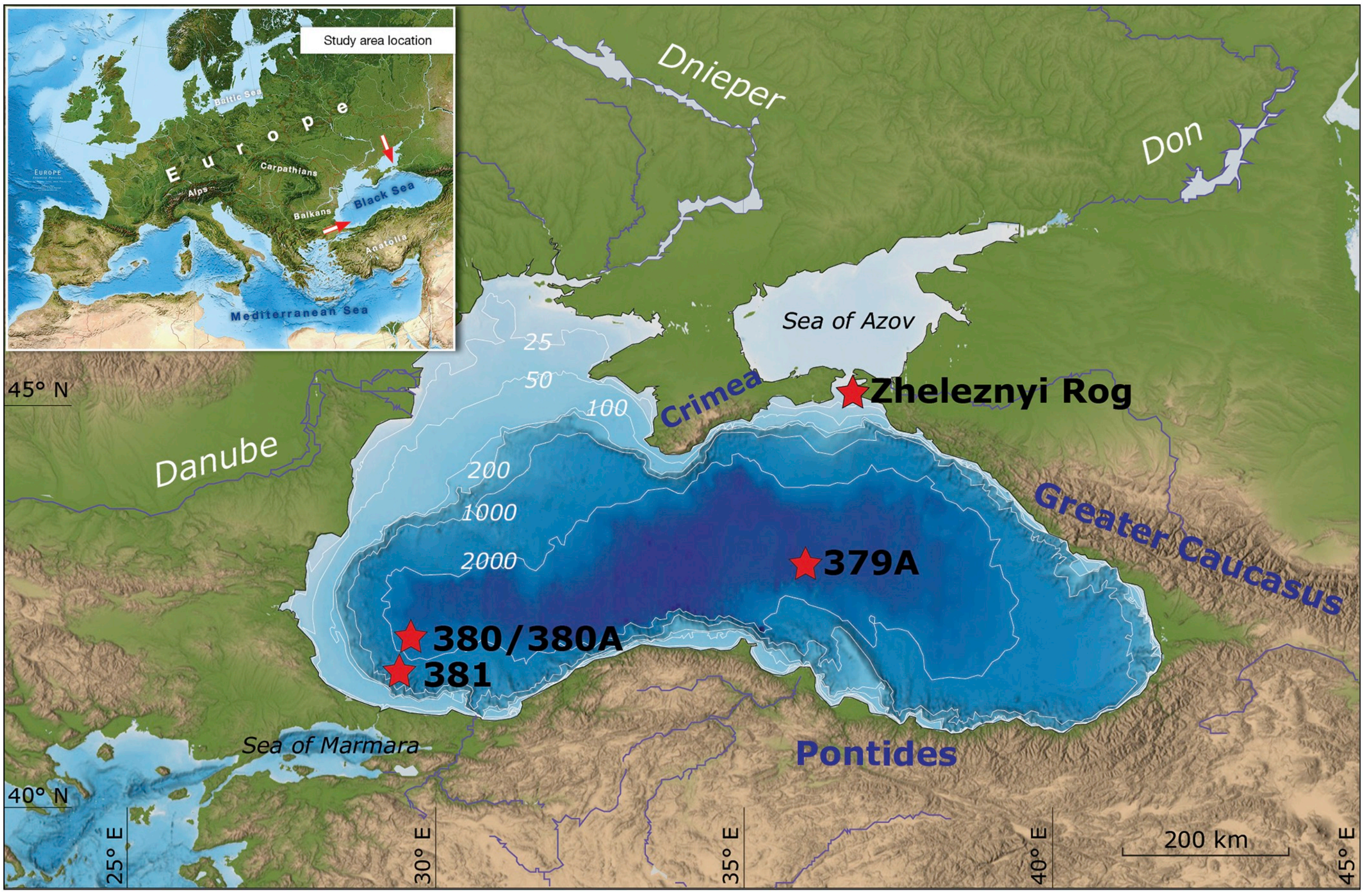


Fig. 1. Map of the Black Sea region with DSDP Leg 42B drilling locations. (after Van Baak et al., 2016b).

and calcareous nannofossil analyses, as these are the key faunal components of the DSDP records. We reanalyse the succession of events in the DSDP Hole 380A and establish a correlation to the extensively studied and magneto-biostratigraphically dated Zheleznyi Rog section on the Taman Peninsula of Russia (Krijgsman et al., 2010; Radionova and Golovina, 2011; Vasiliev et al., 2011, 2013; Chang et al., 2014; Popov et al., 2016; Stoica et al., 2016; Rostovtseva and Rybkina, 2017). This allows us to provide direct age estimates for the Pebbly Breccia that will shed another light on its origin and on the evolution of the Black Sea during the late Miocene to Pliocene.

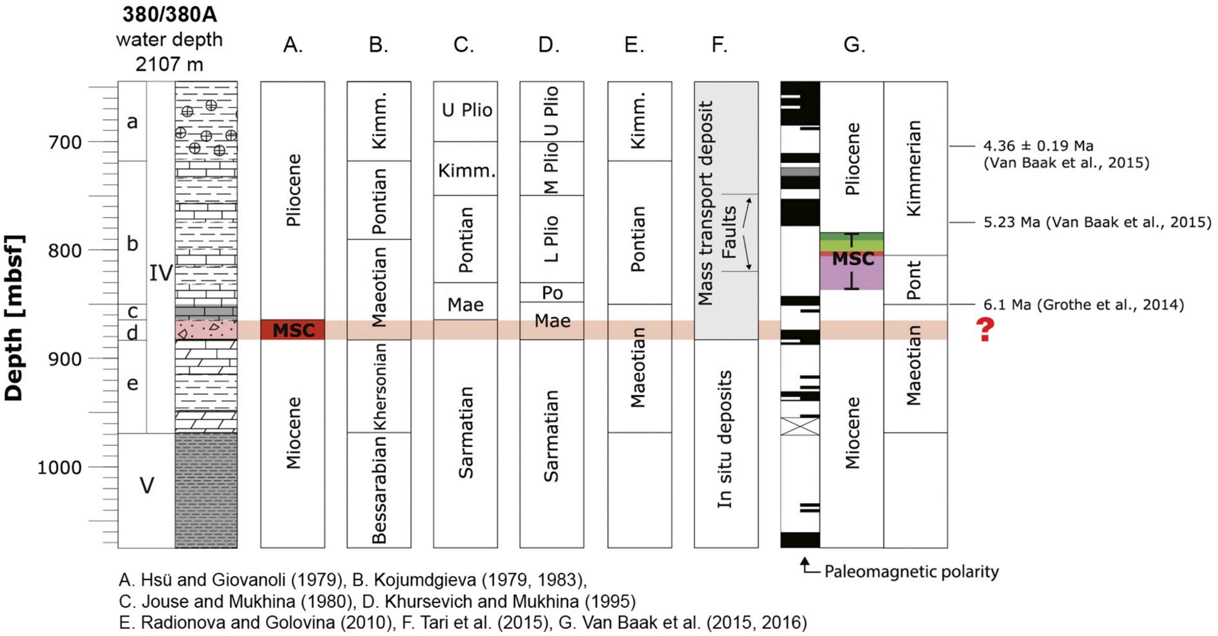
2. Background studies

2.1. DSDP Leg 42 B

DSDP Leg 42b Hole 380A (Fig. 1; 42°05.94 N, 29°36.82 E) was drilled at a water depth of ~2100 m (Shipboard Scientific Staff, 1978). The initial lithostratigraphic subdivision of the DSDP sediments was based on sediment lithology and chemistry, using biotic data as paleoecological indicator (Ross, 1978). The lower part of Hole 380A was divided into six lithological units (Fig. 2); Unit IVa (sideritic and diatomaceous sediments 644.6–718 mbsf), Unit IVb (laminated lacustrine chalk (*Seekreide*), diatomaceous marls 718–816 mbsf); Unit IVc (laminated diatomite, laminated aragonite, diatomaceous shale 820–864.5 mbsf); Unit IVd (coarse clastic, stromatolitic dolomite - 864.5–883.5 mbsf) and Unit IVe (laminated marls and dolomite 883.5–969.0 mbsf). Below this, Unit V – black shale, with dolomite laminations (969–1073.5 mbsf) represents the lowermost part of the core. Subunit IVd, the so-called "Pebbly Breccia", comprises anomalous coarse clasts in a mudstone matrix and laminated stromatolitic dolomite previously interpreted as indicative for a sea level drop in the Black Sea (Stoffers and Müller, 1978; Hsü and Giovanoli, 1979).

A major problem of the DSDP Leg 42 project was that a reliable time frame for the recovered sedimentary succession could not be established. The main reason was that diagnostic paleontological age markers were essentially lacking because the observed faunal elements were mostly endemic to the Black Sea (Jousé and Mukhina, 1978, 1980; Golovina et al., 1987; Ross et al., 2007). Consequently, the Mio-Pliocene geological time scale of the Black Sea basin comprises mainly regional stages (e.g., Khersonian, Maeotian, Pontian, Kimmerian; see Hilgen et al., 2012 for the latest update). The initial correlation of the Pebbly Breccia to the Messinian event (Fig. 2) was considered a working hypothesis at best (Ross, 1978), and has been seriously questioned by several authors. Kojumdgieva (1979, 1983) claimed that the Pebbly Breccia deposits were of latest Khersonian age (~10–8.5 Ma). Based on diatoms and nannoplankton data, Radionova and Golovina (2010) proposed a Maeotian age (8.5–6.1 Ma). Grothe et al. (2014) dated the Pebbly Breccia to be older than 6.1 Ma (=Maeotian or Khersonian), based on dinoflagellate data: the First Common Occurrences of *Caspidinium rugosum* and *Galeacysta etrusca*, corresponding to the base of the Pontian in Zhelezny Rog (Filipova, 2002), which is in agreement with recent magnetostratigraphic results (Van Baak et al., 2015, 2016b). In contrast, Popescu (2006), Popescu et al. (2010) and Suc et al. (2015) supported the MSC correlation mainly based on palynological arguments. The lack of reliable marine marker species in the deep Black Sea basin so far prevented a direct age determination.

Diatoms are the most abundant fossil group in the DSDP Leg 42 cores. Initial studies resulted in two contrasting hypotheses: (I) the drilled sequences correspond to Pliocene–Quaternary deposits, with various breaks inside the section (Schrader, 1978), or (II) the cores



A. Hsü and Giovanoli (1979), B. Kojumdgieva (1979, 1983),
C. Jouse and Mukhina (1980), D. Khursevich and Mukhina (1995)
E. Radionova and Golovina (2010), F. Tari et al. (2015), G. Van Baak et al. (2015, 2016)

Fig. 2. The evolution of the age model of DSDP 380/380A in the southwestern Black Sea. (after Van Baak et al., 2017).

comprise a continuous succession of Upper Miocene–Quaternary deposits (Ross et al., 2007). Jousé et al. (1980) and Jousé and Mukhina (1980) identified, in Unit IVe - IVc, diatom assemblages containing *Thalassiosira maeotica* and *Rhaphaneis maeotica* - species that are known from the regional Maeotian stage - and correlated these deposits to the Upper Miocene. In addition, they noticed a sequence of diatom assemblages changing from typical marine associations at the base (Unit IVc) (through a series of intermediate steps) to freshwater lake associations in the upper (Unit IVb) part and realized that these freshwater-lake conditions did not specifically depend on the geological evolution of the Bosporus region, but were principally a reflection of the general Black Sea basin history.

Calcareous nannoplankton assemblages were initially analysed by Percival (1978) and Shumenko and Ushakova (1980), but this did not provide any significant chronostratigraphic results. Later, Golovina et al. (1987) studied > 500 samples (from Sites 380 - 380a) and confirmed the original conclusion that the nannofossil assemblages of Hole 380/380-A lack stratigraphically significant taxa. In general, the DSDP cores contain only two autochthonous nannoflora species: *Gephyrocapsa caribbeanica,* at the top of Hole 379A and 379B (Shumenko and Ushakova, 1980), and *Braarudosphaera bigelowii* (Percival, 1978; Golovina et al., 1987). *Braarudosphaera bigelowii* is observed in several levels, especially in the lower part of Hole 380A, and was interpreted as indicative of marine environments with low salinity (Müller, 1974; Negri and Giunta, 2001; Giunta et al., 2006); it should be noted that this species cannot survive at salinities lower than 17‰ (Bukry et al., 1974). Later, Alekseev et al. (2012) observed mono-specific assemblages of *Calciosolenia brasiliensis* (Lohmann, 1919) at level 889,5 mbsf. Such coccoliths were previously defined as *Scapholithus fossilis* and recorded in the Lower Maeotian deposits of the Taman Peninsula (Popov et al., 2016).

Popescu et al. (2010) reanalyzed the calcareous nannoplankton assemblages of Hole 380A together with a detailed palynological study. They concluded that the Pliocene marker species *Ceratolithus acutus* was observed et level 840.00 mbsf and proposed to correlate the Unit IVc with the lowermost Zanclean and, as a consequence, the underlying Pebbly Breccia with the MSC event (Popescu, 2006; Popescu et al., 2010, 2016). Van Baak et al. (2015, 2016b) re-studied the 840 mbsf interval in detail to confirm the presence of these Pliocene nannofossils, but were not able to reproduce the findings of *C. acutus* in that core.

2.2. Zheleznyi Rog and Popov Kamen sections

In the last decade, several integrated stratigraphic studies have been performed on the late Miocene-Pliocene sedimentary successions from the shallow Black Sea margin on the Taman Peninsula of Russia. The Zheleznyi Rog and Popov Kamen sections have been investigated for lithostratigraphy (Rostovtseva and Rybkina, 2014; Popov et al., 2016), magnetostratigraphy (Krijgsman et al., 2010; Vasiliev et al., 2011; Trubikhin and Pilipenko, 2011), cyclostratigraphy (Chang et al., 2014; Rostovtseva and Rybkina, 2017), biostratigraphy (Radionova and Golovina, 2011; Stoica et al., 2016; Popov et al., 2016) and geochemistry (Vasiliev et al., 2013, 2019). This provided a unique reference framework for the Eastern Paratethys with well-defined successions of events that can now be used to establish correlations to the DSDP cores (Van Baak et al., 2017). Key constraints are: 1) the base of the Maeotian is estimated at 7.9–7.8 Ma (Radionova et al., 2012), at ~7.6 Ma (Popov et al., 2016), and 7.65 Ma (Palcu et al., 2019); Lower/Upper Maeotian boundary is determined close to the base of chron C3An.2n with an age of ~6.7 Ma (Radionova and Golovina, 2011; Trubikhin and Pilipenko, 2011; Vasiliev et al., 2011) and 6.8–6.7 Ma (Palcu et al., 2019), 3) and the Maeotian/Pontian transition interval starts with a marine flooding dated in the upper part of chron C3An.1n at an age of ~6.1 Ma (Trubikhin and Pilipenko, 2011; Vasiliev et al., 2011; Chang et al., 2014; Rostovtseva and Rybkina, 2017).

3. Methods

In total, we have re-analysed 110 samples from DSDP Hole 380A (42°05.94′N,29°36.82′E) (718–1073.5 mbsf) for diatom and calcareous nannoplankton content (Figs. 3–5). The investigations were done using a light polarizing microscope at ×1600 magnification. Our taxonomic identification follows Perch-Nielsen (1985) and Young (1998). For diatom analyses 37 samples were studied: 21 samples from Unit IVe (969–883.5 mbsf), 3 samples from Unit IVd (864.5–883.5 mbsf) and 13 samples from Unit IVc (850.3–864.5 mbsf) (Fig. 6). These samples are from the collection of the Institute of Oceanology of the Russian Academy of Sciences and were previously studied by Jousé and

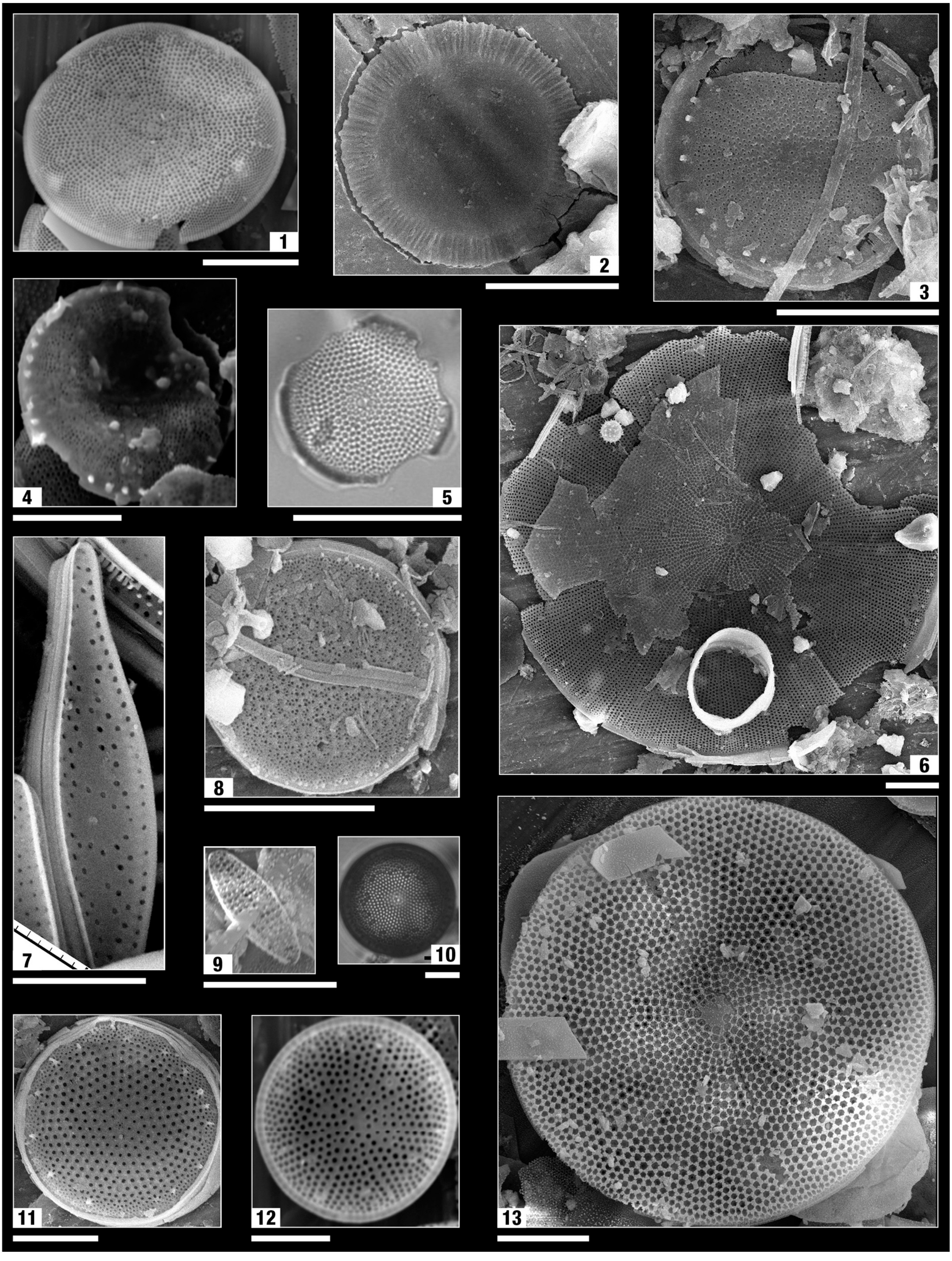


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Fig. 3. Diatom marker species. 1. *Actinocyclus octonarius* var. tamanica; 2. *Ellerbekia arrenaria* (Moore) Crawford; 3. *Stephanodiscus digitatus* Churs. et Mukchina; 4. *Stephanodiscus multifarus* Churs. et Mukchina; 5. *Thalassiosira maeotica* Proch.-Lavrenko; 6. *Coscinodiscus granii* Gough; 7. *Cymatosira savtchenkoi* Proch.-Lavrenko; 8. *Thalassiosira bramaputrae* (Ehr.) Hakansson & Locker; 9. *Rhaphoneis maeotica* (Milov.) Shesh-Poretskaya; 10. *Thalassiosira convexa* Mukchina; 11. *Coscinodiscus jambori* HayÒs; 12. *Thalassiosira miocenica* Schrader; 13. *Coscinodiscus apiculatus* Ehr. Magnification scale 1–6,10,13–20 μ; 7–9,11,12–10 μ.

Mukhina (1980). Five additional samples from the interval 840–856.9 mbsf were provided from the Utrecht collection (Van Baak et al., 2015).

Finally, the deep basin sedimentary succession of the DSDP Hole 380 was reinterpreted by combining the original geologic and lithological information from the DSDP shipboard reports and the paleobathymetric estimations provided by the biostratigraphic analyses and the new available seismic data (Tari et al., 2015).

4. Results

4.1. Diatoms

Diatoms are not found in deposits below 955 mbsf. The diatom assemblages from Unit IVe (sample at 950 mbsf) include *Navicula zychii, Cocconeis pelucides, Nitzschia debilis, Amphiprora* sp., *Amphora* sp., *Rapolodia* sp. (Fig. 3) and can be attributed to Sarmatian. The association is dominated by benthic species, suggesting that the depths in this part of the basin did not exceed 100 m. The interval from 944 mbsf to 940 mbsf shows the planktonic species *Thalassiosira nativa, Th. lineata,* and *Th. maeotica* (marker-species of Lower Maeotian) (Kozyrenko and Temnishkova-Topalova, 1990; Kozyrenko and Radionova, 2002). Sample at 933 mbsf contains planktonic brackish water species of the genus *Stephanodiscus*, but the composition of benthic diatoms assemblages remains the same.

The Upper Maeotian zonal species *Cymatosira savtchenkoi* is present above level 930 mbsf (samples at 929 mbsf; 926.2 mbsf and 926.4 mbsf). This interval also contains several marine species such as *Grammatophora marina, Thalassionema nitzschioides* and semi-marine planktonic species like *Actinocyclus octonarius, Act. variabilis* and *Coscinodiscus granii*. In the interval of 928–921 mbsf, the contribution of brackish water diatoms increases and species of *Coscinodiscus jambori, Stephanodiscus transilvanicus(?), St. multifarus, Cyclotella* sp. are present. The large benthic diatoms *Surirella maeotica, Amphiprora paludosa,* and particularly the highly abundant genus *Hyalodiscus* are typical for sublittoral environments (Prochkina-Lavrenkoe, 1960). We conclude that during this time the composition of diatom associations in Unit IVe reflects an overall brackish-water shallow basin environment, with a short marine incursion around 930 mbsf. The diatoms of this interval may correspond to the layers with *Coscinodiscus jambori* in the Zheleznyi Rog section (Radionova and Golovina, 2010). Diatoms are absent in the top of Unit IVe (912–883 mbsf), Unit IVd (883–864 mbsf) and the base of Unit IVc (864–859 mbsf). In the samples D5 (856.6 mbsf) and D4 (856.2 mbsf) organic-walled phytoplankton is present, and diatoms are scarce. We found only several valves of *Thalassiosira sp., Th type. burckliana, Lyrella* sp. and some Paleogene species. The diatom assemblages from Unit IVc (sample at 851 mbsf) contain the brackish water species *Coscinodiscus jambori, Coscinodiscus granii, Stephanodiscus transilvanicus(?), St. multifarus, Cyclotella sp.,* and rare species of *Rhaphoneis maeotica* and *Rhyzosolenia bezrukovii.* The diatoms of this interval correspond completely to the layers with *Coscinodiscus jambori*. The top of Unit IVb (846–841 mbsf) shows three levels with abundant diatom flora and a predominance of *Actinocyclus octonarius*. The lowermost sample D2 (846 mbsf) contains common *Actinocyclus octonarius* together with the marine species *Coscinodiscus asteromphalus, Rhaphoneis maeotica, Rhyzosolenia bezrukovii, Thalassiosira aff. convexa, Th. praeconvexa* and the brackish-water diatoms *St. multifarus, Pliocaenicus sp., Cyclotella* sp. In sample 55-4 (78–96 cm) at 844mbsf, *Actinocyclus octonarius* dominates, while brackish water species *St. multifarus, Thalassiosira bramaputra,* and *Ellerbekia arrenaria* are also present (Fig. 3). The sequence and structure of the diatom assemblages in the interval are similar to the microflora composition described as “Transitional strata” from the Zheleznyi Rog section (Radionova and Golovina, 2011). However, the thickness of the beds is greatly reduced, and the sediments show signs of mixing.

In Unit IVb (lacustrine chalk) diatoms are scarce and their composition changes completely. The freshwater planktonic species *Melosira praeislandica* is the dominant diatom, and it is accompanied by *Coscinoiscus rotii, Stephanodiscus multifarus* and *Actinocyclus octonarius.* Benthic diatoms are absent at level 818.2 mbsf.

4.2. Calcareous nannofossils

Our re-analysis of the DSDP material confirms the presence of scarce nannofossils that are not stratigraphically significant. The composition of the nannoplankton assemblages in Unit V (969–1073.5 mbsf) includes predominantly rare species of *Braarudosphaera bigelowii, Coccolithus pelagicus, Reticulofenestra pseudoumbilicus, Reticulofenestra minuta, Sphenolithus abies* and some reworked Paleogene species. The deposits of subunits IVe (883.5–969 mbsf) and IVd (864.5–883.5 mbsf) contain more abundant nannofossils. The deposits of subunit IVd (864, 6 and 867,6 mbsf) are characterized by the presence of *Helicosphaera carteri, Helicosphaera sp., Rhabdosphaera sp.*, and abundant *Braarudosphaera bigelowii* (Fig. 4). Furthermore, we observed in IVd several species of *Perfocalcinella fusiformis, Lacunolithus menneri* and some specific nannofossils that belong to the genus *Micrascidites* (Figs. 4,5). In polarized light, these are round spindle-shaped grains that have high interference colours and sizes from 13 to 25 μm. Their surface is sometimes granulated and they often have longitudinal ridges or depressions bordered ribs. We note here that the genera of *Micrascidites* are morphologically similar to *Perfocalcinella* (Golovina, 2008). These calcareous elements belong to the so-called ascidian spicules. It has been noted before that “ascidians are benthic tunicates, and have nothing to do with nannoplankton. The spicules they produce commonly occur in nannoplankton preparations, especially from shallow marine environments” (Nannotax3 website.2017). In the marginal sections on the Taman and Kerch Peninsulas, these ascidian spicules are a typical component of the Maeotian nannoplankton associations (Luljeva, 1989a; Golovina, 2008). An overview and classification of ascidian spicules is presented in several papers (e.g., Varol and Houghton, 1996; Varol, 2006; Łukowiak et al., 2016). Ascidians are temperature and salinity-sensitive, they prefer normal marine habitats (Monniot et al., 1991), so abundant ascidian spicules can be used for paleoecologic reconstructions as they are indicators of sublittoral and littoral marine conditions (Varol, 2006; Golovina, 2008; Łukowiak et al., 2016). It should be noted that abundant ascidian spicules, together with specimens of *Braarudosphaera bigelowii,* are present below (at 883.6 mbsf) and above (at 855.2 mbsf) the Pebbly Breccia. The sequence and structure of the nannofossil assemblages in the interval 904.2–855.2 mbsf probably correspond to several stages of slope instability.

The youngest studied subunit IVb (817–850.3 mbsf) contains only a few samples with rare nannoplankton. Samples from interval 818.5–816.2 mbsf show an abundance of *Isolithus semenenko* Luljeva (Fig. 6). This species was first described from Pontian deposits of the Zheleznyi Rog section, and was considered an index species for the Pontian stage (Luljeva, 1989b). Later, it was established that it originated from the Pannonian basin (Cziczer et al., 2009) and it was also observed in older and younger sediments from the Central and Eastern Paratethys (Coric, 2005; Chira, 2006; Chira and Malacu, 2008; Popov et al., 2016). Special attention has been devoted to the interval straddling ~840 mbsf where Popescu et al. (2010) mentioned the presence of *Ceratolithus acutus*, but this species has not been observed by us.

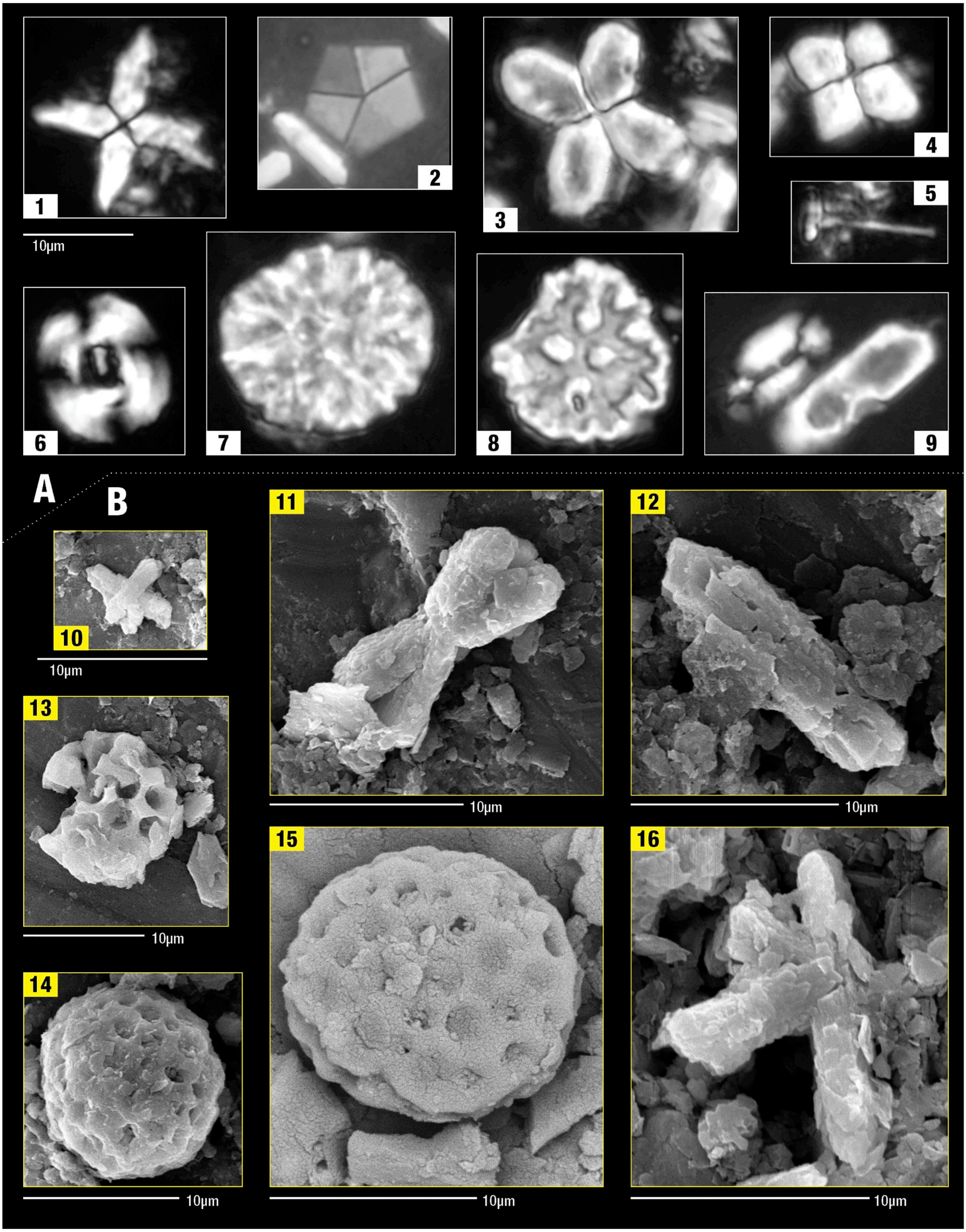

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Fig. 4. A: LM microphotographs of nannofossils from Hole 380-A (crossed-nicols photographs magnification ×1600). 1–*Perfocalcinella fusiformis* Bona 1966 (874,6 mbsf); 2 – *Braarudosphaera bigelowii* (Gran & Braarud 1935) Deflandre, 1947 (864,6 mbsf); 3,4 – Perfocalcinella fusiformis Bona 1966 (866,17 mbsf); 5 –Rhabdosphaera sp. (864,6 mbsf); 6 – *Reticulofenestra pseudoumbilicus* (Gartner, 1967) Gartner, 1969 (866,17 mbsf); 7 – *Lacunolithus menneri* Lyul'eva 1989 (864,6 mbsf); 8 – *Lacunolithus menneri* Lyul'eva 1989 (874,6 mbsf); 9 – *Helicosphaera carteri* (Wallich 1877) Kamptner, 1954 (864,6 mbsf). 4B: SM microphotographs. Scale bar in microns. 10, 16 – *Perfocalcinella fusiformis* Bona 1966 (874,6 mbsf); 11, 12 – destroyed fragments *Perfocalcinella fusiformis* Bona 1966 (867,67 mbsf); 13, 14, 15 – *Lacunolithus menneri* Lyul'eva 1989 (867,67 mbsf). Fig. 5

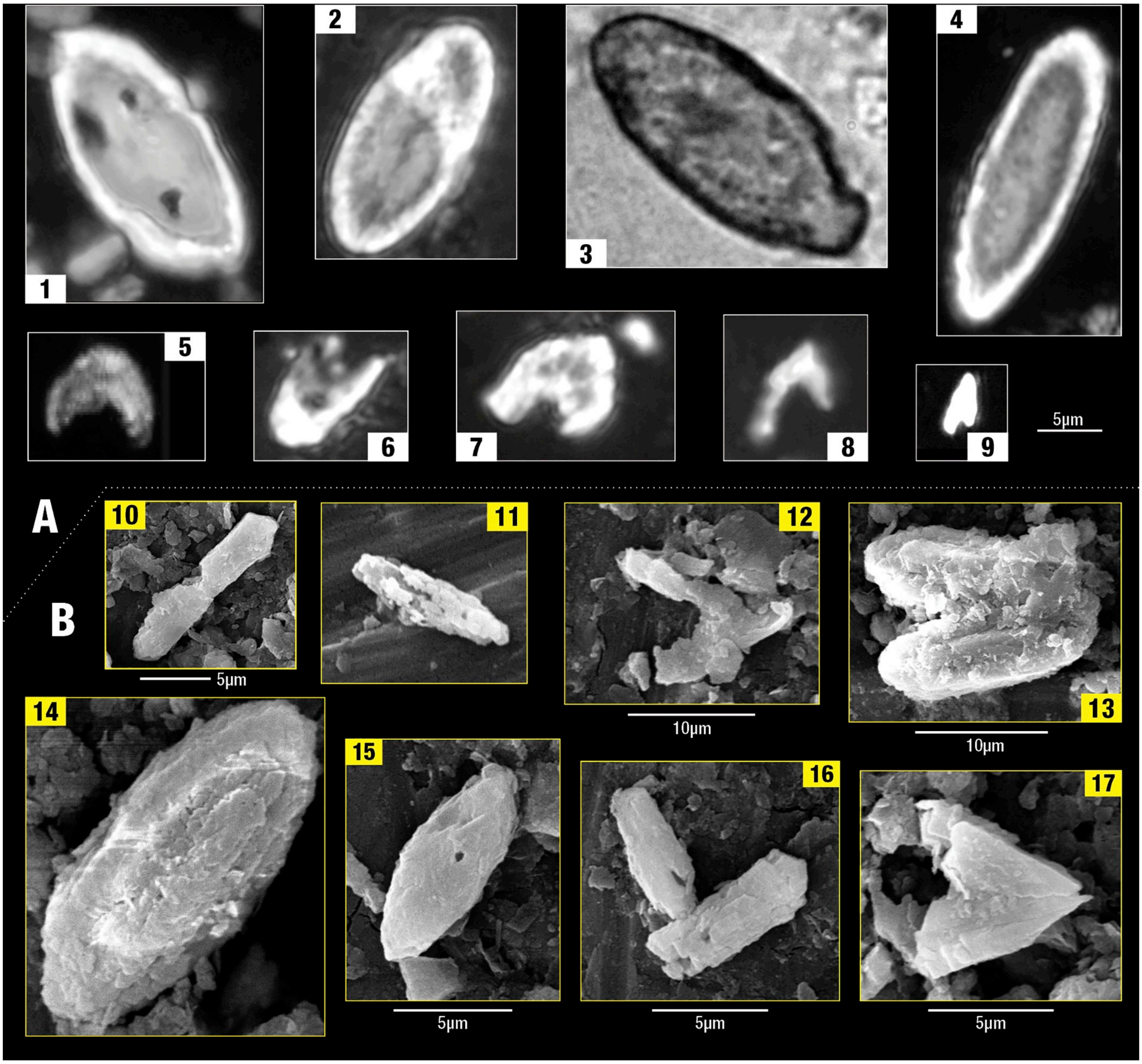

Fig. 5. A: LM microphotographs of nannofossils from Hole 380-A and Taman section ((top of Upper Maeotian) crossed-nicols photographs magnification ×1600). 1-*Micrascidiscus sp.* (923,4 mbsf); 2,3 – *Micrascidiscus sp.* (sample 55, Taman section); 4 – *Micrascidiscus sp.* (874,6 mbsf); 5, 6, 7 destroyed fragments of the spicules (sample 55, Taman section); 8 – destroyed fragments of the spicules (846,45 mbsf, DSDP); 9 (883,63 mbsf, DSDP). 5B: SM microphotographs. Scale bar in microns. 10, 16 – destroyed fragments *Perfocalcinella fusiformis* Bona 1966 (867,67 mbsf); 11,12,15 – *Micrascidiscus sp.* (867,67 mbsf); 13, 17 – destroyed fragments of the spicules (sample 55, Taman section, top of Upper Maeotian); 14 – *Micrascidiscus sp.* (sample 55, Taman section).

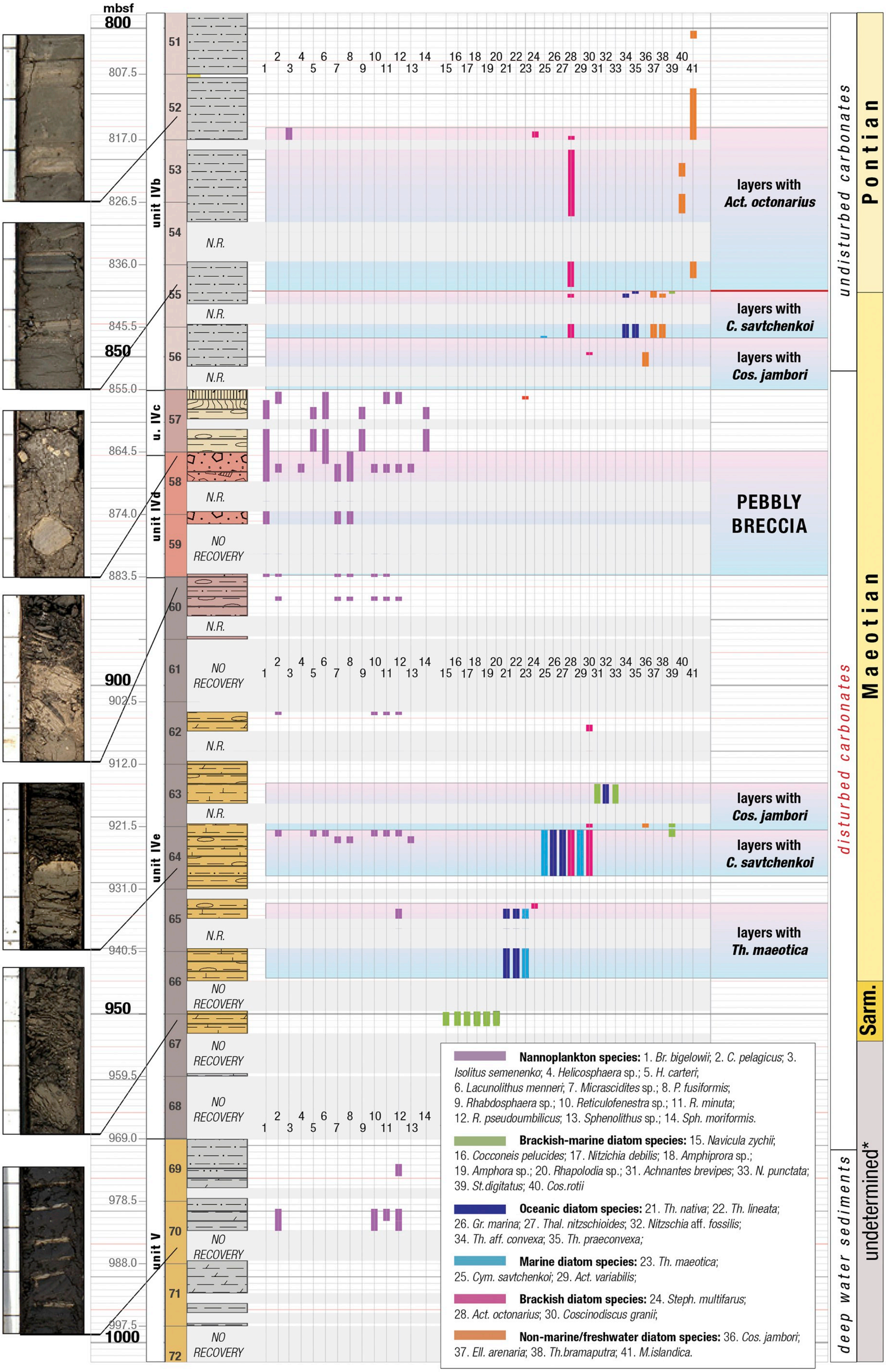

Fig. 6. High resolution observations on the lithology and paleontology (nannoplankton and diatoms) from the Pebbly Breccia interval part of DSDP 380.

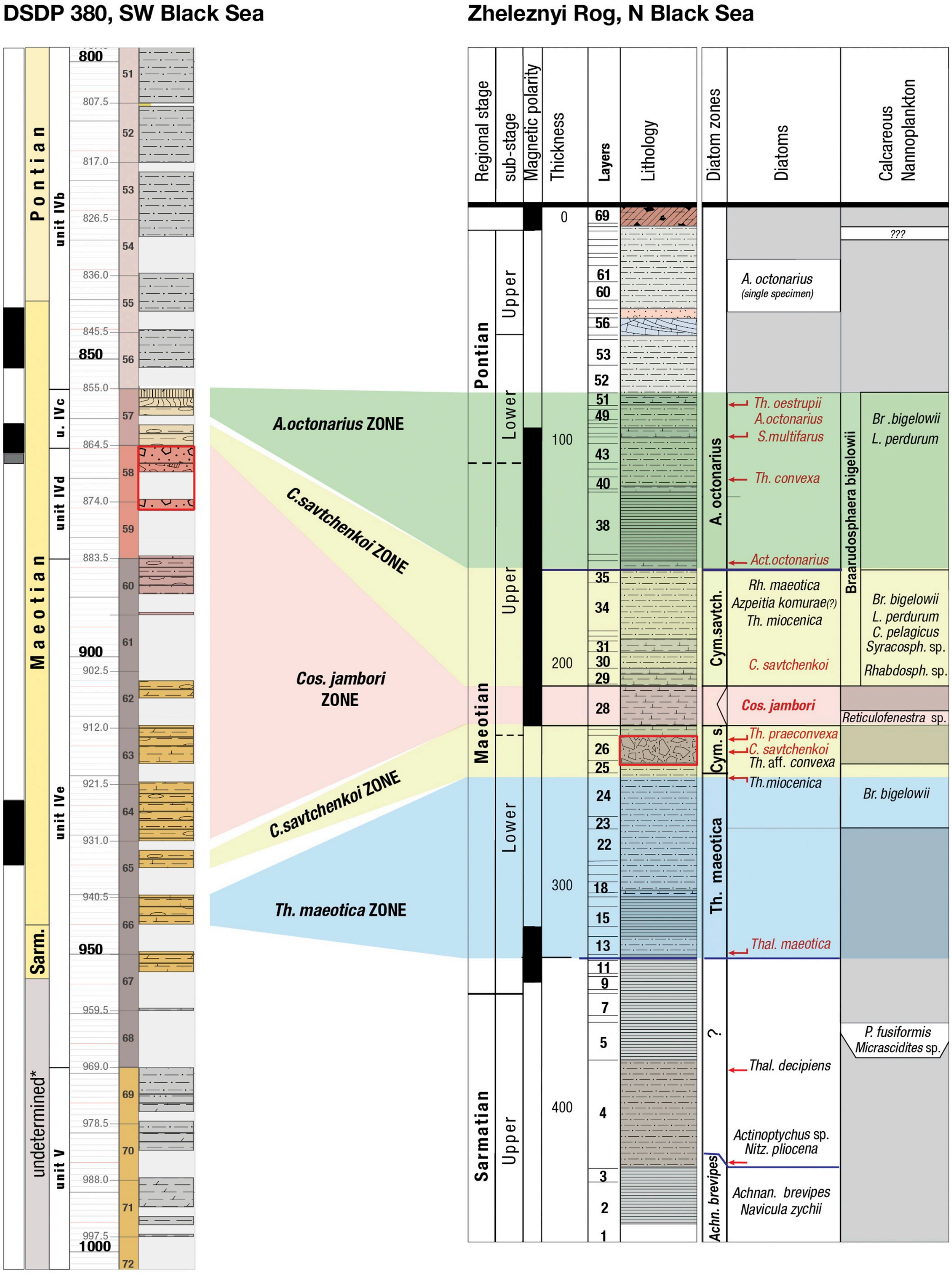

Fig. 7. Biostratigraphic correlation of DSDP 380 and the Zheleznyi Rog sections in the Black Sea.

5. Discussion

5.1. The age of the Pebbly Breccia

The diatom assemblages of DSDP Hole 380A can directly be compared to the recently established bio-magnetostratigraphic framework of the Zheleznyi Rog, Popov Kamen and Taman sections of Russia (Popov et al., 2016). The sequence of the diatom assemblages of the units IVe- IVc show strong similarities with the diatom complexes from Maeotian - Lower Pontian deposits of the Taman sections (Radionova and Golovina, 2011) (Fig. 7). We observe a sequence of changes in diatom associations below the Pebbly breccia: the layers with *Thalassiosira maeotica* (interval from 944 mbsf to 933mbsf); the layers with *Cymatosira savtchenkoi* (interval from 933 mbsf to 922 mbsf); the layers with *Coscinodiscus jambori* (interval from 921mbsf to 916.5 mbsf); the interval from 920 mbsf to 883 mbsf does not contain diatoms (Fig. 3). The Pebbly Breccia interval is from 883 mbsf to 864 mbsf. Above the Pebbly Breccia (the interval from 864 mbsf to 856 mbsf) there are also no diatoms. Then layers with *Coscinodiscus jambori* return in the interval from 850 mbsf to 846 mbsf. Accordingly, the stratigraphic position of Pebbly Breccia is intercalated between sediments with this specific diatom assemblage. The presence of some species of diatoms is particularly important for dating the interval of Unit IVe –IVc. The diatom *Thalassiosira maeotica* (FO -7.9–7.8 Ma), frequently observed in the interval 947–940 mbsf, is considered a zonal species of the Lower Maeotian. Cymatosira *savtchenkoi* (FO ~6.7 Ma) is a zonal species of the Upper Maeotian and appears at 930 mbsf. The presence of the marine diatom species *Thalassiosira convexa* and *Thalassiosira praeconvexa* in subunit IVc (846 mbsf – 840 mbsf) above the Pebbly Breccia, dates this interval between 6.6 and 6.2 Ma (Barron, 2003) (Fig. 7). Another age constraint for Hole 380A is given by the short marine influx at 850 mbsf, especially shown in the nannofossil record, that coincides with the Pontian Flood event of the Paratethys, dated in many sections at ~6.1 Ma (Radionova and Golovina, 2011; Grothe et al., 2014; Chang et al., 2014; Van Baak et al., 2015, 2016a, 2016c).

Our new biostratigraphic correlations indicate that the Pebbly Breccia unit (subunit IVd) is intercalated within Upper Maeotian strata. Because of the poor magnetostratigraphic resolution in this interval in both DSDP and Taman records (Vasiliev et al., 2011; Van Baak et al., 2016b) and the presence of several potential unconformities in the stratigraphic successions, we conservatively estimate the Pebbly Breccia to be deposited within the Late Maeotian at an age range of 6.7 and 6.3 Ma.

In Zheleznyi Rog, the Upper Maeotian is marked by several hiatuses in the sedimentary succession, expressed as gravity flows with reworked lithoclasts, consisting of clayey breccias with boulders and pebbles of diatomitic clays (Popov et al., 1996; Vasiliev et al., 2011). Second suspect interval is located 60 m above the Lower-Upper Maeotian transition and is marked by an angular unconformity (Vasiliev et al., 2011). We conclude that the Upper Maeotian is characterized by several phases of basin margin instability, which is in good agreement with the hypothesis that the Pebbly Breccia relates to a gravity induced unconformity (Grothe et al., 2014; Tari et al., 2015).

Recently the continuity of core DSDP 380A has been questioned by new seismic studies which indicate the Pebbly Breccia may represent the basal surface of a large mass transport deposits (Tari et al., 2015, 2016). Our biostratigraphic results, however, do not reveal any obvious breaks in stratigraphy in this part of the core and we do not see any biostratigraphic argument to question the continuity of the succession across the Pebbly Breccia (Fig. 7).

5.2. On the presence of *Ceratolithus acutus* in the Eastern Paratethys

Our Late Maeotian age for the Pebbly Breccia unit is in good agreement with previous magnetostratigraphic (Van Baak et al., 2015) and biostratigraphic correlations based on diatoms (Radionova and Golovina, 2010) and dinoflagellates (Filippova and Trubikhin, 2009; Grothe et al., 2014, 2016). The First Common Occurrences of *Caspidinium rugosum* and *Galeacysta etrusca*, corresponding to the base of the Pontian in Zhelezny Rog, are both found above the Pebbly Breccia interval suggesting a Maeotian (or older) age (Grothe et al., 2014). This age is, however, in serious contrast with the observation of the Pliocene ($<$ 5.4 Ma) nannofossil *Ceratolithus acutus* at level 840 mbsf in DSDP Hole 380A (Popescu et al., 2010) which we now date at ~6 Ma (see also Van Baak et al., 2015).

The *Ceratolithus acutus* Zone comprises an extremely short chronostratigraphic interval and is therefore an important marker species in the Atlantic Ocean where it first occurs in the latest Messinian at an age of 5.4 Ma (Gartner and Bukry, 1974; Müller, 1974; Raffi et al., 1998). In the Mediterranean it is considered a marker species for the Zanclean, although it is also observed in the Lago Mare deposits of the Messinian, suggesting Atlantic inflow occurred before the Mio-Pliocene boundary (Popescu et al., 2016). In the Lago Mare deposits and lowermost Pliocene marine marls, *C. acutus* is so scarce that its reliability as a marker species for the Mediterranean is seriously questioned (Di Stefano and Sturiale, 2010; Stoica et al., 2016). Consequently, it should even be more difficult to find *C. acutus* in the Black Sea and other Paratethys basins, but several case studies exist where it has been reported as a single find. *Ceratolithus acutus* was documented from very short intervals in Kimmerian deposits in Zheleznyi Rog section (Luljeva data in Semenenko and Pevzner, 1979; Semenenko and Luljeva, 2006; Luljeva, 1989b), but until now this information has not been confirmed (Golovina et al., 1989; Popov et al., 2016). We therefore decided to pay special attention and close investigation to the reported presence of *C. acutus* in DSDP Hole 380A at level 840 mbsf (Popescu et al., 2010).

The modern hydrological environment of the Black Sea serves as an excellent model for understanding paleoenvironments of the Miocene basins of Eastern Paratethys. In the Black Sea, it is well known that nannoplankton reflects the most marine conditions, and that they are highly sensitive to changes in salinity, temperature, bathymetric conditions, transparency of water, availability of nutrients and terrigenous dilution (Bukry et al., 1974; Auer et al., 2014; Incarbona et al., 2016). Changes in one of these factors generally lead to the loss of some species of the assemblage complex, especially those species that are very sensitive to changes in environmental conditions. The Black Sea is a semi-enclosed basin, connected with the Mediterranean Sea through the Bosporus Strait, Marmara Sea, and Dardanelles Strait. The qualitative and quantitative composition of nannoplankton assemblages, however, show significant differences between Black Sea and Mediterranean. *Ceratolithus cristathus* is living in the Eastern Mediterranean now, but it is present in very small amounts in the nannoplankton community and is very sensitive to variations in salinity and temperature. For instance, *Ceratolithus* spp. is recorded in the studied sediment trap samples only in the southern deep-water part of the Aegean Sea (Cretan Sea), while it is absent in the northern Aegean Sea and in the Ionic Sea (Skamba et al., 2019). In addition, species of the genus *Ceratolithus* are absent in the modern calcareous nannoplankton of the Black Sea, while *Emiliania huxleyi* have flourishing populations in the Eastern Mediterranean now (Skamba et al., 2019) and form finely laminated coccolith oozes in the modern Black Sea (Golovina et al., 1987; Giunta et al., 2006; Kouwenhoven et al., 2006; Oaie and Melinte-Dobrinescu, 2012; Gozhyk et al., 2015).

We re-analysed the 840 mbsf interval in great detail, but did not find any evidence for *C. acutus*. Perhaps even more important, we also did not find any species of the typical nannofossil associations of the *C. acutus* Zone. Short-lived species like *C. acutus* form the top of the ecological community and can be considered as the "*kings*" of the nannoplankton assemblage. In stressed (e.g., low salinity) paleoenvironmental conditions, often only the "*entourage of the king*" is observed, as only the most tolerant and environmentally plastic nannoplankton species could adapt to the new tough living conditions. In our samples, however, we did not find the open marine Pliocene "entourage" of *C.*

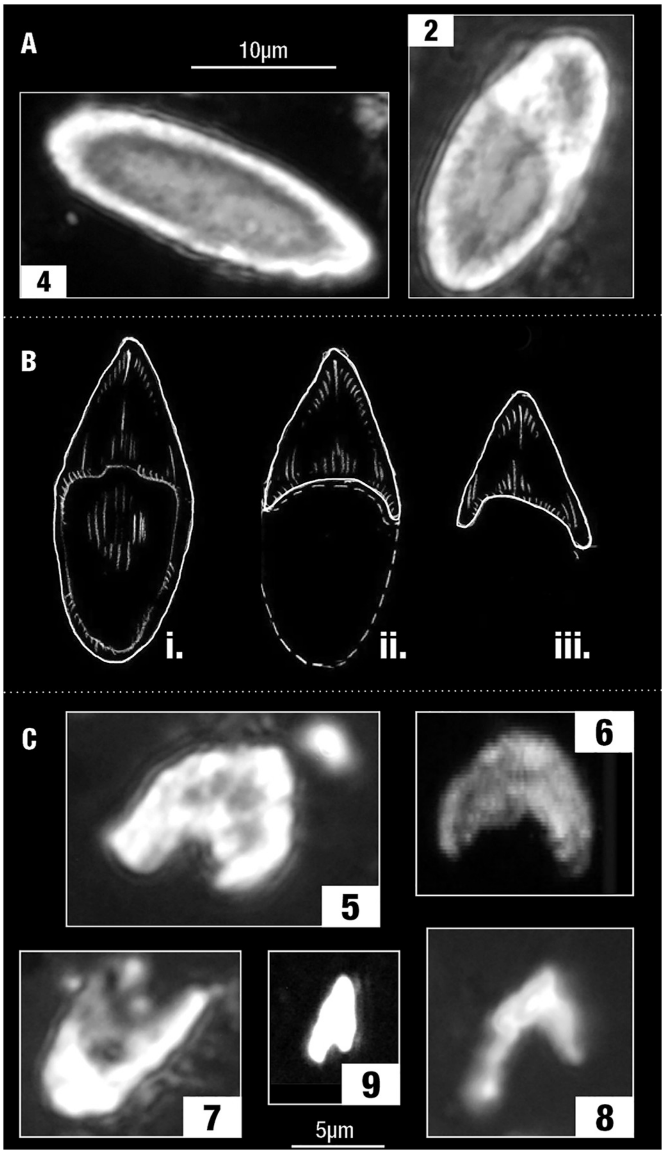

Fig. 8. Destroyed ascidian spicules can easily be misinterpreted as *Ceratolithus acutus*. 8A: Intact ascidian spicules of *Micrascidiscus sp.* 8B: The sequence of destruction of ascidian spicules and the formation of debris (i – spicula, ii – partially resolved spicula, iii – fragment of spicula). 8C: Fragments of the spicules resembling *C. acutus*.

acutus. The nannoplankton associations in the Eastern Paratethys sections indeed primarily represent the most persistent cosmopolitan and long-lived species. In the case of findings of single specimens of *C. acutus* without the other zonal typical species (cf. Popescu, 2006), it is hard to imagine that here only the index-species has overcome all environmental barriers, and that its entire "entourage" failed.

What we did find at level 840 mbsf, there are calcareous elements (ascidian spicules), which are very often present in Maeotian deposits in Kerch and Taman Peninsulas (Popov et al., 2016). These abundant ascidian spicules occur in intergrowths in the X-shaped and radiating rosette as well as in the individual elements. They have high interference colours, are highly birefringent in crossed nicols, and go out with polarized light. The observed spicules have strong similarities with *Perfocalcinella fusiformis* and *Micrascidites latens* Luljeva of the genus *Micrascidites* (Luljeva, 1989a). The partial destruction of these spicules could be misleading and may create a "pseudo-*Ceratolithus*" (Fig. 8). These partially destroyed spicules may have a morphological similarity with 'real *Ceratolithus*' since it also goes to extinction when it is parallel to the direction of polarization. The interval from cores 886,51 mbsf – 846,45 mbsf is characterized by abundant ascidian spicules (Figs. 4–5). Partially destroyed spicules are morphologically similar to *Ceratolithus*. These pseudo-*Ceratolithus* forms are observed in the Upper Maeotian of Hole 380A (846,45 mbsf) (Fig. 3 -Plate A) and were previously observed in the Upper Maeotian of the Taman section (Golovina, 2008). The fossil ascidian spicules are known from the Mesozoic and are abundant in the modern seas (Varol, 2006). The presence of ascidian spicules is also known from the middle Miocene deposits of Hungary (Bóna and Gál, 1985), Croatia (Galović and Young, 2012), Moldova (Łukowiak et al., 2016).

In our opinion, true *Ceratolithus acutus* is not present in Unit IVb at 840 mbsf, and that this species may be confused with some destroyed elements of ascidian spicules (Fig. 8).

5.3. The entangled stories of debris flow and slide deposits of the deep Black Sea basin. A reinterpretation of the DSDP380 sedimentary succession

The lithological data that describes the sedimentary anomalies from the deepest parts of the Black Sea basin has also been re-examined. From the lithological perspective, a 20–100 m thick breccia was intercepted in the two cores (DSDP380 and 381) drilled in the basin. A closer inspection of the cores and the photographic material (Fig. 6) confirms that this sedimentary unit is characterized by matrix supported material, random fabric, variable clast size, variable matrix. Rip ups and rafts. The pebbly breccia would thus fall in the debris flow category (Moscardelli and Wood, 2007).

The seismic data from the SW Black Sea region published by Tari et al. (2015) reveal several mass transport complexes (MTC). The seismic line bks01-0222 (Fig. 9), that crosses the location of site 380 reveals a larger picture of the sedimentary anomalies in the basin. Close to the basin rim a thick MTC (X) is identified and interpreted as a series of stacked blocks, slided on a gliding plane (b). The slided blocks do not appear internally deformed and bear high-amplitude, continuous reflections. Towards the deeper part of the basin the authors interpret a different, much thinner MTC (a) characterized by low-amplitude, semi-transparent chaotic reflections that would fit to a seismic expression of a debris flow.

The palaeontological results of this work show the presence of sediments (Unit IVe) formed at shallow depths (< 100 m) below the Pebbly Breccia. Within the Pebbly Breccia interval, the carbonatic clasts have been interpreted as shallow deposits, but this feature seems to characterize a larger package. It suggests that the blocks identified by Tari et al. (2015) are not limited to the Pebbly Breccia but go further down, which implies two different episodes of instability with different expressions in the basin, in agreement with the two types of MTC visible on this single seismic section.

We speculate here that a two-step scenario explains the anomalies found in the sedimentary succession of the deepest part of the Black Sea. In a chronological succession, the first event (a in Fig. 9) is the formation of the Pebbly Breccia level. This represents a widespread debris flow in the basin, linked with an episode of slope instability, probably related to the Intra-Maeotian Event (Palcu et al., 2019). A second instability event (b in Fig. 9) transported thick sedimentary packages, containing also the anomalous Pebbly Breccia level, deep into the basin, far from their initial shallow and marginal location. While the first event was a debris flow related to shelf edge collapse (Tari et al., 2015); we interpret the second event to be the consequence of loading of the slope sediments. This two-step scenario requires future confirmation by additional seismic data, preferably by 3D seismics that exists for the SW Black Sea region.

6. Conclusions

Our micropaleontologic investigations identified the overall sequence of events in the development of phytoplankton at both DSDP

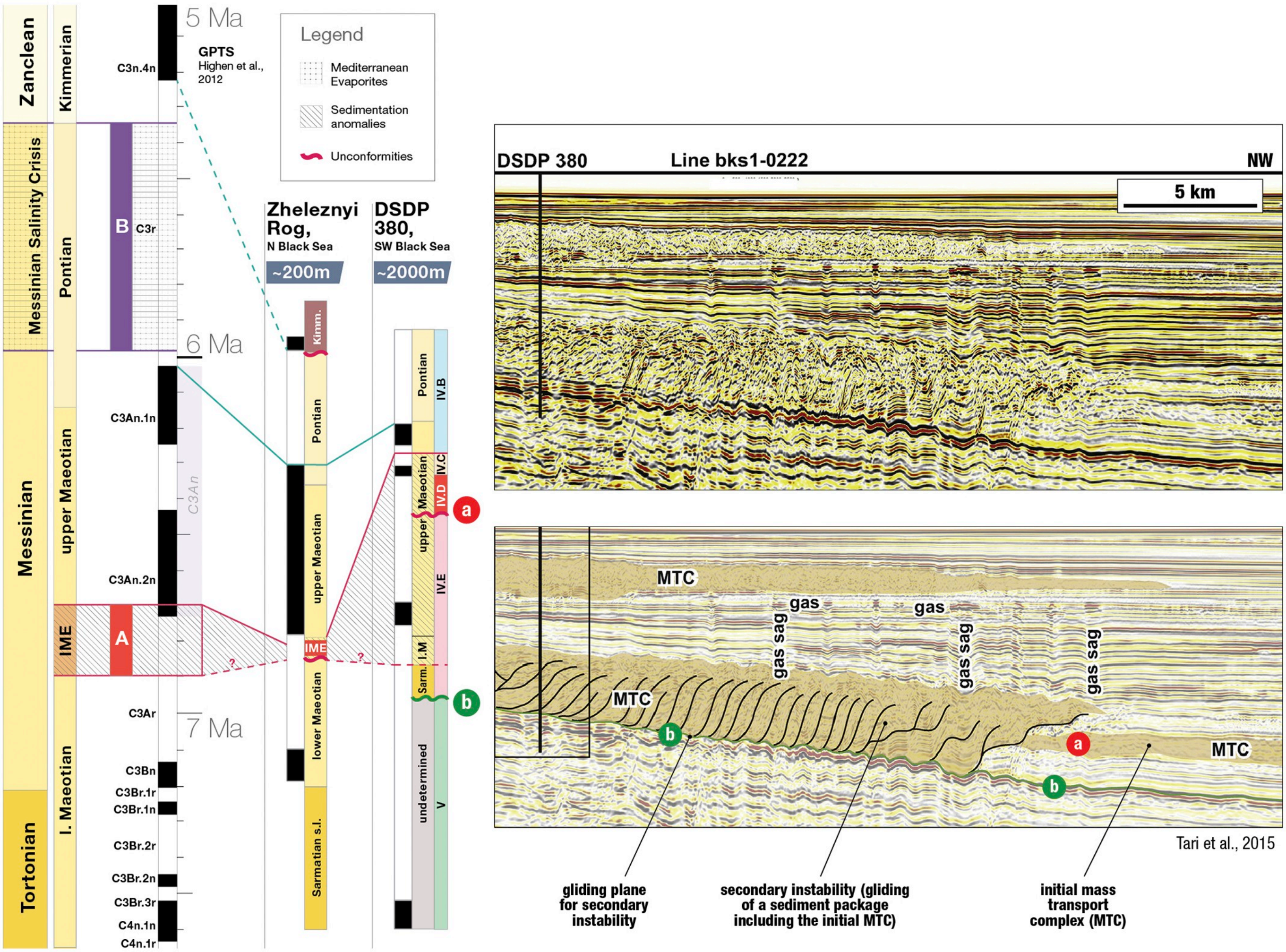

Fig. 9. New age model for the Pebbly Breccia unit and the northern Black Sea analogues with highlights on the sediment instability episodes encountered in the DSDP 380 drill core and surroundings.

Hole 380/380A and the Zheleznyi Rog section and established the same sequence of appearance of diatom markers species. Mainly based on the presence of *Thalassiosira maeotica*, our micropaleontological records show a close correlation of the lower Subunit IVe of DSDP Hole 380A to the Lower Maeotian sediments of Zheleznyi Rog. The base of the Upper Maeotian is observed at level 930 mbsf, in the middle part of Subunit IVc, based on the first occurrence of *Cymatosira savtchenkoi* at an age of about 6.9–6.6 Ma. The upper part of Subunit IVc (853–850 mbsf) comprises mainly non-marine microflora and probably formed in a closed basin, which had no connection with the Mediterranean. Our diatomaceous data determine the position of the Maeotian-Pontian boundary at 841 m (at the base of the *Layers with Act. octonarius*). During the main part of the Pontian the diatom fauna are indicative of brackish water, containing mainly lacustrine flora.

The previously reported presence of the calcareous nannofossil *Ceratolithus acutus* at level 840 mbsf in Hole 380A is not confirmed by our detailed micropaleontological re-investigation, neither did we observe other nannofossil species of the *C. acutus* Zone that are expected to co-occur at that time. We believe that the proposed specimens of *C. acutus* have been confused by look-alikes of some destroyed elements of ascidian spicules of *Micrascidites*.

The Pebbly Breccia unit (864–883 mbsf) Subunit IVd is thus dated within the Upper Maeotian at an age between 6.7 and 6.3 Ma. The formation of the Pebbly Breccia is most likely linked to a period of gravitational instability of the Black Sea margins leading to slumping and downslope mass transport in Late Maeotian times.

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