Paleoenvironmental evolution of the East Carpathian foredeep during the late Miocene–early Pliocene (Dacian Basin; Romania)

M. Stoica a,⁎, I. Lazăr a, W. Krijgsman b, I. Vasiliev b, D. Jipa c, A. Floroiu a

a Department of Geology, Faculty of Geology and Geophysics, Bucharest University, Bălcescu Bd. 1, 010041, Romania
b Paleomagnetic Laboratory Fort Hooffdijk; Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands
c National Institute of Marine Geology and Geoecology, GeoEcoMar, Dimitrie Onciul Street 23-25, Bucharest, RO-70318, Romania

A R T I C L E   I N F O
Article history:
Received 27 May 2011
Accepted 12 April 2012
Available online 21 April 2012

Keywords:
Paratethys
Carpathian foredeep
biostratigraphy
paleoenvironment
Messinian
ostracods
Dacian Basin

A B S T R A C T
The thick and continuous Mio-Pliocene sedimentary successions of the Foçani Depression in the Dacian Basin of Romania provide an excellent opportunity to study the paleoecological changes in the Eastern Paratethys during the time when the Mediterranean and Black Sea experienced major sea level fluctuations related to the closure and re-opening of the marine connection to the Atlantic Ocean during the Messinian Salinity Crisis. These successions form the basis of high-resolution magneto-biostratigraphic studies that allow a detailed correlation to the standard Geological Time Scale. Here, we analyze the paleoenvironmental evolution of the East Carpathian foredeep by integrating micro- and macropaleontological data and sedimentological analyses. The ostracod and mollusc fossil associations from the Râmnicu Sărat river section indicate that the late Maastrichtian depositional environment was characterized by shallow waters and littoral to fluvisol-deltaic sediments. The Maeotian–Pontian boundary (6.04 Ma) is marked by a marine ingression, comprising benthic (agglutinated and calcareous) and planktonic (Streptochilus spp.) foraminifera and nanofossils. Following this marine ingression, the Lower Pontian (Odessian; 6.04–5.8 Ma) fauna shows an increased bathymetry of the basin. The presence of ostracod species with eye tubercles indicates depositional environments within the photic zone (<100 m). The Middle Pontian (Portaferrian; 5.8–5.5 Ma) is marked by a widespread sea level lowering resulting in dominant fluvo-deltaic conditions. This ecostratigraphy demonstrates that the main Messinian sea-level draw down (at 5.6–5.5 Ma) occurred in mid-Portaferrian times. Paleoenvironmental indicators show that the water level in the Foçani Depression dropped less than 100 m during Mediterranean desiccation. The Dacian Basin remained filled with water, suggesting a positive hydrological balance for the region. This is compatible with the presence of a shallow barrier at Dobrogea (the Galati passage), separating the Dacian Basin from the Black Sea Basin during the late Miocene. The Portaferrian–Bosphorian boundary (5.5 Ma) is marked by a second transgressive event, but this time without marine foraminifera. We conclude that the Dacian Basin formed a semi-isolated entity during the Portaferrian and experienced connectivity to the Black Sea domain during the Odessian and Bosphorian.

© 2012 Elsevier B.V. All rights reserved.

1. Introduction

The Miocene paleoenvironmental evolution of the Mediterranean and Paratethys regions is largely influenced by the opening and closure of the marine connections that strongly regulated the water exchange between the two domains and with the Indian and Atlantic oceans (e.g. Harzhauser and Kowalke, 2002; Popov et al., 2006; Harzhauser et al., 2007; De Leeuw et al., 2010). This progressively resulted in restricted conditions, significant water level variations, development of endemic faunas and changes of salinities, culminating in the deposition of massive evaporites during the Badenian in the Paratethys (Peryt, 2006) and the Messinian in the Mediterranean (Hsiu et al., 1973).

The Paratethys–Mediterranean water connection during the Messinian is still heavily debated and the location of such a marine gateway has not been proven so far (Popov et al., 2006; Krijgsman et al., 2010). The present-day connection through the Bosphorus is believed to have originated much later in the Pliocene (e.g. Çagatay et al., 2006), but the presence of many fossils of Paratethyan affinity in the latest Messinian Mediterranean successions (Esu, 2007) support the hypothesis that the Paratethys Sea drained into the Mediterranean after its desiccation phase, refilling it progressively with brackish water and resulting in the establishment of Lago Mare facies all over the Mediterranean Basin (Cita et al., 1978; Cosentino et al., 2006; Orszag-Sperber, 2006). It has also been shown that the water level in the Black Sea dropped because of Mediterranean desiccation (Dinu et al., 2005; Gillet et al., 2007; Krijgsman et al., 2010; Vasiliev et al.,...
indicating that a marine Paratethys–Mediterranean connection must have been present at Messinian times.

In this paper we focus on the thick and continuous sedimentary successions of the Foçani Depression, one of the main late Miocene depocenters in the Dacian Basin of Romania, to investigate the paleoenvironmental changes in the Eastern Paratethys during the Messinian. We integrate paleoecological information from ostracods, foraminifera and molluscs with sedimentological analyses and a recently developed chronology (Krijgsman et al., 2010). This allows making a detailed reconstruction of the paleogeographic and paleoenvironmental evolutions of the East Carpathian foredeep during the late Miocene and early Pliocene.

2. Geological background

2.1. The Dacian Basin of the Eastern Paratethys

The Paratethys domain (Laskarev, 1924) developed as the northern branch of the former Tethys Ocean and became progressively separated from the southern Mediterranean branch by ongoing tectonic movements in the African–Eurasian collision process (Fig. 1). The initiation of Paratethys took place 35 millions of years ago, from where it subsequently evolved as a large intra- and intercontinental marine domain that extended from the Alps to the Aral Sea (Báldi, 1980; Rusu, 1988; Schultz et al., 2005). Until the Middle Miocene, Paratethys was in communication with the normal marine environments of the Mediterranean Basin and Indian Ocean. The different Paratethys basins, mainly the Alpine–Carpathian Basin, the Black Sea Depression and the Caspian Depression, were intercommunicating, with periodical phases of isolation. By the end of the Middle Miocene (late Badenian–Sarmatian), Paratethys communications with the Mediterranean and Indian Ocean were restricted and eventually closed (Rögl, 1998). Subsequently, Paratethys itself subdivided into several brackish (Lake Pannon) and low salinity restricted marine basins (Eastern Paratethys) during the late Miocene, all of them developing their own endemic fauna.

The Carpathian orogen was tectonically uplifted to become a barrier in Sarmatian times (~11–12 Ma), separating the Pannonian and Transylvanian Basins of the Central Paratethys from the Dacian and Euxinian Basins of the Eastern Paratethys (Sanders et al., 1999; Cloetingh et al., 2004; Vasiliev et al., 2009). In the Central Paratethys, this resulted in a major environmental change from marine (Sarmatian) to mainly fresh water environments (Pannonian), recently magnetostratigraphically dated to take place between 11.6 and 11.3 Ma (Vasiliev et al., 2010; Paulissen et al., 2011; Ter Borgh et al., 2013-this volume; De Leeuw et al., 2013). The Dacian Basin evolved as a separate paleogeographic entity where marine conditions prevailed much longer than in the Central Paratethys (Saulea et al., 1969). This resulted in the confusing nomenclature of a Sarmatian s.l. stage, commonly used in Eastern Paratethys time scales, which was recently solved by using Volhynian, Bessarabian and Khersonian stages instead (Fig. 1c).

2.2. The Râmnicu Sărat section in the East Carpathian foredeep

The Dacian Basin developed as a part of the Eastern Paratethys, located in between the Southern Carpathians, Pre-Balkan area and the Dobrogean High (Matenco and Bertotti, 2000). The eastern part of the Dacian Basin (called Foçani Depression because of its high subsidence character) comprises the thickest Neogene sedimentary cover of the Dacian Basin, approaching ~13 km (Tarapoanca et al., 2003). Excellent exposures are on the western flank of the basin along the

![Fig. 1. Schematic paleogeographic maps of the a) late Eocene and b) late Miocene indicating Paratethys retreat (after Blakey, 2011). The star locates the relative position of the study area in the East Carpathian foredeep. Time scale for the Dacian Basin (after Vasiliev et al., 2004 and Krijgsman et al., 2010) and its relation with the standard GTS.](image-url)
almost continuously outcropping Putna and Râmnicu Sărat river sections (Andreescu and Papaianopol, 1970; Andreescu, 1973, 1975; Andreescu and Ticleanu, 1976; Vasiliev et al., 2004). These sections consist in the lower part (Upper Bessarabian–Maeotian) of alternating shallow sandstones and shales (Saulea et al., 1969), tilted to near vertical positions, and in the upper part (Pontian to Romanian) of shales, siltstones, sandstones and coals (Pana, 1966; Grasu et al., 1999; Panaiotu et al., 2007), progressively less tilted to about 20–30°E. An extensive network of seismic profiles shows the absence of large tectonic and erosional structures in the basin indicating continuous subsidence and deposition from the Upper Bessarabian to Romanian (Fig. 2b; Tarapoanca et al., 2003). Paleomagnetic data furthermore showed that no significant rotations affected the region after the deposition of the Upper Bessarabian sediments (Dupont-Nivet et al., 2005).

The 7.2 km thick Râmnicu Sărat river section (Fig. 2c) is excellently exposed and its Maeotian, Pontian and Dacian deposits comprise abundant micro and macrofossils. The changes in characteristic faunal assemblages allowed the subdivision and correlation to regional Eastern Paratethys Stages (Maeotian, Pontian, Dacian) and Pontian substages (Odessian, Portaferrian, Bosphorian) according to historic biostratigraphic definitions (e.g. Stevanovic et al., 1989).

2.3. Biochronology

In the framework of the Dutch research school of Integrated Solid Earth Sciences (ISES), magnetostratigraphic time scales have been constructed for the sedimentary sequences of the East and South Carpathian foredeeps (Vasiliev et al., 2004; Vasiliev et al., 2005). This resulted in high-resolution chronologies for the Maeotian to Romanian (~8 to ~4 Ma) sediments of the Focșani Depression and the Getic Depression (southern Carpathians). The reliability of the magnetic signal has been confirmed by detailed rock magnetic studies, that showed the presence of two distinctly different types of greigite, a primary magnetosomal greigite and an early diagenetic (<10 kyr) authigenic greigite, both providing stable and reliable paleomagnetic directions (Vasiliev et al., 2007; Vasiliev et al., 2008). One problem with these studies was that they were lacking direct biostratigraphic control and that boundary locations from geological maps had to be used to calculate the ages for the Paratethys Stage boundaries.

The Eastern Paratethys stages and substages are all represented in the East Carpathian foredeep and can very well be identified by means of their individual ostracod assemblages (Fig. 3, Plates 1, 2). This method allowed determination and magnetostratigraphic dating of the regional stage boundaries in the Râmnicu Sărat section (Krijgsman et al., 2010). The Maeotian–Pontian transition is located close to the top of chron C3An.1n and is thus very accurately dated at 6.04±0.01 Ma. The Odessian–Portaferrian and Portaferrian–Bosphorian transitions are both located within chron C3r. Their ages have been determined by assuming constant sedimentation rates and interpolation of the paleomagnetic age constraints from the reversal boundaries C3An.1n(y) and C3n.4n(o). This resulted in ages of 5.8±0.1 Ma for the Odessian–Portaferrian and 5.5±0.1 Ma for
the Portaferrian–Bosphorian boundary, respectively. The Pontian–Dacian boundary, and thus also the Bosphorian–Getian substage boundary, is located within the reversed chron C3n.2r at an age of 4.70±0.05 Ma, in excellent agreement with earlier results from the south Carpathian foredeep (Vasiliev et al., 2005; Krijgsman et al., 2010).

3. Paleoenvironmental evolution of the East Carpathian foredeep

3.1. Methods

The Râmnicu Sărat river section was investigated in detail for micropaleontological analyses primarily focusing on foraminifera and ostracods. In addition, sedimentological and stratigraphic investigations have been performed on the Maeotian–Pontian successions. The sedimentological data coverage is discontinuous, as detailed study locations have been chosen according to outcrop conditions, but additional observations have been made on smaller-sized outcrops located in between the main exposures. Samples were processed by standard micropaleontological methods, sieved over sieves of 63 μm and hand-picked under a microscope. Macro-/micropaleontological analyses on mollusks have been performed in less detail. Taxonomic identifications and ecological inferences were based on Stancheva (1968, 1990); Sokač (1972, 1990a, 1990b); Hanganu (1974); Hanganu and Papaianopol (1977; 1982); Krstić and Stancheva (1989); Olteanu (1989, 1995); Papaianopol (1989); Meisch (2000); Gliozzi et al. (2005, 2008); Stoica et al. (2007); Harzhauser et al. (2008); and Czicz et al. (2009).

3.2. The Upper Maeotian

The Upper Maeotian of the Râmnicu Sărat river valley is well exposed on the outcrops downstream of Jitia village (Fig. 2c). In general, the Upper Maeotian is represented by alternations of sandstone and silt. Many sandy units display channel structures, and wave ripples are frequently observed on the upper part of the sandstone beds. Internal

Plate 1. Most relevant ostracod species (Superfamily Cypridoidea) from the Upper Maeotian and Pontian of the Râmnicu Sărat valley section (all valves of ostracods belong to adult individuals, external lateral views, LV = left valve, RV = right valve, RM = micropaleontological samples no.): 1. Amphiocypris ex gr. dorsobrevis Sokáč, LV, RM 215, Middle Pontian; 2) Candona (Caspiocypris) pontica Sokáč, carapace, view from RV, RM 207, Lower Pontian; 3) Candona (Caspiocypris) alta (Zalányi), carapace, view from RV, RM 88, Upper Pontian; 4) Candona (Typhlocypris) ankae Krstić, RV, RM 215, Middle Pontian; 5) Candona (Typhlocypris) sp., carapace, view from the RV, RM 207, Lower Pontian; 6) Candona (Compocypris) osiosanensis Kristić. carapace, view from RV, RM 88, Upper Pontian; 7) Candona neglecta G.O. Sars, carapace, view from RV, RM 87, Upper Pontian; 8) Fabaeoformiscandona sp., carapace, view from RV, RM 89, Upper Pontian; 9), 10) Candoniella sp., 9) carapace, view from RV, 10) LV; all from RM 207, Lower Pontian; 11) Candona (Hastacandona) lotzyi (Zalányi), carapace, view from RV, RM 207, Lower Pontian; 12) Candona (Hastacandona) hysterica Kristić & Stancheva, carapace, view from RV, RM 207, Lower Pontian; 13) Pontoniella acuminata (Zalányi), carapace, view from RV, RM 94, Upper Pontian; 14) Pontoniella striata (Mandeldstam), RV, RM 220, Upper Pontian; 15) Pontoniella quadrata (Kristić), carapace, view from RV, RM 220, Upper Pontian; 16) Zonocypris membranae Stancheva, fragmented LV, RM 215, Middle Pontian; 17), 18) Candona (Zalanyiella) venusta (Zalányi); 17) carapace, view from RV; 18) carapace, view from RV; all specimens from RM 207, Lower Pontian; 19), 20) Cypria tocorjescui Hanganu; 19) carapace, view from LV; 20) carapace, view from RV; all specimens from RM 88, Upper Pontian; 21), 22) Cypria sp.; 21) carapace, view from RV; 22) carapace, view from LV; RM 207, Lower Pontian; 23), 24) Pseudocandona sp. (juveniles), LV, RM 201, Upper Maeotian; 25) Ilyocypris sp., carapace, view from LV, RM 79, Upper Pontian; and 26), 27) Bakunella dorsosarcua (Zalányi); 26) LV; 27) carapace, view from RV; RM 88, Upper Pontian.
Fig. 4. Stratigraphy, lithology and paleontology of the Upper Maeotian of the Râmnicu Sărat valley section: a) wave ripples on the upper bedding plane of a sand layer; b) ostracod assemblage dominated by Cyprideis sp.; c) accumulation of microgastropods (Hydrobia spp.); d) oolite sandstones with abundant gastropods (Theodoxus spp.); e) Psilunion (Psilunion) ex. gr. subrecurvus (Sinzow).

sedimentary structures consist of small scale cross-lamination, which are occasionally disturbed, probably due to the elimination of water during sediment compaction. The most valuable paleoenvironmental signal comes from the presence of wave rippled sediments, pointing to deposition in shallow water, probably on the lower shoreface. Based on these structures the thick bedded sandy layers are interpreted as shallow water deposits that probably accumulated in the proximity of the river mouth under strong fluvial control.

The ostracods are highly abundant but very poor in species number (Figs. 3, 4, Plate 1). The ostracod assemblages consist of several species of Cyprideis (Cyprideis pannonica and C. ex. gr. torosa) and some rare candonids like Pseudocandona sp. (juveniles) and Candoniella sp. Sporadically, Leptocythere blanda is present.

The dominance of fresh–brackish water and littoral conditions is also shown by the presence of abundant microgastropods like Hydrobia sp. and Theodoxus sp. and Unionidae bivalves — Psilunion (Psilunion) ex. gr. subrecurvus (Fig. 4).

The observed macro and micro faunas indicate low salinity (0–5‰) environments, typical of littoral setting or within lakes of short life time. In the upper part of the Maeotian, intercalations of oolitic sandstones with micro-gastropods are common (Fig. 4c,d).

3.3. The Maeotian–Pontian transition

An important transgressive event takes place at the Maeotian–Pontian boundary, characterized by a sudden lithological change to

Plate 2. Most relevant ostracod species (Superfamily Cytheroidea) from the Upper Maeotian, Pontian and Lower Dacian of the Râmnicu Sărat valley section (all valves of ostracods belong to adult individuals, external lateral views, LV = left valve, RV = right valve, RM = micropaleontological sample no.:) 1) Cyprideis pannonica (Méhes), carapace, view from RV, RM 116, Upper Maeotian; 2) Cyprideis ex. gr. torosa (Sars); 2) smooth specimen, carapace, view from RV, RM 114, Upper Maeotian; 3) nodded specimen, RV, RM 226, Upper Pontian; 4, 5) Cyprideis sp. 1; 4) LV; 5) RV; RM 54, Lower Dacian; 6) Cyprideis sp. 2, 6) LV; 7) RV; RM 65, Upper Pontian; 8) Cytherissa bogatschovi Livental; 8) LV, female; 9) LV, male; RM 5, Lower Dacian; 10) Cytherissa sp., LV, RM 79, Upper Pontian; 11) Pontooleberis pontica (Stancheva), fragmented RV, RM 209, Lower Pontian; 12) Tyrhenocythere motasi Olteanu; 12) LV, male; 13) carapace, view from RV, female; RM 220, Upper Pontian; 14) LV, 15) Tyrhenocythere ex gr. motosi Olteanu; 14) LV, 15) carapace, view from RV; RM 94, Upper Pontian; 16) Tyrhenocythere filipes (Hungar), LV, RM 88, Upper Pontian; 17) Tyrhenocythere pannonicum (Olteanu), LV, RM 209, Lower Pontian; 18) Maetocythere ex. gr. bosqueti (Livental); LV, RM 88, Upper Pontian; 19) Amnicythere cymbula (Livental); 19) LV; 20) carapace, view from RV; RM 220, Upper Pontian; 21) Amnicythere ex. gr. cymbula (Livental); 21) LV; 22) RV; RM 207, Lower Pontian; 23) Amnicythere costata (Olteanu); 23) LV; 24) RV; RM 220, Upper Pontian; 25, 26) Amnicythere ex. gr. lata Schneider; 25) LV; 26) RV; RM 207, Lower Pontian; 27) leptocythere blanda, LV, RM 215, Upper Maeotian; 28) Amnicythere ex. gr. polymorpha Olteanu, LV, RM 219, Upper Pontian; 29, 30) Amnicythere andrasovi (Livental); 29) LV; 30) RV; RM 94, Upper Pontian; 31, 32) Amnicythere palimpsesta (Livental); 31) LV; 32) RV; RM 207, Lower Pontian; 33, 34) Maetocythere bacuna (Livental); 33) LV; 34) RV; RM 220, Upper Pontian; 35, 36) Maetocythere incusa Olteanu; 35) LV; 36) RV; RM 203, Lower Pontian; 37) Loxoconcha petasa Livental, LV, RM 220, Upper Pontian; and 38) Loxoconcha babazananica Livental, RV, RM 96, Upper Pontian. (see on page 140)
dominantly silty clays. This event coincides with a short-time replacement of the fresher water fauna by a fauna of significantly higher salinity. These assemblages are dominated by the occurrence of benthonic calcareous foraminifers (species of Ammonia and Porosonion) and especially of agglutinated foraminifers (species of Ammotium). The enigmatic planktonic foraminifera genus Streptochilus has also been observed in large numbers at the same level (Fig. 5). The biserial planktonic foraminifera were earlier described from the Upper Maeotian deposits of the Western Caucasus as belonging to the genus Bolivina, and some Bolivina species were also reported from the Taman peninsula (Maisuradze, 1988). Several morphological species of Streptochilus (Foraminifera) were described in the Miocene of the western Indian Ocean and the eastern Atlantic. They had previously been assigned to the benthic genus Bolivina, but evidence on their apertural morphology, together with accumulation rate data and isotopic composition shows that they lived as plankton, and should be assigned to the planktic genus Streptochilus (Smart and Thomas, 2006, 2007). It was suggested that Streptochilus may have evolved polyphyletically, either from biserial planktic or benthic ancestors, possibly in response to the occurrence of relatively eutrophic environmental conditions caused by intermittent upwelling, leading to high algal growth rates but low transport efficiency of organic matter to the sea floor (Smart and Thomas, 2007). Recent investigations of the Upper Badenian and Sarmatian of the Transylvanian Basin revealed particular, small sized planktonic foraminiferal assemblages that include also the biserial foraminifera Streptochilus occurring in relation to a transgressive event close to the end of Badenian and provide evidence for a paleogeographic connection to the Indo-Pacific area at that time (Filipescu and Silye, 2008).

Starting with the Pontian, a large diversification of the ostracod fauna took place, marked by a sudden increase of species of Pontoniella and Candona: Pontoniella acuminata, Candona (Hastacandona) lotzy, Candona (Hastacandona) hysterica, Candona (Zalanyiella) venusta, Fabaeformiscandona sp., Candona (Caspicypris) alta, Candona (Caspicypris) pontica (Fig. 3, Plate 1). Cyprideis species are still very frequent.

The transitional interval is further characterized by shell accumulations with the bivalve Congeria (Andrusoviccona) amygdaloides novorossica, a biostratigraphic marker for the Maeotian–Pontian boundary. The association of C. (A) amygdaloides novorossica, micro-gastropods and unionids (Psilunion sp.) macrofauna is abruptly replaced by an association of limnocardiids (Fig. 5), marking the base of the Pontian according to its original definition.

The Maeotian–Pontian boundary as defined here, is thus marked by an influx of marine water into the Paratethys, probably coming from the Mediterranean or alternatively from the Indian ocean (Krijgsman et al., 2010; Ruban, 2010). After this very rapid marine water influx, the environment became less saline, as testified by the abundance and diversity of Candoninae in the Lower Pontian.

3.4. The Lower Pontian (Odessian)

As a consequence of the Maeotian–Pontian transgression, the Lower Pontian starts with fine pelitic successions, deposited in deeper waters (~100–150 m). The littoral and fluvial facies from the latest Maeotian are replaced by more distal ones; gray marls and clays with frequent intercalations of ferruginous marls and silts (Fig. 6).
An important rejuvenation of the ostracod fauna is observed in the Lower Pontian, resulting in colonization by a large number of species: C. (Caspiocypris) alta, C. (Caspiocypris) pontica, Candona (Camptocypris) ossinaeensis, C. (Zalanyiella) venusta, C. (Hastacodona) hysterica, C. (Hastacodona) lotzyi, P. acuminata, Pontoniella quadra, Pontoniella striata, Fabaeformiscandona sp., Candona (Typhlocythere) ankæ, Cypria tocorjescui, Cypria sp., Bakunella dorsoarcuata, Cytherissa sp., C. pannonica, Tyrrhenocythere pannonicum, Amnicythere cymbula, Amnicythere ex.gr., cymbula, Amnicythere costata, Amnicythere andrusovi, L. blanda (Figs. 3, 6; Plates 1, 2). The presence of ostracods with eye tubercles indicates the need of the photic zone for their development, in agreement with the presence of green charophyta algae in the same samples. At the base of the Lower Pontian there is a level with pyrite filled ostracods (Fig. 6), which is similarly observed in the Taman Peninsula of Russia (Krijgsman et al., 2010), pointing to large-scale dissoxic conditions throughout the Eastern Paratethys.

The Upper Maeotian mollusc fauna is replaced by limnocardiids bivalves: Paradacna abichi, Pseudoprosodacna littoralis littoralis, Prosodacna sturti, Caladacna steindachneri, Didacna subcarinata, Limnocardium (Tauricardium) subsquamulosum, Monodacna (Pseudocatillus) pseudocatillus and Congeria zagabriensis (Fig. 6).

These faunal assemblages indicate that immediately after the short marine influx, the salinity of the Dacian Basin waters decreased again because of the high influx of continental waters. The Lower Pontian paleoenvironment was generally fresh to brackish with salinities of 7–8‰ (Fig. 3).

3.5. The Middle Pontian (Portaferrian)

The Middle Pontian represents a regressive phase in the Dacian Basin. There are a large number of fluvial sandstones (Fig. 7), fossil soils, coaly clays and even thin coal levels. Rare occurrences of sandstones with limnocardiids bivalves are found. The sedimentary record becomes scarce in fossils, although ostracods and molluscs typical of shallow water environment (littoral, fluvial and even subaerially exposed) have been found.

The ostracod fauna is rather scarce if compared with the Lower Pontian one (Fig. 3). The Middle Pontian species are represented by: Amplocypris ex. gr. dorsobrevis (a species with robust shell capable of living in littoral environment where sands are deposited in hydrodynamically active regimes), Candoniella sp., Zonocypris membranae (species able to quickly colonize temporary, short-living lakes), Cyprideis ex.gr. torosa (littoral species), Tyrrhenocythere motasi (a species with robust shell capable of living in sandy–silty environments). These species are known to adapt rapidly in changing environments from the lakes located close to rivers, to marshes and lagoons (Plate 2).
The molluscan fauna is also rare and represented by fresh water lacustrine and fluvial forms: unioniids — *Unio (Rumanunio) rumanus* and dreissenids — *Dreissena polymorpha* (Fig. 7). Frequently, planorbid gastropods typical of continental environments (temporary ponds and lakes) have been identified. These sedimentological and faunistic changes were caused by an important base level drop from basinal environments to flood plain deposits. The changes in lithofacies were reflected in changes in fauna that became taxonomically poorer and have visible effects in the marginal areas of the basin (Stoica et al., 2007). The faunal assemblages indicate fresh water environments (0–4‰) and a relatively small drop (~100 m) of the water level (Fig. 3).

3.6. The Upper Pontian (Bosphorian)

The Upper Pontian deposits accumulated in a more distal setting, where finer, pelitic sediments are alternated with sandy units. These fine deposits are represented by massive or stratified gray marls and clays, rich in fossils, alternating with thinner sandstones and shell accumulations (Fig. 8). The Upper Pontian is marked by a gradual upward increase in littoral and fluvial deposits, evolving into deltaic and fluvial deposits toward the Pontian–Dacian boundary. This is caused by a transgressive episode that marks the base of Upper Pontian.

A new faunal bloom occurs and some of the species common in the Lower Pontian become dominant again (Fig. 3). Next to the Lower Pontian species, some new species appear that will continue to exist up to Dacian (Hanganu, 1974; Hanganu and Papaianopol, 1982; Olteanu, 1989, 1995; Stoica et al., 2007). The main ostracod species from the Upper Pontian of the Râmnicu Sarat Valley are: *A. ex. gr. dorsobrevis*, *C. (Caspiocypris) alta*, *C. (Camptocypria) ossoinaensis*, *Candona (Camptocypria) balcanica*, *C. (Zalanyiella) venusta*, *P. acuminata*, *P. quadrata*, *P. striata*, *Candona neglecta*, *C. (Zalanyiella) venusta*, *P. acuminata*, *P. quadrata*, *P. striata*, *Candona neglecta*, *Candoniella sp.*, *Cypria tocorjescui*, *Cypria sp.*, *B. dorsoarcuata*, *Cytherissa boghatschovi*, *C. ex. gr. pannonica*, *Cyprideis ex. gr. torosa*, *Cyprideis sp.*, *T. motasi*, *T. ex. gr. motasi*, *Tyrrenocythere filipespecis*, *A. cymbula*, *A. ex. gr. cymbula*, *A. costata*, *A. andrussovi*, *Amnicythere palimpsesta*, *Amnicythere ex. gr. lata*, *Maeotocythere ex. gr. bosqueti*, *Maeotocythere bacuana*, *Maeotocythere incusa*, *Loxoconcha babazananica*, *Loxoconcha petasa* (Plate 2). Two species of the *Amplocypris* genus are recorded in the Upper Miocene and Pliocene deposits of the Dacian Basin (Hanganu and Papaianopol, 1977; Olteanu, 1995; Floroiu et al., 2011): *A. dorsobrevis Sokač and Amplocypris odessaensis* Ilnitzkaia. More additional morphometric studies (Danielopol et al., 2011a) are needed to find out which is the real taxonomic affiliation of *Amplocypris* species in Paratethys. The presence of Leptocytheridae in the Paratethys Neogene is also questioned. Many species formerly attributed to the genus *Leptocythere* are now re-evaluated and assigned to other leptocytherids genera like *Amnicythere*, *Callistocythere*, *Euxinocythere*, *Maeotocythere*, *Mediocysterideis* (Stancheva, 1968; Gliozzi et al., 2005; Boomer et al., 2010). There is still a lack of consensus in the literature on the...
generic assignment of leptocytherid species (Namiotko et al., 2011) and detailed comparative morphological studies must be developed for this group of ostracods (Danielopol et al., 2011b).

The bivalves are represented by numerous species that are mostly typical for brackish waters (Papaianopol, 1989): D. polymorpha, Prosodacna (Prosodacna) mrazeci, Prosodacna (Prosodacna) savae, Prosodacna sturi, Pseudocatillus sp., Plagiodacna sp., C. steindachneri, Limnocardium nobile, Limnocardium sp., D. subcarinata, Lunadacna lunae, Phyllocardium planum giganteum, L. (Tauricardium) subsquamulosum, Limnocardium (Tauricardium) sp., Unio (Rumanunio) rumanus, Congeria botenica, and Chartoconcha bayerni (R. Hoernes); b) Limnocardium (Tauricardium) sp.; and i) Valenciennius annulatus Rousseau.

Paleoenvironmentally, the base of the Bosphorian corresponds to a second transgressive event in the Dacian Basin, showing a major faunal change in the ostracod assemblages and a lithological change to more basinal fine grained sediments at the base of Upper Pontian; b) wave ripples on the upper bedding plane of a sandy layer from the Middle Pontian–Upper Pontian boundary interval; c) ostracod assemblage from the basal part of the Upper Pontian marked by the abundancy of Tyrrhenocythere spp.; d)–i) most abundant mollusc species from the basal part of the Upper Pontian; d) Plagiodacna sp.; e), f) Pseudocatillus sp.; g) Chartoconcha bayerni (R. Hoernes); h) Limnocardium (Tauricardium) sp.; and i) Valenciennius annulatus Rousseau.

4. Discussion

4.1. Dacian Basin water level changes during the late Miocene–early Pliocene

The presence of agglutinated and calcareous foraminifera of marine origin at the Maeotian–Pontian boundary interval suggests that a major flooding event has taken place in the Dacian Basin by marine waters, probably by establishing a connection to the Mediterranean or Indian Ocean. An Odessian transgression has also been recognized in seismic profiles from the western Dacian Basin (Getic Depression) where the Lower Pontian corresponds to a progradational–aggradational unit developed during rising water levels (Leever et al., 2010). A Lower Pontian transgression has further been documented in other Paratethys basins and is biostratigraphically marked by a migration of faunal elements from the Pannonian Basin (Hungary) into the Eastern Paratethys and by a migration of typical Aegean species into the Black Sea domain (Stevanovic et al., 1989; Popov et al., 2006). In addition, a marine nano-fossil influx, comprising assemblages that are correlative to Subzone NN11b, has been reported from the Maeotian–Pontian boundary interval in the Dacian Basin (Marunteanu and Papaianopol, 1998). Fossil

Fig. 8. Stratigraphy, lithology and paleontology of the Upper Pontian of the Râmnicu Sărat valley section; a) the transition from littoral sandy deposits of Middle Pontian to more basinal fine grained sediments at the base of Upper Pontian; b) wave ripples on the upper bedding plane of a sandy layer from the Middle Pontian–Upper Pontian boundary interval; c) ostracod assemblage from the basal part of the Upper Pontian marked by the abundancy of Tyrrhenocythere spp.; d)–i) most abundant mollusc species from the basal part of the Upper Pontian; d) Plagiodacna sp.; e), f) Pseudocatillus sp.; g) Chartoconcha bayerni (R. Hoernes); h) Limnocardium (Tauricardium) sp.; and i) Valenciennius annulatus Rousseau.
assemblages from the Taman Peninsula of Russia show similar marine associations at the Maeotian–Pontian boundary interval indicating that this transgression extended at least into the eastern part of the Black Sea Basin (Krijgsman et al., 2010).

A major water-level drop in the Dacian Basin took place during Portaferrian times (between 5.8 and 5.5 Ma) and resulted in the re-establishment of fluvo-deltaic conditions in the Focșani Depression. Our paleontological data indicate that depositional environments within the photic zone (<100 m) abruptly change to faunal assemblages typical of shallow waters (~0–50 m) and terrestrial environments during the Portaferrian. This implies that only a relatively small water level drop has taken place (~100 m) in the Dacian Basin during the Portaferrian, although the exact amplitude is still a matter of debate. In seismic profiles of the western part of the Dacian Basin, the Portaferrian shows mainly progradational units, deposited during periods of low water levels (Leever et al., 2010). The corresponding water level drop is here roughly estimated at a maximum of 200 m, based on the elevation difference between the shelf edges above and below the sequence boundary. The other regions of the Dacian Basin that developed in water depths of ~100 m in the early Pontian started to evolve in deltaic, fluvial, lacustrine and/or littoral environments at the beginning of the Middle Pontian. This indicates that the water level in the entire Dacian Basin dropped during the Portaferrian, which would be compatible with the presence of a shallow barrier at Dobrogea, separating the Dacian Basin from the Black Sea Basin.

The Upper Pontian is marked by a second transgression in the East Carpathian foredeep. Interpolation assuming constant sedimentation rates suggests that this Bosphorian transgression started at an age of 5.5 ± 0.1 Ma. In the western Dacian Basin, seismic profiles show a transgressive system tract at the base of the Bosphoranic as well (Leever, 2007). In the Topolog region of the south Carpathian foredeep, the Bosphorian is found transgressive on Maeotian deposits while the uppermost Maeotian, Odessian and Portaferrian are missing (Stoica et al., 2007; Floroiu et al., 2011). Our detailed micropaleontological studies show that the base of the Bosphoranic consists of fresh to brackish water ostracods, indicating a continental origin for this transgression, probably related to a regional climatic change toward a positive hydrological balance for the Paratethys region (e.g. Krijgsman et al., 2010).

A Pliocene marine flooding of the Dacian Basin was previously suggested based on the Hinova section (western Dacian Basin), which was interpreted to represent the bottom set of a ‘Gilbert fan delta’ produced by Mediterranean inflow water (Clauzon et al., 2005). We have resampled this Hinova section of Clauzon et al. (2005); their Fig. 6 for biostratigraphic dating. Our micropaleontological analyses show that this section corresponds to the Lower Pontian (6.0–5.8 Ma), and thus not to the Pliocene, because it comprises the Odessian ostracods, C. (Caspiocypris) alta, C. (Camptocypris) balcanica, P. acuminata, P. striata, C. tocorjescui, B. dorsoarcuata, A. andrusosi, Amnicythere sp., Mediocytheridées sp. and abundant limnocardiid bivalves, especially P. abichi. In addition, recent micropaleontological and stratigraphic studies of the assumed foreset beds (Clauzon et al., 2005) clearly indicate a Badenian–Sarmatian age for these coarse clastic sediments that are most likely tectonically tilted Middle Miocene alluvial fan conglomerates (Marinescu, 1978; Jipa et al., 2011).

4.2. Paratethys–Mediterranean connectivity during the late Miocene and early Pliocene

The Black Sea itself has experienced significant water level changes during the Portaferrian. The sedimentary succession exposed at the Black Sea margin of Russia (Taman Peninsula) shows a conspicuous environmental change in Portaferrian, by brackish marls with Pontian fauna indicative of the lower photic zone (50–100 m deep) abruptly changing to condensed coastal sequences of reddish sands, attributed there to the base of the Kimmerian (= Middle Portaferrian, Krijgsman et al., 2010). This indicates that the Black Sea experienced a sea level drop of at least 50–100 m as well.

Drilling in the Black Sea Basin (DSDP Leg 42B) had earlier revealed a peculiar sedimentary layer at the Mio-Pliocene boundary, interpreted as shallow, supratidal and intertidal sediments in the otherwise deep-water sequence and as caused by a sudden drastic (~1600 m) lowering of the Black Sea water-level (Hsu and Giovannoni, 1979). In addition, seismic profiles of the Black Sea Basin show evidence of deep canyon cutting (Dinu et al., 2005; Gillet et al., 2007). This major drop down scenario of the Black Sea implies a negative water budget for the Paratethys. In contrast, the hydrological balance of the Black Sea basin is also considered as positive to explain overspilling of Paratethys waters during the Mediterranean Lago Mare facies (Cita et al., 1978; Esu, 2007; Gloižz and Grossi, 2008). In that scenario it is envisaged that the water level of the Black Sea only dropped to the sill height of the paleo-Bosphorus. The magnitude and, in some cases, even the sign of the Paratethys sea or lake level changes during the Messinian are thus still seriously debated and subject to ongoing controversy.

Paleogeographic data from the Aegean region indicate that no (significant) gateway existed between Mediterranean and Paratethys (Cagatay et al., 2006) and that only ephemeral marine incursions took place in the Eastern Paratethys during the Mio-Pliocene period (Stevanovic et al., 1989; Marunteanu and Papaianopol, 1998; Popov et al., 2006). Consequently, water level in the Paratethys could be expected to have fluctuated in relation to Messinian paleoclimatological changes.

Our biostratigraphic results suggest that a marine connection existed at the Maeotian–Pontian boundary at 6.05 Ma, evidenced by the influx of foraminifera in the Dacian Basin. This is further confirmed by earlier observations of a short calcareous nanofossil influx at the Maeotian/Pontian boundary interval (Marunteanu and Papaianopol, 1998). According to earlier paleogeographic reconstructions, the most likely marine connection is to the Mediterranean (Popov et al., 2006), but the available biostratigraphic data also do not exclude a gateway to the Indian Ocean (Krijgsman et al., 2010). Our new biochronology for the Dacian Basin furthermore shows that the successively younger nanofossil influx at the Pontian–Dacian boundary, previously suggested to correlate to the Zanclean flooding event of the Mediterranean (Marunteanu and Papaianopol, 1998), is now dated at 4.7 Ma.

5. Conclusions

New biostratigraphic data from the thick and continuous sedimentary successions of the Focșani Depression are incorporated into a magnetostatigraphic time frame. The integration of paleoecological information from ostracods, foraminifera and molluscs with sedimentary structures enables detailed reconstructions of the paleogeographic and paleoenvironmental evolutions of the East Carpathian foredeep during the Messinian.

- The Upper Maeotian is marked by sedimentary structures that indicate the coexistence of fluviol and littoral environments. The faunal record suggests low salinity (0–4‰) environments, typical of perennial-lake or littoral setting or of temporary lakes and ponds.
- An important transgression takes place at the Maeotian–Pontian boundary, characterized by a short-time paleoenvironmental change to significantly higher salinities (20–30‰). The faunal assemblages are dominated by the occurrence of benthic (agglutinated and calcareous) and planktonic foraminifera. It is the first time that these have been observed at the Maeotian/Pontian interval in the Dacian Basin, and they indicate an influx of marine waters at 6.05 Ma.
- The Lower Pontian starts with fine pelitic sediments, deposited in deeper water, but still within the photic zone. The salinity decreased to 7–8‰ because of a positive water balance determined by the higher influx of continental waters.
The Middle Pontian shows a base level drop with visible effects in the marginal areas of the basin. It is scarce in fossils, and mainly os- tracods and molluscs typical of shallow and fresh water (0–4‰) lacustrine environments have been found, species known to adapt rapidly to changing environments from lakes located close to rivers.

The Upper Pontian deposits accumulated in a more distal setting, with finer pelitic sediments, alternated with sandy units. The upper part is marked by an increase in littoral and fluvial deposits, evolving into deltaic and fluvial deposits (salinity between 7 and 8‰) toward the Pontian–Dacian boundary as a consequence of pro- gressive basin filling with sediments.

Acknowledgments

We thank especially Georghe Popescu for his help with bio-stratigraphical analyses of the Râmnicu Sărat data (foraminifera). We acknowledge the constructive comments of Oleg Mandic and two anonymous reviewers. This work was financially supported by the Netherlands Research Centre for Integrated Solid Earth Sciences (NWO) and the Netherlands Geosciences Foundation (ALW) with support from the Netherlands Organization for Scientific Research (NWO). This research was also supported by CNCSIS Romania funding (ID 960 and 1 Euro).

References

Hanganu, E., Mawake, T., 2002. Sarmatian (Late Middle Miocene) gastropod assemblages of the Central Paratethys. Facies (46), 57–82.
}