Basin Research (2005) doi: 10.1111/j.1365-2117.2005.00269.x

Influence of Mediterranean sea-level changes on the Dacic Basin (Eastern Paratethys) during the late Neogene: the Mediterranean Lago Mare facies deciphered

Georges Clauzon*, Jean-Pierre Suc†, Speranta-Maria Popescu†, Mariana Marunteanu‡, Jean-Loup Rubino¶, Florian Marinescu‡ and Mihaela Carmen Melinte§

**C.E.R.E.G.E. (UMR 6635 CNRS), Université Paul Cézanne, Europôle de l'Arbois, Aix-en-Provence, France*
†Laboratoire PaléoEnvironnements et PaléobioSphère (UMR 5125 CNRS), Université Claude Bernard-Lyon 1, Villeurbanne, France
‡Geological Insitute of Romania, Bucharest, Romania
¶TOTAL,TG/ISS, CSTTF, Pau, France
§National Institute of Marine Geology and Geoecology, Bucharest, Romania

ABSTRACT

A recently published scenario viewing the Messinian salinity crisis as two evaporitic steps rather than one has led to a search for new indices of the crisis in the Eastern Paratethys. Fluvial processes characterized the southwestern Dacic Basin (Southern Romania, i.e. the Carpathian foredeep) whereas brackish sediments were continuously deposited in its northern part. This is consistent with previously evidenced responses of the Black Sea to the Messinian salinity crisis. High sea-level exchanges between the Mediterranean Sea and Eastern Paratethys are considered to have occurred just before and just after desiccation of the Mediterranean. This accounts for two successive Mediterranean nannoplankton-dinocyst influxes into the Eastern Paratethys that, respectively, belong to zones NN 11 and NN 12. Meanwhile, two separate events that gave rise to Lago Mare facies (with Paratethyan Congeria, ostracods and/or dinoflagellate cysts) arose in the Mediterranean Basin in response to these high sea-level exchanges and located 5.52 and 5.33 Ma (isotopic stages TG 11 and TG 5, respectively), i.e. just before and just after the almost complete desiccation of the Mediterranean). These Lago Mare facies formed independently of lakes with ostracods of the *Cyprideis* group that developed in the central basins during the final stages of desiccation. The gateway faciliting these water exchanges is not completely identified. A proto-Bosphorus strait seems unlikely. A plausible alternative route extends from the northern part of the Thessaloniki region up to the Dacic Basin and through Macedonia and the Sofia Basin. The expression 'Lago Mare' is chronostratigraphically ambiguous and should be discontinued for this purpose, although it might remain useful as a palaeoenvironmental term.

INTRODUCTION

The relationships between the Mediterranean Sea and the Paratethys realm have been debated for a long time (Seneš, 1973). Before 16 Ma, connections were unobstructed and faunal exchanges (planktonic and benthic foraminifers, molluscs, dinocysts, etc.) are almost continuously well documented (Rögl & Steininger, 1983). From 12 Ma, Paratethyan conditions evolved into restricted marine environments (Sacchi *et al.*, 1997), and the complete isolation of the Pannonian Basin (Western Paratethys) is generally considered to have occurred in the early Tortonian (Magyar *et al.*, 1999). Then, Paratethys became a succession of more or less separated brackish to freshwater basins (Stevanović *et al.*, 1990).

Normal connections between the Mediterranean Sea and Paratethys are therefore commonly considered to have ended in the Late Miocene. Nevertheless, Paratethys seems to have had a strong influence on the Mediterranean region during the Messinian salinity crisis, i.e. during the so-called Lago Mare event (Cita *et al.*, 1978a). In many Mediterranean localities, the Lago Mare facies is characterized by the presence of brackish shallow water fauna (molluscs: *Congeria*, *Dreissena*, *Melanopsis*, etc.; ostracods: *Cyprideis pannonica* gr., *Loxoconcha*, *Tyrrhenocythere*, etc.) of Paratethyan origin (Ruggieri, 1967; Cita & Colombo, 1979). More recently, latest Miocene endemic Paratethyan dinocysts including *Galeacysta etrusca* (Müller *et al.*, 1999) have been frequently found in the Mediterranean (Corradini & Biffi, 1988) and added to the Lago Mare biofacies

Correspondence: J.-P. Suc, Laboratoire PaléoEnvironnements et PaléobioSphère (UMR 5125 CNRS), Université Claude Bernard-Lyon 1, 27-43 boulevard du 11 Novembre, 69622 Villeurbanne Cedex, France. E-mail: jean-pierre.suc@univ-lyon1.fr

(Bertini *et al.*, 1995; Bertini, 2002). It has been proposed that the Lago Mare event was caused by the 'capture' of Paratethyan waters by an almost desiccated Mediterranean Basin (Hsü *et al.*, 1973, 1977), the specific process of which is poorly documented (Cita, 1991). Another interpretation is proposed by Orszag-Sperber *et al.* (2000) who consider the Lago Mare event as the development of lakes within depressions caused by strong erosion in the desiccated Mediterranean without any direct linkage with Paratethys. This resulted in a broad confusion between the marginal and deep basin Lago Mare facies that is striking on Fig. 8 of Iaccarino & Bossio (1999, p. 538) who postulate two successive Lago Mare events in the late Messinian.

To explain both the Lago Mare facies in the Mediterranean realm and some Middle Tortonian (Maeotian) Mediterranean brackish mollusks and ostracods in the Eastern Paratethys (Rögl, 1996, 1998), Sprovieri *et al.* (2003) have envisaged a seaway between the Mediterranean Sea and Paratethys in the area of the present Black Sea, and repeated exchanges forced by climate fluctuations since the Tortonian.

An important part of the Eastern Paratethys constits of the Dacic Basin (Fig. 1a, b). It corresponds to the Southern Romania and is delimited to the north and west by the Carpathians, to the south by the Balkan Chain (i.e. the Moesian Platform) and to the east by the Black Sea. This area comprises the foredeep of the Carpathians and it acumulated a very thick succession of terrigenous Neogene sediments (Marinescu *et al.*, 1998). From the Early to Late Miocene (i.e. from about 25 to 10 Ma), the Dacic Basin existed as a transitional basin between the Pannonian Basin (Western Paratethys) and the Euxinian Basin (i.e. the western part of the Eastern Paratethys which extended from the present-day Black Sea across to the Aral Sea) (Rögl & Steininger, 1983; Marinescu, 1992). At about 10 Ma, it became the western appendage of the Euxinian Basin, the connection between the two basins being moderately restricted because of the presence of the Dobrogea horst (Rögl & Steininger, 1983).

The discovery of some late Neogene calcareous nannofossil floras both in Southern Romania (Mărunţeanu, 1992) and the Crimea (Semenenko & Lyuljeva, 1978; Semenenko & Olejnik, 1995) has presented a new means to understand Late Neogene relationships between the Mediterranean Sea and Eastern Paratethys, and has stimulated an intensive and very fruitful research of nannofossils in the Dacic Basin. Hence, almost seventeen recurrent discoveries of Mediterranean nannofossil occurrences have been recorded within the Dacic Basin from about 13.5 Ma up to about 3.5 Ma (Papaianopol & Mărunţeanu, 1993; Mărunţeanu & Papaianopol, 1995, 1998; Drivaliari *et al.*, 1999; Snel *et al.*, in press). This suggests that transient relationships occurred repeatedly between the Mediterranean Sea and the Dacic Basin during the late Neogene.

Accordingly, we can consider the possible influence of Mediterranean sea-level changes over the Eastern Paratethys: some Mediterranean sea-level drops might have caused the fluvial drainage of Paratethyan waters into the Mediterranean Basin; whereas some Mediterranean sea-level rises might have caused the influx of marine surface water in the Eastern Paratethys (Sprovieri *et al.*, 2003). Such a process would explain the repeated nannofossil records in the Dacic Basin. In particular, two successive Mediterranean nannoplankton influxes have been recorded in Bosphorian sediments of the northern Dacic Basin (Mărunţeanu & Papaianopol, 1998; Snel *et al.*, in press). These sediments belong to the earliest Chron C3r (Snel *et al.*, in press). The first influx correlates to Zone NN11 zone, and the second to Zone NN12 (see Fig. 2 for the chronological assignment of the NN11–NN12 boundary, characterized by the disappearance of *Discoaster quiqueramus* and *Triquetrorhabdulus rugosus* and/or the appearance of *Ceratolithus acutus*: Berggren *et al.*, 1995a, b). These data imply two brief successive connections at high-sea level between the Mediterranean Sea and the Dacic Basin.

In the Black Sea, seismic profiles (Letouzey *et al.*, 1978; Gillet *et al.*, 2003; Gillet, 2004) and the results from three coreholes (Sites 379, 380, 381; Fig. 1a) drilled on DSDP Leg 42B (Ross *et al.*, 1978) suggest that the two main signatures of the Messinian salinity crisis in the Mediterranean exist in this basin: evaporite deposition in the abyssal plain, and an erosional surface on the margin (Hsü & Giovanoli, 1979; Gillet, 2004). Such a similar and coeval response of the Black Sea to the Messinian salinity crisis in the Mediterranean implies that the basins (including the Dacic appendage) were connected at high-sea level just before the crisis.

Several field investigations within the Dacic Basin starting in 1998 (Clauzon & Suc, 1998) were organized to test the hypothesis of Hsü & Giovanoli (1979). The Dacic Basin was chosen because of its dense record of Late Neogene Mediterranean nannofossils that should document the most elevated Mediterranean sea levels in the area. Moreover, the lack of latest Miocene sediments in the Ţicleni borehole may be due to an erosional phase consistent with the Messinian salinity crisis (Drivaliari *et al.*, 1999). We focus on the time interval 6–5 Ma, i.e. the period including two major successive global low sea levels (isotopic stages TG 22 and TG 20 of Shackleton *et al.*, 1995) and three main high sea levels (isotopic stages TG 11, TG 9 and TG 5 of Shackleton *et al.*, 1995). Precise ages have been allocated to these isotopic stages by Vidal *et al.* (2002): TG 22 (5.81 Ma), TG 20 (5.76 Ma), TG 11 (5.52 Ma), TG 9 (5.43 Ma) and TG 5 (5.33 Ma). It has been established that the Messinian salinity crisis belongs to the C3r reverse chron (Gautier *et al.*, 1994; Clauzon *et al.*, 1996), its age (5.96–5.33 Ma) being specified by Krijgsman *et al.* (1999a). These successive eustatic events are manifested in the Mediterranean Basin by strong signatures (Clauzon *et al.*, 1996), respectively:

- the deposition of the marginal evaporites caused by a moderate sea-level fall,
- the final phase of carbonate platform deposition on the margins dated at about 5.60 Ma (Cornée *et al.*, 2004) and corresponding to a moderate sea-level rise,

  Basin Research, doi: 10.1111/j.1365-2117.2005.00269.x

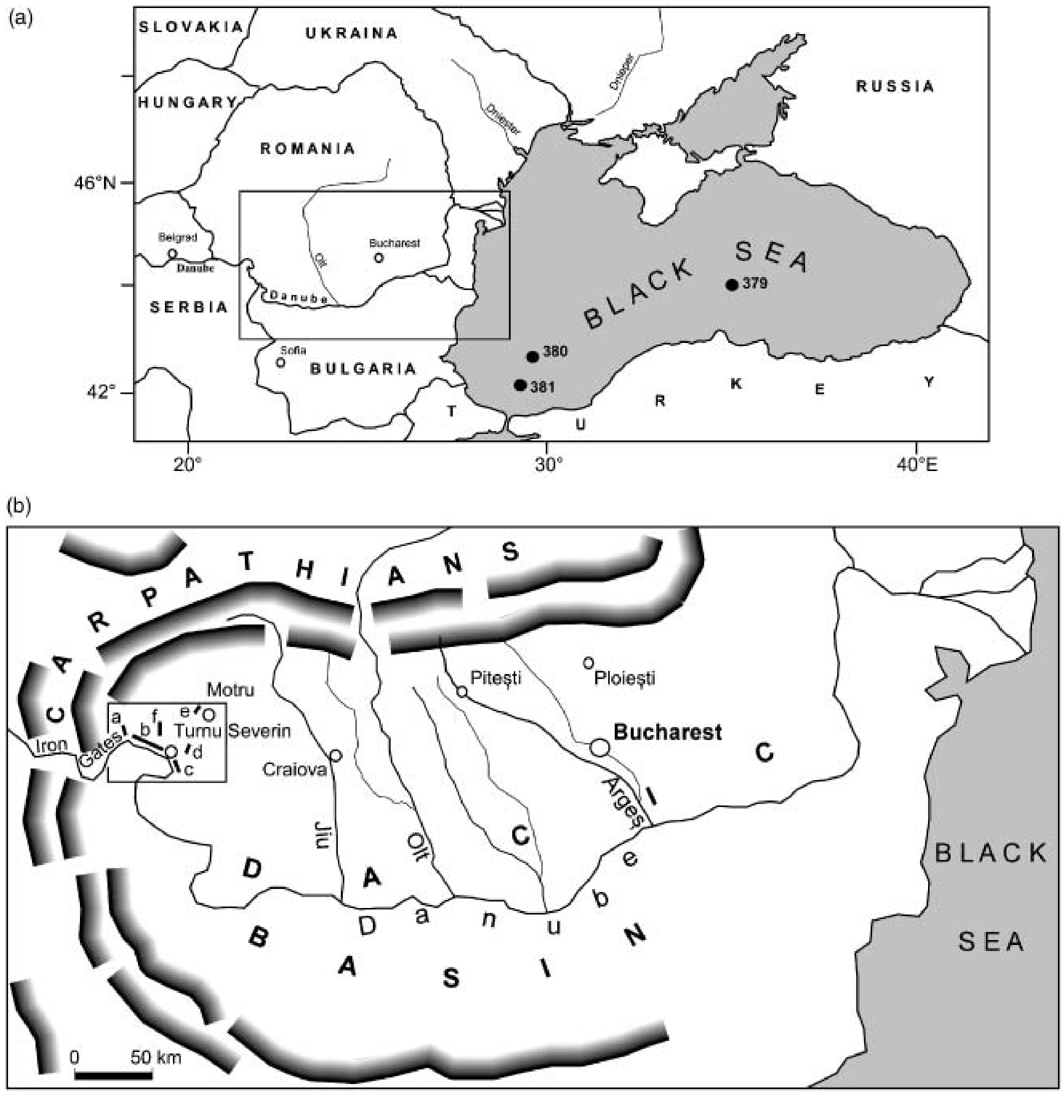

Fig. 1. Map of the Black Sea and its Western edge. (a) Location map of the Dacic Basin (box) with respect to the Black Sea and Sites 379, 380, and 381 of DSDP Leg 42B. (b) Detailed map of the Dacic Basin with the studied sections: a, Gura Văii; b, Turnu Severin; c, Hinova; d, Husnicioara; e, Motru (Lupoaia section); f, Vărănic.

- the Messinian erosional surface cutting, depending on the place, carbonate platform and marginal evaporites (Clauzon, 1997), marginal evaporites (Delrieu *et al.*, 1993; Fortuin *et al.*, 1995) or other older deposits (Clauzon, 1999), and corresponding to the deep desiccated basin evaporites (strong sea-level drop),
- the earliest Zanclean high-stand characterized in many places by Gilbert-type fan delta constructions (Clauzon, 1990, 1999).

In the Northwestern Mediterranean region, the two last signatures are obvious at the base of elevations, especially at the outlet of deep transverse valleys (Clauzon, 1999). For this reason, we have developed our field investigations mainly in the area of Turnu Severin where the Danube River achieves its crossing of the Carpathians (Iron Gates) (Fig. 1b). If the Black Sea and Dacic Basin have been affected by the Messinian salinity crisis, similar impacts must also exist in the Turnu Severin area and on the Northwestern Mediterranean region.

SIGNATURES OF THE MESSINIAN SALINITY CRISIS

The Messinian salinity crisis induced two kinds of results: immediate events as deposition of (marginal and deep basin) evaporites, and erosion of the shelf and downcutting of deep subaerial canyons, and distant effects ranging from the Gilbert-type fan delta mode of sedimentary filling of the Zanclean rias, to the complete rebuilding of the shelf (Lofi *et al.*, 2003). First, we will recount the main immediate and delayed) signatures of the Messinian salinity crisis within the Mediterranean Basin and the resulting scenario (Clauzon *et al.*, 1996). We will then describe our field observations in the Dacic Basin and discuss if similar or distinct signatures might have existed in the Eastern Paratethys and whether characterize the Messinian salinity crisis in this area.

In the Mediterranean Basin

Evaporites deposited in the Mediterranean abyssal plains (reported only by seismic records) are the first consequence of the desiccation of the Mediterranean Sea (Hsü *et al.*, 1973, 1977, 1978b; Ryan *et al.*, 1973). The idea of an almost complete desiccation of the Mediterranean Sea has been supported by the dismantling of the Messinian margins under a generalized erosional surface (Ryan & Cita, 1978; Gorini *et al.*, 1993) and deep subaerial canyons along the course of rivers (Chumakov, 1973; Clauzon, 1973, 1978, 1979, 1982, 1990) because of the strong drop in sea level. The product of this erosion mostly accumulated in detritic cones at the bottom of canyons (Rizzini *et al.*, 1978; Barber, 1981; Savoye & Piper, 1991; Lofi, 2002). The erosion of the margins and their hinterland, especially by rivers, during the Messinian salinity crisis created large voids that were later occupied by Zanclean waters (the so-called Pliocene rias: Denizot, 1952; Clauzon, 1990) and infilled by Zanclean sediments. Such depositional areas possess two peculiarities from a sedimentary viewpoint: (1) they may exceed 1000 m in thickness (Nile and Rhône rias) that is unusual in a margin and (2) in space, interfluves partitioned the deposition realm so that no lateral export of material could occur from one ria to the next. As a consequence, the Zanclean rias have served as outstanding sediment traps, depriving the basin of terrigenous material (Hsü *et al.*, 1973; Cita *et al.*, 1978a, 1999). The flooding of the Mediterranean Basin by Zanclean marine waters during the global high sea level of cycle TB3.4 (Haq *et al.*, 1987) was sudden as evidenced by the general development of downlap sedimentary constructions, i.e. the absence of any transgressive interval, as observed both within the rias (Clauzon *et al.*, 1995) and in the deep basin (Lofi *et al.*, 2003). Accordingly, the high sea-level prisms are prograding Gilbert-type fan delta constructions (Clauzon, 1990, 1999; Clauzon *et al.*, 1995).

The time interval of the Messinian salinity crisis is now well defined: it started just after the beginning of the Gilbert magnetochron (Chron C3r) (Gautier *et al.*, 1994) and more precisely at 5.96 Ma (Krijgsman *et al.*, 1999a) and ended at 5.33 Ma. (Lourens *et al.*, 1996) in correspondence with isotope stage TG 5 (Shackleton *et al.*, 1995).

A scenario was proposed by Clauzon *et al.* (1996) that reconciles discrepancies between previous models (deep basin–shallow water: Hsü *et al.*, 1973; shallow basin–shallow water: Nesteroff, 1973; deep basin–deep water: Busson, 1990). The so-called 'two-step' model has a new chronology constrained by the oxygen isotope curve of Vidal *et al.* (2002) and tuned to the astronomical time-scale. It is also compatible with the cyclostratigraphy proposed by Krijgsman *et al.* (1999b) for the Italian evaporites (Fig. 2). This scenario includes two evaporitic episodes forced by two sea-level drops separated by a brief sea-level rise corresponding to the Upper Evaporites of Sicily (topped by the Lago Mare Formation which is rich in Paratethyan elements Congeria, ostracods, and dinocysts and the Arenazzolo Formation), and culminating in the nearest isotopic low-^{18}O isotope stage (isotope stage TG 11: Shackleton *et al.*, 1995) (Fig. 2):

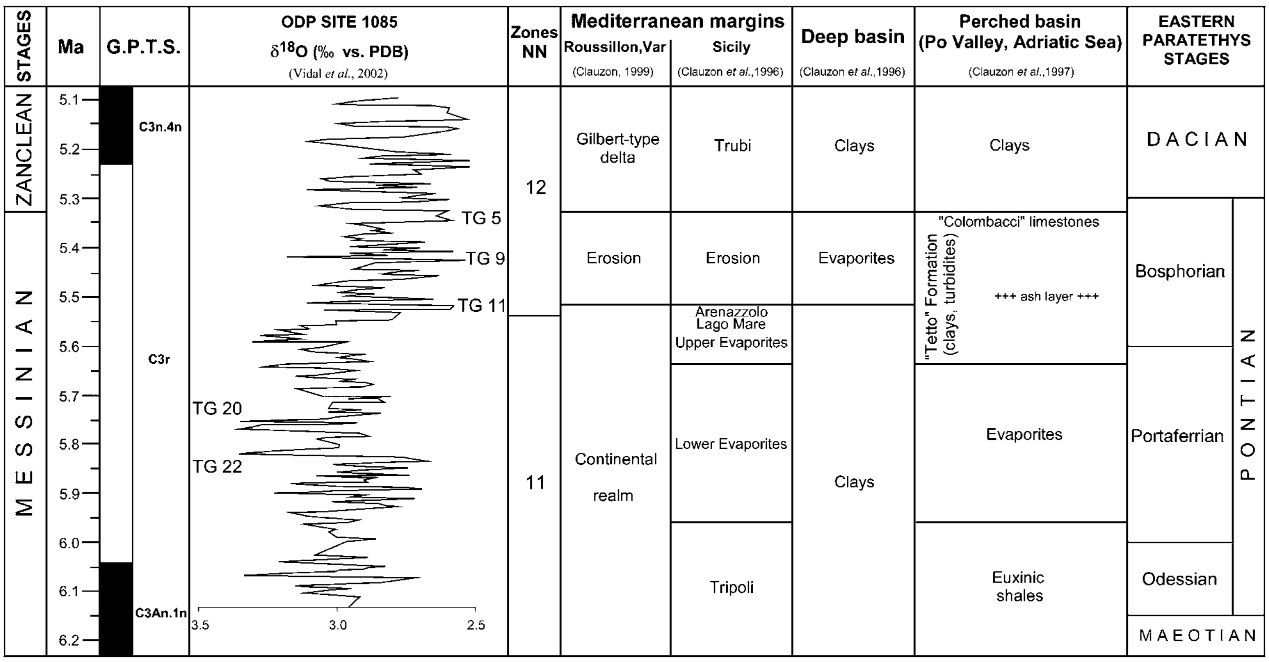

Fig. 2. The two-step scenario for the Messinian salinity crisis (Clauzon *et al.*, 1996) and its various expressions on the margins and in the deep basin. Chronology is based on Vidal *et al.* (2002). Late Miocene–Early Pliocene chronostratigraphic relationships between the Mediterranean Sea and the Dacic Basin revised by Snel *et al.* (in press) are followed in the present work. Age of boundary between nannofossil Zones NN11 and NN12 is from Backman & Raffi (1997).

- the first episode (5.96–5.64 Ma) was a global sea-level drop of moderate amplitude (less than 100 m), including glacial Antarctic isotope stages TG 22 and TG 20 (Shackleton *et al.*, 1995), that precipitated marginal evaporites (Sicily, Sorbas, Po Valley, Tyrrhenian realm) in some more or less isolated basins;
- the second episode (5.52–5.33 Ma) was sea-level drop of very large amplitude (1500–2000 m) that dried up most of the abyssal plains of the Mediterranean Sea, resulting in the deposition of abyssal evaporites and cutting of deep subaerial canyons. Some areas, such as the Po Valley and Adriatic Sea, were not affected by the second sea-level drop, and received persistent and continuous brackish to freshwater sedimentation (Corselli & Grecchi, 1984; Clauzon *et al.*, 1997) (Fig. 2).

This scenario has some basic discrepancies with the models of Rouchy & Saint-Martin (1992), Butler *et al.* (1995), Riding *et al.* (1998) and Krijgsman *et al.* (1999b) that place the Sicilian Upper Evaporites just before the Zanclean flooding. The Sicilian Upper Evaporites (including the Lago Mare and Arenazzolo episodes) are understood by some of these authors as being the transgressive interval before Zanclean flooding (Brolsma, 1976; Butler *et al.*, 1995; Krijgsman *et al.*, 1999b). Such an interpretation is severely contradicted by an absence of any earliest Zanclean transgressive interval within the sedimentary filling of Zanclean rias (Clauzon *et al.*, 1995). New offshore data reinforce the absence of any transgressive interval in the basin during the earliest Pliocene (Lofi *et al.*, 2003). Accordingly, the Sicilian Upper Evaporites (including the Lago Mare and Arenazzolo formations) cannot be considered to onlap the margin at the Messinian/Zanclean transition as considered by Krijgsman *et al.* (1999b). This supports our positioning of the Sicilian Lago Mare at the end of the sea-level rise which tops the first evaporitic phase (Clauzon *et al.*, 1996), i.e. in correspondence with the isotope stage TG 11 according to the adopted chronology (Fig. 2). In some places such as the Rhône Valley, the Barcelona area and the Corsica, a Lago Mare facies undoubtedly belongs to the Zanclean deposits (Rhône Valley: Denizot, 1952; Ballesio, 1972; Barcelona area: Gillet, 1965; Almera, 1894; Corsica: Pilot *et al.*, 1975; Magné *et al.*, 1977), i.e. to isotope stage TG 5 or later.

In the Eastern Paratethys: Dacic and Euxinian Basins

Seismic profiles (Letouzey *et al.*, 1978) and results from three cored boreholes (Sites 379, 380, 381; Fig. 1a) during DSDP Leg 42B (Ross *et al.*, 1978) suggested that the two main signatures of the Messinian salinity crisis in the Mediterranean exist also in the Black Sea: namely, evaporite deposition in the abyssal plain and a erosional surface on the margin (Hsü & Giovanoli, 1979). At Site 380A (cored in the deep basin), a coarse clastic pebbly breccia (19-m thick) was recovered between 864.5- and 883.5-m depth. It includes blocks of a stromatolitic dolomite considered to have formed in an intertidal to supratidal environment (Stoffers & Müller, 1978). This suggests that the level of the Black Sea was very shallow at that time, in agreement with data from diatoms (less than 50-m water depth) (Schrader, 1978). According to Schrader (1978: p. 856), the comparable horizon at the nearby Site 381, which was cored in a more marginal position 'contains only a few scattered freshwater assemblages, and lies approximately 900 m above the one at Site 380A'. Hsü & Giovanoli (1979) have interpreted these data as evidence of the drop in level of the Black Sea to 1600 m below global sea level in asociation with the Messinian salinity crisis in the Mediterranean. Such an interpretation was also supported by the record of a seismic reflector (reflector 'S') showing that the pebbly breccia is related to a deltaic system, speculatively a Messinian erosional surface in the Black Sea (Letouzey *et al.*, 1978). Such an interpretation is supported by a recent high-resolution pollen study at Site 380A where the lowermost Zanclean age of the aragonite overlying the pebbly breccia is demonstrated according to a global climatostratigraphic approach (Popescu, in press). All the major and secondary climatic variations of the early Zanclean have been recorded at Site 380 and exhibit the same range in intensity as in other European regions regardless of latitude or longitude. In addition, this study confirms the coastal status of the uppermost laminated carbonates underlying the pebbly breccia. Gillet (2004) has evidenced a clear erosional surface below Pliocene and Pleistocene deposits in several seismic profiles of the western Black Sea, especially from Site 380 up to Site 381. This strikingly confirms the previous assumptions of Letouzey *et al.* (1978).

NEW DATA FROM THE WESTERN DACIC BASIN

In order to validate these offshore data on land, the erosional signature of the Messinian salinity crisis was searched in the Dacic Basin along the Danube River that is expected to have offered the same response as the other large rivers (Rhône, Nile). Accordingly, we developed our investigation at the outlet of the Iron Gates (Figs 1 and 3) in the Turnu Severin area. Here, the Danube River has cut a gorge through the Carpathians (Figs 3b and c), the context of which is physiographically similar to Zanclean Gilbert-type fan delta constructions evidenced in the northwestern Mediterranean region, and demonstrates the Messinian age to the underlying erosional surface (Clauzon, 1999).

Evidence of a prominent Danube erosional surface at the outlet of the Iron Gates

At Gura Văii (Figs 1b and 3), a strong erosional surface that we refer to the Messinian salinity crisis cuts Jurassic

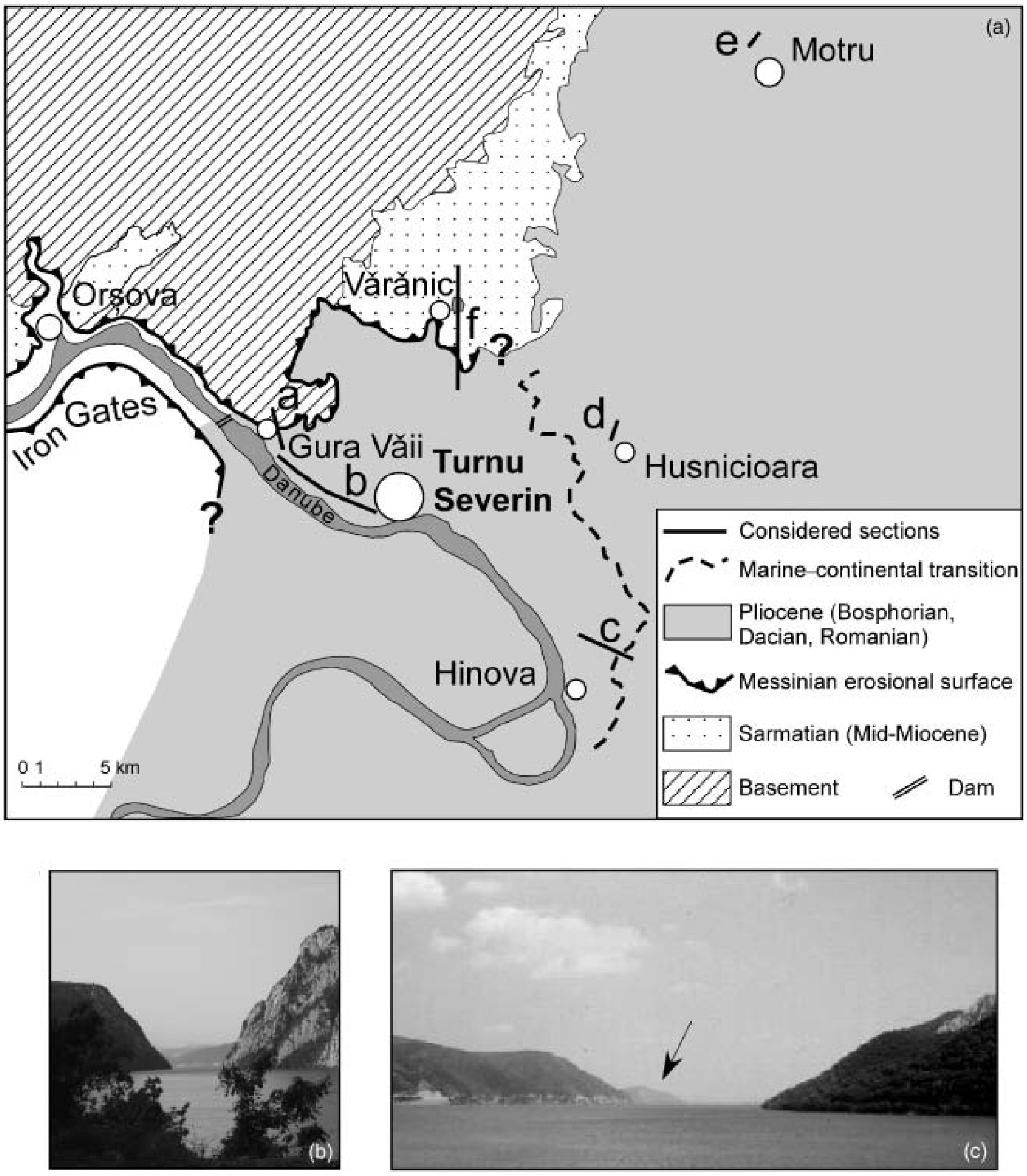

Fig. 3. The Zanclean Gilbert-type fan delta of Turnu Severin. (a) Simplified geological map of the Romanian part of the Iron Gates area. Considered sections: a, Gura Văii; b, Turnu Severin; c, Hinova; d, Husnicioara; e, Motru (Lupoaia section); f, Vărănic. Basement comprises Jurassic limestones and metamorphic rocks. (b) The Iron Gates 15-km upstream from Orşova. (c) Outlet of the Iron Gates 5-km downstream from Orşova, with the residual Zanclean deposits (indicated by the arrow).

limestones and is overlain by lateral Zanclean foreset beds (Fig. 4). This erosional surface belongs to a past tributary of the Danube River on its left side. The axial erosional surface cannot be observed but is almost parallel to the Danube' modern thalweg according to geological information given in the Exhibition Hall of the Iron Gates 1 Dam. The dam was built on the Carpathian basement which reached 35 m in altitude. Wells have penetrated conglomerates just in front of the foreset beds. It is deduced that the present-day thalweg, which is less steep than the former one, intersects the erosional surface downstream from the dam. The erosional surface was mapped in this area but is not exposed downstream (Fig. 3a).

The units of the Pliocene Gilbert-type fan delta of Turnu Severin

At the outlet of the Iron Gates (Figs 1b and 3), the Danube River cuts thick conglomerates, dipping 20° eastward on average, that have been erroneously considered as Middle-Late Miocene in age ('Tortonian–Sarmatian': Savu & Ghenea, 1967; Nastaseanu & Bercia, 1968) because of their likeness to a detrital tilted formation overlying Badenian clays 25 km northward (Marinescu, 1978). The Turnu Severin clastic exposure begins close the village of Gura Văii, immediately donwstream from the Iron Gates 1 Dam, and is only exposed along the left side of the Danube Valley and valleys of its northern tributaries (Fig. 3).

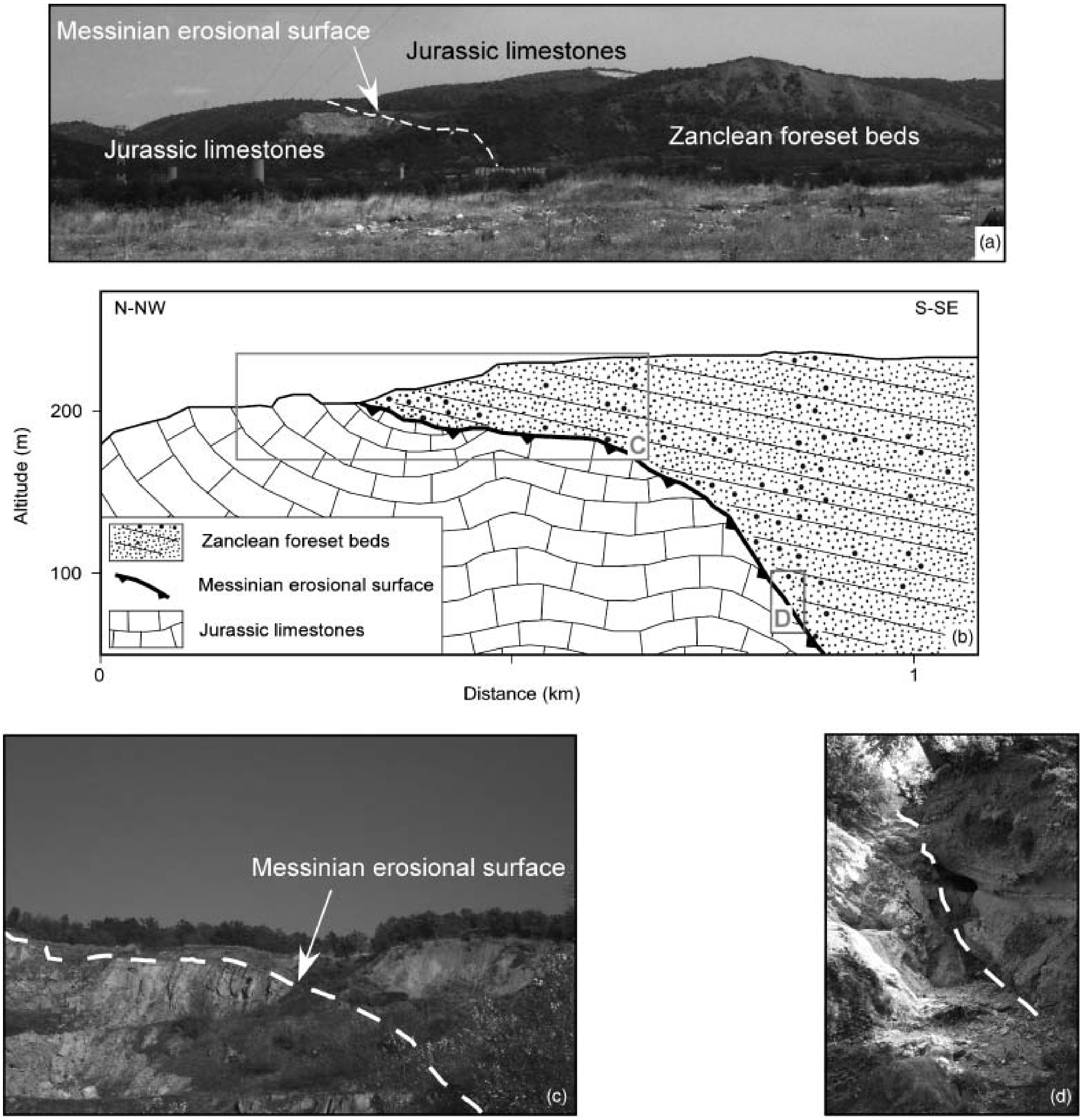

Fig. 4. The Messinian erosional surface and the foreset beds of the Zanclean Gilbert-type fan delta of Turnu Severin at Gura Văii. (a) General view of the area. (b) Cross section at Gura Văii (section 'a' on Figs 1b and 3a). (c) Detail of box C from Fig. 4b (dotted white line: the Messinian erosional surface). (d). Detail of box D from Fig. 4b (dotted white line: the Messinian erosional surface).

These thick conglomerates constitute the foreset beds of a very large Gilbert-type fan delta, and are exposed for more than 20 km. Extending from Gura Văii to the western suburbs of Turnu Severin, they comprise pebbles within a sandy, unevenly cemented matrix (Figs 5a–c, e); and further along the section they become more or less indurated white sands including some conglomeratic channels (Figs 5d and f). They contain rare molluscs.

The silty bottomset beds outcrop upstream from Hinova where they are overlain by sandy foreset beds (Figs 6a–c) containing a thin layer from which several molluscs have allowed assignment to the Bosphorian regional substage (Marinescu, 1978) (Table 1). This same layer, and two layers that overlie it have provided us with assemblages of nannofossils and dinocysts (Table 1). In the absence of *Discoaster quinqueramus*, nannofossils are considered as belonging to Zone NN12 which spans the Miocene/Pliocene boundary (Fig. 2; Berggren *et al*., 1995a, b; Backman & Raffi, 1997). Nevertheless, they reveal an intense Mediterranean sea-level rise and crossing off the sill separating the Mediterranean from the Eastern Paratethys, and illustrate the Zanclean deluge into this Mediterranean appendage. In the Mediterranean, two remarkable successive changes in sea-level occurred within this brief time-window: the

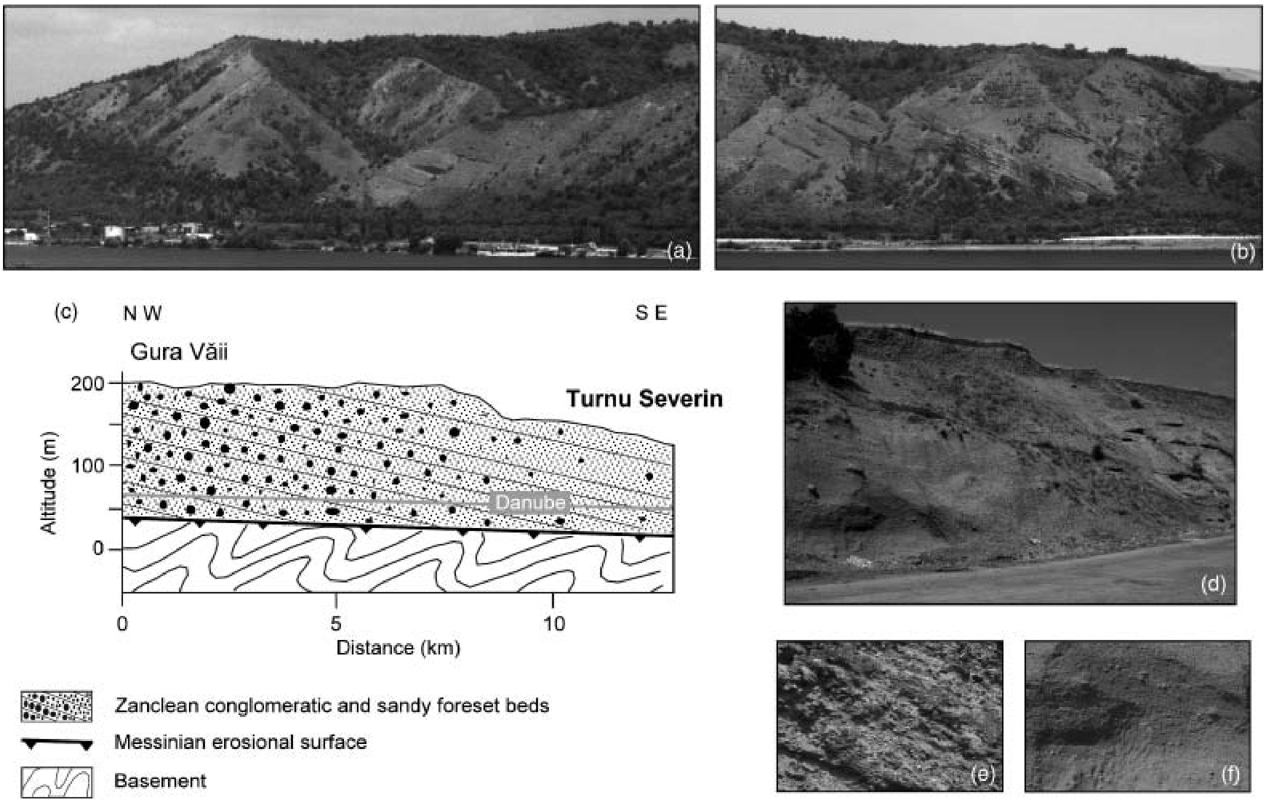

Fig. 5. Foreset beds of the Zanclean Gilbert-type fan delta between Gura Văii and Turnu Severin. (a) Conglomeratic foreset beds at Gura Văii. (b) Conglomeratic foreset beds between Gura Văii and Turnu Severin. (c) Cross section between Gura Văii and Turnu Severin (section 'b' on Figs 1b and 3a). (d) Sandy foreset beds at Turnu Severin (back the swimming pool). (e). Detail of the conglomeratic foreset beds. (f) Detail of the sandy foreset beds.

Messinian draw down and the Zanclean deluge. As a consequence, bottomset beds of the Turnu Severin Gilbert-type fan delta inevitably date the underlying erosional surface of the Messinian salinity crisis. We found at Hinova the same dinocysts as those we found at Cernat Valley in the area of Ploiesti where NN12 nannofossils occur (Snel *et al.*, in press). These floras are characterized by endemic Paratethyan species (Sütöné Szentai, 1989), but also include many typical Mediterranean elements (Table 1).

The top of the overlying sandy foreset beds is marked by (1) an angular discordance (15–20°) at the base of subhorizontal topset beds and (2) a thin lignite layer (Fig. 6d) which probably corresponds to lignite A of Ţicleanu & Diaconiţa (1997). This marks the marine/continental transition that takes place at a present altitude of 220 m. Another lignite (lignite B of Ţicleanu & Diaconiţa (1997) is exposed just above (Fig. 6e). Both clays of the bottomset beds and those clays overlying lignite B are reversely magnetized and belong to Chron C3r (Popescu *et al.*, in press) (Fig. 6c).

Above this submarine deltaic wedge, the topset beds have a total thickness of about 200 m, and comprise alternating sands (with conglomeratic channels) and lignites (20 layers of unequal thickness, including lignites A and B), some of which are intensively worked particularly in the Husnicioara and Motru areas (Ţicleanu & Diaconiţa, 1997; Fig. 3a). At Husnicioara (Fig. 7), lignites I, IV and V of the regional nomenclature are overlain by thick (42 m) fluvial sands indicating the strong, continuous influence of the Danube River. The section shows lignites XIII to XV at its top. Palaeomagnetic measurements have been done (Fig. 7a), and the oldest normal event is related to Chron C3n.4n (Popescu *et al.*, in press), with the others to be interpreted later. In the Motru area, the Lupoaia quarry shows a continuous, 137-m thick, succession of lignites, extending from lignite V to lignite XIII (Fig. 8), alternating with clays and some fluvial sands. This section, which represents the almost complete continental accretion in the Carpathian foreland, is Zanclean in age based on the remains of small and large mammals (Fig. 8). Therefore, palaeomagnetic reversals complemented by pollen records (reliably correlated to climatic cycles forced by eccentricity) indicate that the section starts at Chron C3n.3n and includes Chron C3n.2n (Popescu, 2001; Popescu *et al.*, in press). As a consequence, the normal episode recorded at Husnicioara between lignites XIV and XV is Chron C3n.1n (Popescu *et al.*, in press). The high-resolution pollen records evidence the forcing of eccentricity (100-kyr cycles) for the lignite–clay alternations (Popescu, 2001; Popescu *et al.*, in press). According to plant remains (leaves, fruits, pollen grains), the vegetation of the area resembled the modern vegetation of Florida and the Mississippi Delta (Ţicleanu & Diaconiţa, 1997; Popescu, 2001).

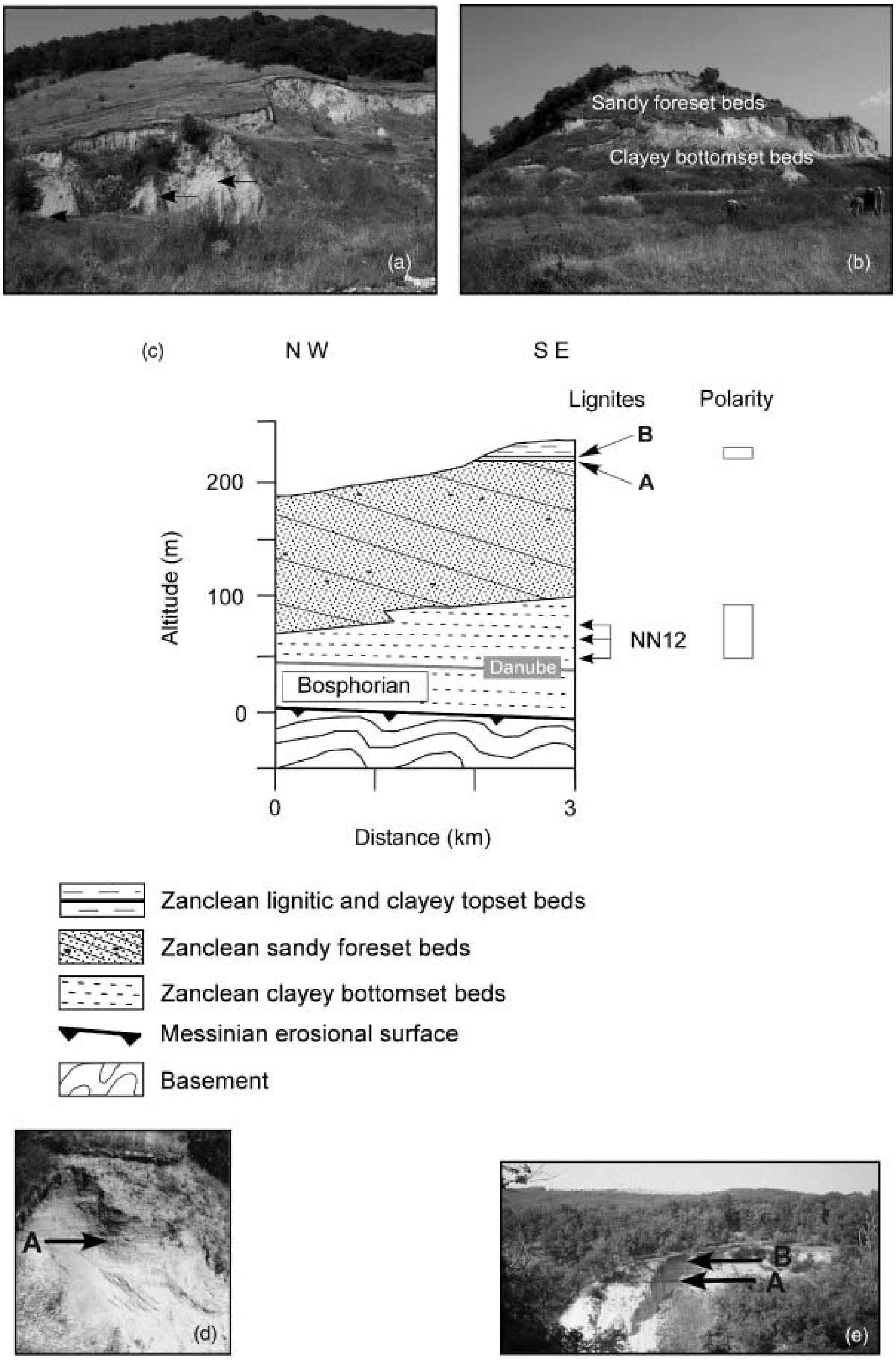

Fig. 6. Distal part of the Zanclean Gilbert-type fan delta of Turnu Severin in the area of Hinova. (a) Clayey bottomset beds (the arrows indicate the levels with Mediterranean nannofossils assigned to Zone NN12). (b) Clayey bottomset beds overlain by sandy foreset beds. (c) Cross section at Hinova (section 'c' on Figs 1b and 3a). (d) Detail of the marine-continental transition (the arrow indicates lignite A). (e) Overlying deposits with the marine-continental transition (i.e. the topset beds overlying the foreset beds; the arrows indicate lignite A corresponding to this transition, and lignite B).

Upstream and to the west of Turnu Severin, material becomes coarser and the continental prism is less than 100-m thick because of Late Pliocene and Pleistocene erosion.

The prism is topped with a conglomeratic abandonment surface marked by some residual siliceous pebbles (Fig. 9a), as can be observed on a topographic bench at 433-m altitude at Vărănic (Fig. 9d) developed on a lapiaz morphology (Fig. 9b). Karstic Jurassic and/or Sarmatian limestones have probably been overlain by the final continental deposits of the Gilbert-type fan delta construction (Fig. 9c). These deposits aggradated up to the beginning of the Plio-Pleistocene cutting which was probably forced

Table 1. Fossil content of the bottomset beds of the Turnu Severin Gilbert-type fan delta at Hinova

Paratethyan molluscs	Mediterranean nannofossils	Paratethyan dinocysts
Limnocardium emarginatum	*Reticulofenestra minuta*	*Galeacysta etrusca*
L. petersi	*R. pseudoumbilicus*	*Spiniferites cruciformis*
Plagiodacna auingeri	*R. minutula*	*Tectatodinium psilatum*
Dreissena rostriformis group	*R. doronicoides*	Mediterranean dinocysts
Dreissenoyma aperta	*Sphenolithus abies*	*Achomosphaera andalousiensis*
Phyllocardium planum planum	*Calcidiscus leptoporus*	*Operculodinium centrocarpum*
	Amaurolithus primus	*Impagidinium patulum (?)*
	A. amplificus	*Spiniferites bentori*
	Coccolithus pelagicus	*S. elongatus*
	Helicosphaera kamptneri	*S. hyperacanthus*
		S. ramosus
		Nematosphaeropsis labyrinthus
		Tectatodinium pellitum

mostly by the earliest Northern Hemisphere glaciations starting at 2.6 Ma. Indeed, the surface is dated at about 2.2 Ma according to the Slatina mammal faunas which are augmented by magnetostratigraphy (Rădulescu *et al.*, 1997). Such erosion explains the karstic evolution and preservation of siliceous remnants only (Fig. 9a).

The Turnu Severin Zanclean Gilbert-type fan delta compared with the Mediterranean Pliocene Gilbert-type fan deltas

It should be recalled that the only relatively brief and intense drop – rise succession in sea level of profound importance during the Late Miocene–earliest Pliocene interval corresponds to the Messinian salinity crisis followed by the Zanclean deluge (Fig. 2). This assumption is additionally supported strongly by all the chronological data obtained from the topset beds of the Gilbert-type fan delta; namely mammals, magnetostratigraphy and climate fluctuations via pollen records.

The evolution of this Gilbert-type fan delta extending over more than 3 Myrs (from 5.33 to *ca*. 2.10 Ma) is summarized in Fig. 10. This construction, exceeding 400 m in thickness, is strikingly similar to the Western Mediterranean deltas that characterized the Pliocene reflooding after the Messinian desiccation. For example, they are nested within all the earlier Miocene deposits, they rest on an erosional surface (the pronounced fluvial Messinian canyons related to the desiccation phase), and they have clayey bottomset beds of earliest Zanclean age (Zone NN12, Zone MPl1) (Clauzon, 1996). They unanimously show three characteristic well-expressed surfaces: the Messinian erosional surface (at 5.33 Ma), the diachronous marine–nonmarine transition (because of its prograding genesis) very often expressed by a lignite, and the isochronous abandonment surface expressed everywhere a little earlier than 2 Ma (probably caused by the earliest glacials in the Northern Hemisphere). Such similarities have never been reported outside of the Mediterranean context except in the Dacic Basin. The Dacic Basin Gilbert-type fan delta differs from the Mediterranean Gilbert-type fan deltas in its number of lignite layers probably owing to the generally humid feature of the region.

It is demonstrated that the Danube River existed a long time before the Pleistocene. Indeed, such an impressive Gilbert-type fan delta system could not be built without the presence of a powerful river. The first appearance of the modern hydrographic network in southern Romania has generally been placed within the Late Pliocene–Early Pleistocene (Jipa, 1997). Our results lower this event to Late Miocene.

Regional extension of the Messinian erosional surface in the Dacic Basin

Exposed sections, such as Valea Vacii and Călugăreni (Ploieşti area; Fig. 11), and Badislava (Rîmnicu Vîlcea area; Fig. 11), exhibit continuous sedimentation during the Late Miocene and Early Pliocene (Marinescu *et al.*, 1981), as inferred from nannofossil analyses (Mărunţeanu & Papaianopol, 1998) and palaeomagnetic measurements (Snel *et al.*, in press). Subsurface data are consistent with these field observations, with many wells revealing a complete Late Miocene sedimentation (C. Dinu, personal information; Fig. 11). In contrast, some other wells, mostly from the western and southern Carpathian foredeep, are characterized by a hiatus below the Pontian (generally thin) and the Dacian (often easily recognizable because of the presence of lignites). These deposits directly overlie Sarmatian (with the entire Maeotian missing) or older layers such as Oligocene or Cretaceous (Fig. 11). This break in sedimentary record might illustrate an erosional gap because of the 'proto-Danube' and its tributaries. Fig. 11 provides an overview of the two palaeogeographically contrasted areas in the Carpathian foreland during the Messinian salinity crisis: (1) an erosional zone resulting from the palaeo-fluvial network and (2) a continuous sedimentary zone within a perched 'palaeo-lake'. Clarifying the exact expanse of these areas eastward and southward requires examination of additional boreholes.

  Basin Research, doi: 10.1111/j.1365-2117.2005.00269.x

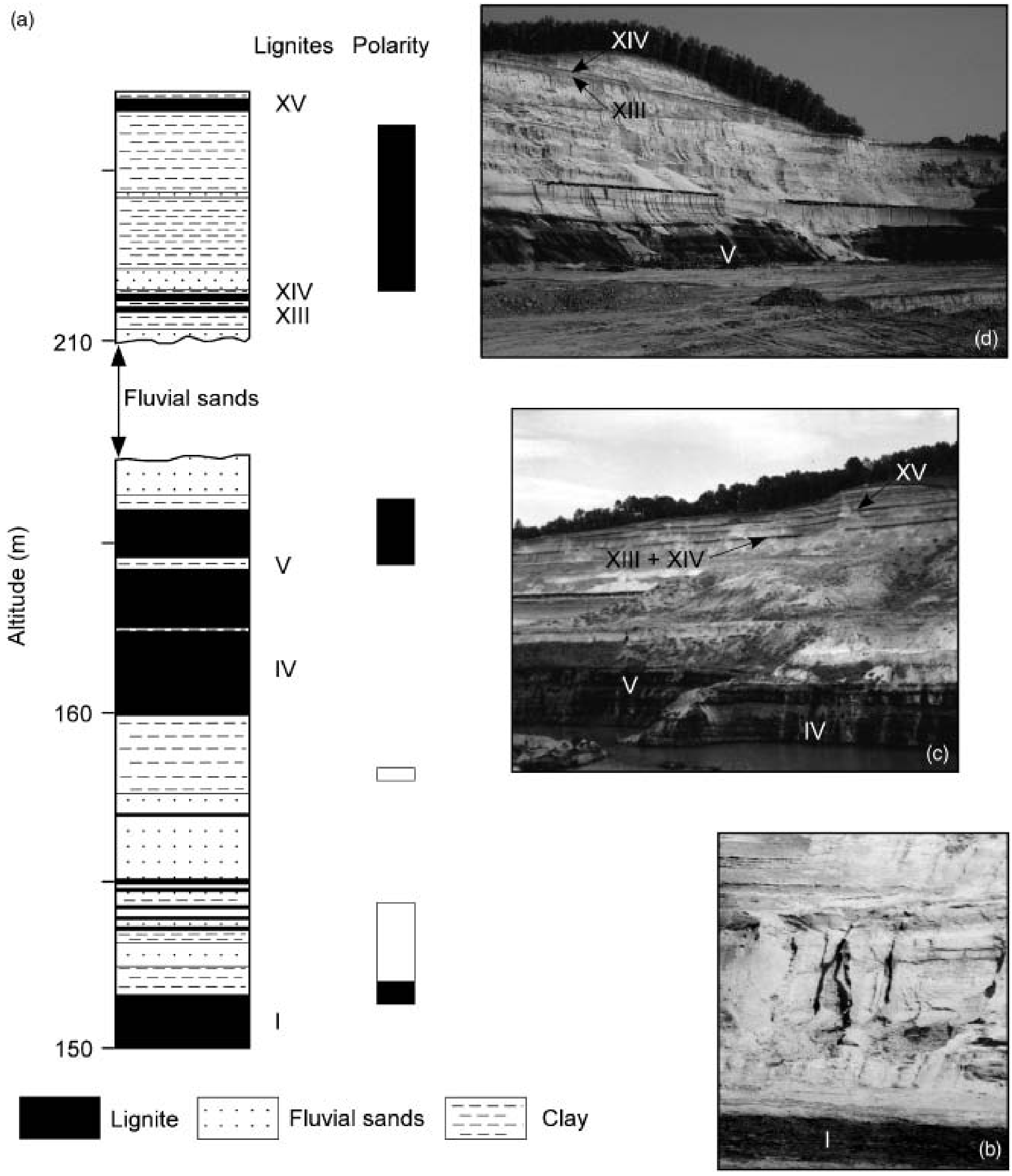

Fig. 7. Vertical section of the Husnicioara quarry (section 'd' on Figs 1b and 3a). (a) Lithological succession and palaeomagnetic polarity. Forty-four metres of fluvial sands represent the time-interval between lignites V and XIII (i.e. about 500 kyr from *ca*. 4.800 to *ca*. 4.300 Ma) during which the Danube flood plain aggradated in the area. (b) Lignite I and of overlying clays. (c) From lignite IV to lignite XV. (d) From lignite V to lignite XIV.

A NEW IDEA ON MEDITERRANEAN–PARATETHYS LATE NEOGENE RELATIONSHIPS

Discoveries of repeated Mediterranean nannoplankton influxes into Paratethys have considerably changed the concept of Mediterranean–Paratethys isolation since the Sarmatian. These influxes occurred (1) from earliest Sarmatian up to Romanian (Dacic Basin: Mărunţeanu, 1992; Papaianopol & Mărunţeanu, 1993; Mărunţeanu & Papaianopol, 1995; Mărunţeanu & Papaianopol, 1998; Drivaliari *et al*., 1999; Snel *et al*., in press) and (2) from Maeotian to Kimmerian (regional stage following Pontian) in the Ponto-Caspian Basin (Semenenko & Lyuljeva, 1978; Semenenko *et al*., 1995; Semenenko & Olejnik, 1995) (where Mediterranean dinocysts were also found: Semenenko & Olejnik, 1995). It has been proposed that there were many brief incursions of Mediterranean waters into the brackish-freshwaters of the Paratethys, and that 'many species (nannoplankton) died immediately, marking exactly the moment of the connections' (Mărunţeanu & Papaianopol, 1998, p. 121). Such influxes were necessarily forced by high sea levels in the Mediterranean Sea because coccolithophores and many dinoflagellates live within the photic zone of surface waters (Sarjeant, 1974; Winter *et al*., 1994).

As a consequence, based on two successive records of Mediterranean nannofossils (and dinocysts) in the Eastern Paratethys, we consider the possibility that an inflow of

 Basin Research, doi: 10.1111/j.1365-2117.2005.00269.x

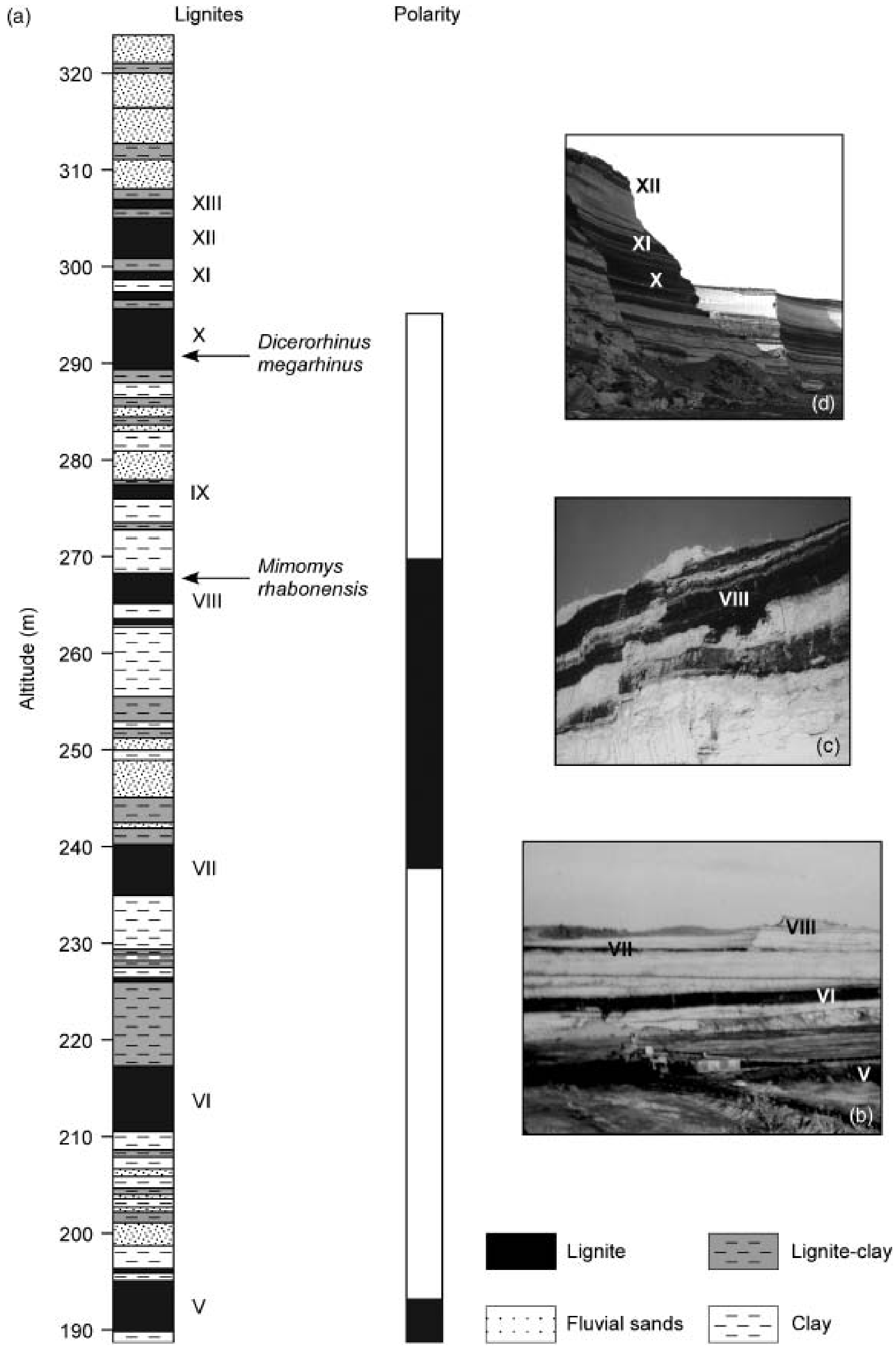

Fig. 8. Vertical section of the Lupoaia quarry (section 'e' on Figs 1b and 3a). (a) Lithological succession and palaeomagnetic polarity from lignite V to lignite XIII and the overlying clays and sands, with indication of the mammal remains. (b) Southern part of the quarry where sediments run from lignite V to lignite VIII. (c) The threee layers of lignite VIII. (d) Northern part of the quarry where worked lignites X to XII are located.

Paratethyan waters reached the Mediterranean realm not just once (Hsü *et al*., 1973) but that two influxes may have occurred via surface currents. The first influx, corresponding to Zone NN11, occurs before a strong erosional surface in the Eastern Paratethys, and just before the deep basin evaporite deposition in the Mediterranean (isotope stage TG 11). The second influx, corresponding to Zone NN12, occurs just above this erosional surface in the Eastern Paratethys (see also Semenenko, 1995; Gillet *et al*., 2003) and corresponds to the earliest Zanclean in the Mediterranean (starting at isotope stage TG 5) (Fig. 12).

Mediterranean water influxes into Paratethys during the Late Miocene – Early Pliocene

Two influxes of Mediterranean nannoplankton and dinocysts occurred (Mărunţeanu & Papaianopol, 1998; Snel *et al*., in press). The Late Portaferrian–Borphorian influx

© 2005 Blackwell Publishing Ltd, *Basin Research*, doi: 10.1111/j.1365-2117.2005.00269.x

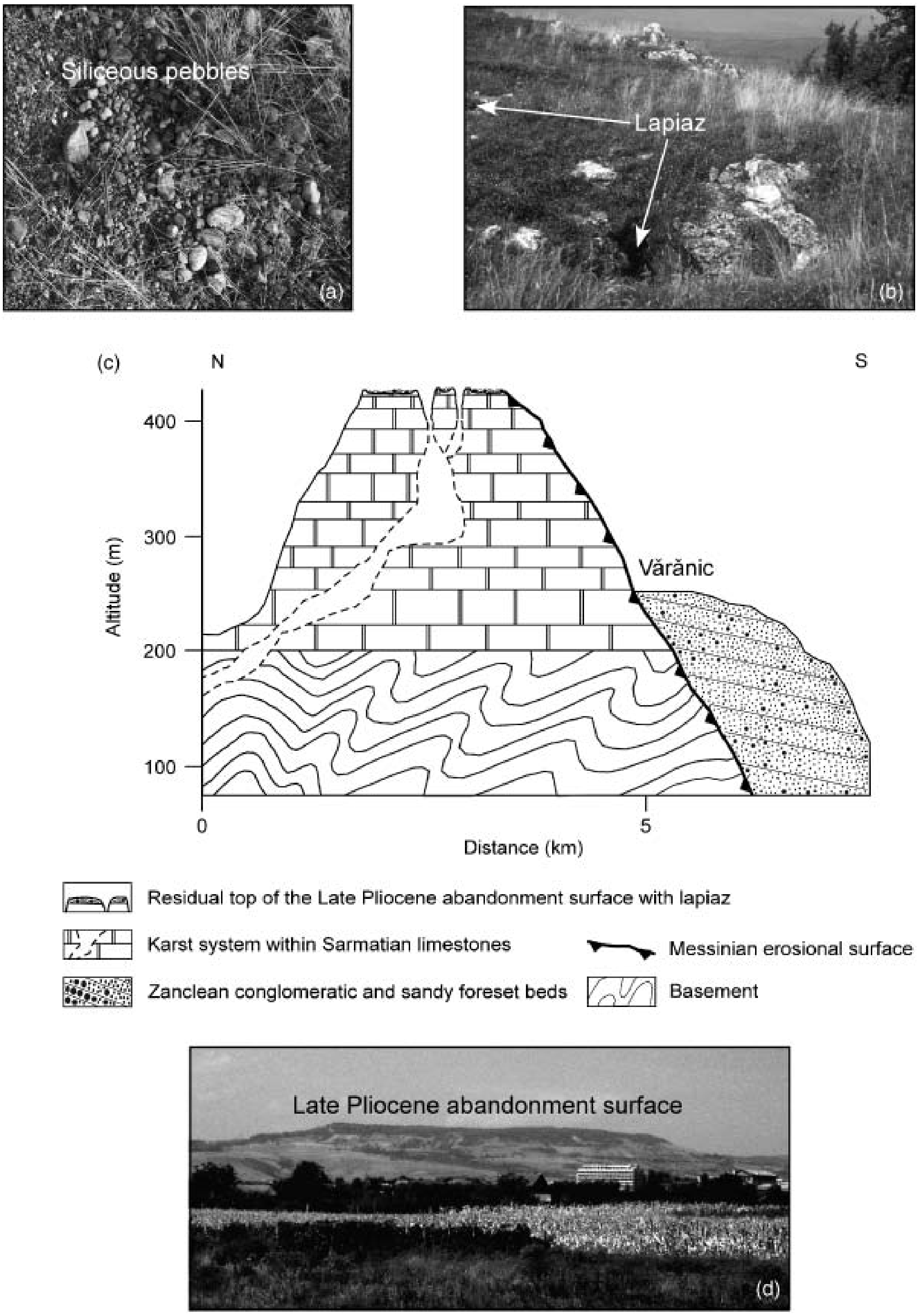

Fig. 9. Residual Late Pliocene abandonment surface near Vărănic. (a) Residual siliceous pebbles at altitude 424 m. (b) Lapiaz at altitude 424 m. (c) Cross section near Vărănic (section 'f' on Figs 1b and 3a) showing the residual top of the Late Pliocene abandonment surface characterized by remnant siliceous pebbles and lapiaz, the karst system through the Samatian limestones and the basement. The conglomeratic and sandy foreset beds of the Turnu Severin Gilbert-type fan delta are separated from the Sarmatian limestones and basement by the Messinian erosional surface. (d) W–E oriented view of the flat morphology of the Late Pliocene residual abandonment surface.

has been recorded at Valea Vacii, Călugăreni and Badislava (Fig. 11), and belongs to Zone NN11. The Bosphorian influx has been recorded at Valea Vacii, Călugăreni, Doiceşti, Hinova (Fig. 11) and Argova Valley (SE Bucharest, well 68913/67), and belongs to Zone NN12. In contrast to other localities, the nannoplankton (NN12) and dinocyst influx at Hinova overlies an important erosional surface considered to belong to the Messinian salinity crisis. The nannoplankton (NN12) influx recorded at Ţicleni overlies a gap within Late Pontian deposits (Drivaliari *et al*., 1999). We therefore conclude that these two successive influxes correspond to two successive high Mediterranean sea levels occurring immediately before and after the Messinian salinity crisis, i.e. to isotope stages TG 11 and TG 5 (Fig. 12) which are referred to high global sea levels (Vidal *et al*., 2002; Warny *et al*., 2003).

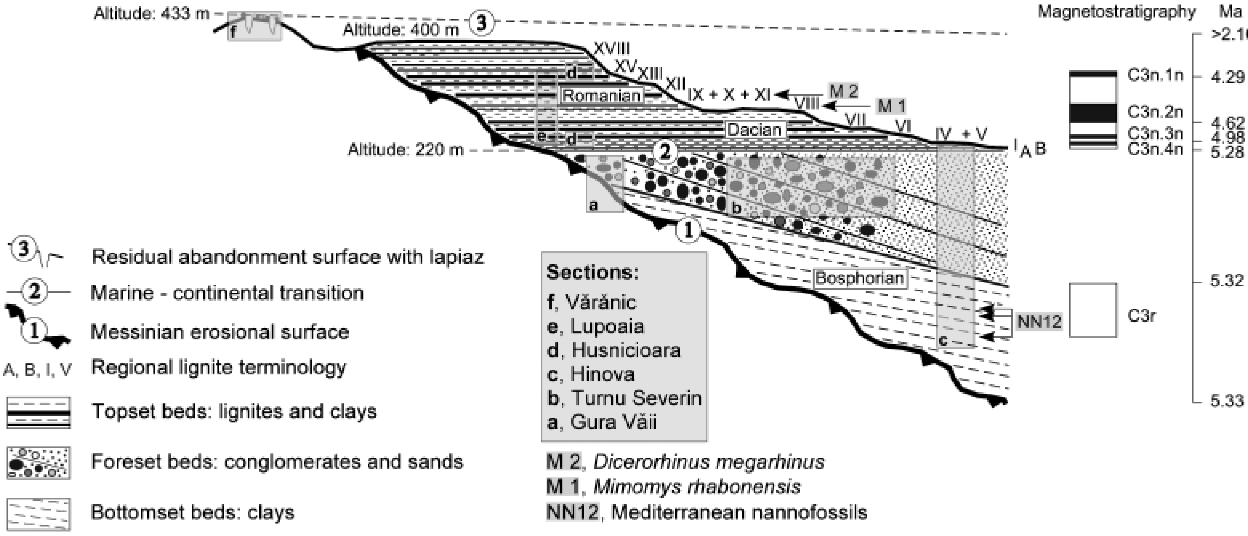

Fig. 10. Location of studied sections 'a'–'f' of the Zanclean Gilbert-type fan delta of Turnu Severin with respect to the structure of a Gilbert-type fan delta as found in the Mediterranean (Clauzon, 1990, 1999; Clauzon *et al.*, 1995) and to the chronology of this exceptionally exposed sedimentary body based on bio- and magnetostratigraphy. Complete details on bio- and chronostratigraphic assignements are given by Popescu (2001) and Popescu *et al.* (in press).

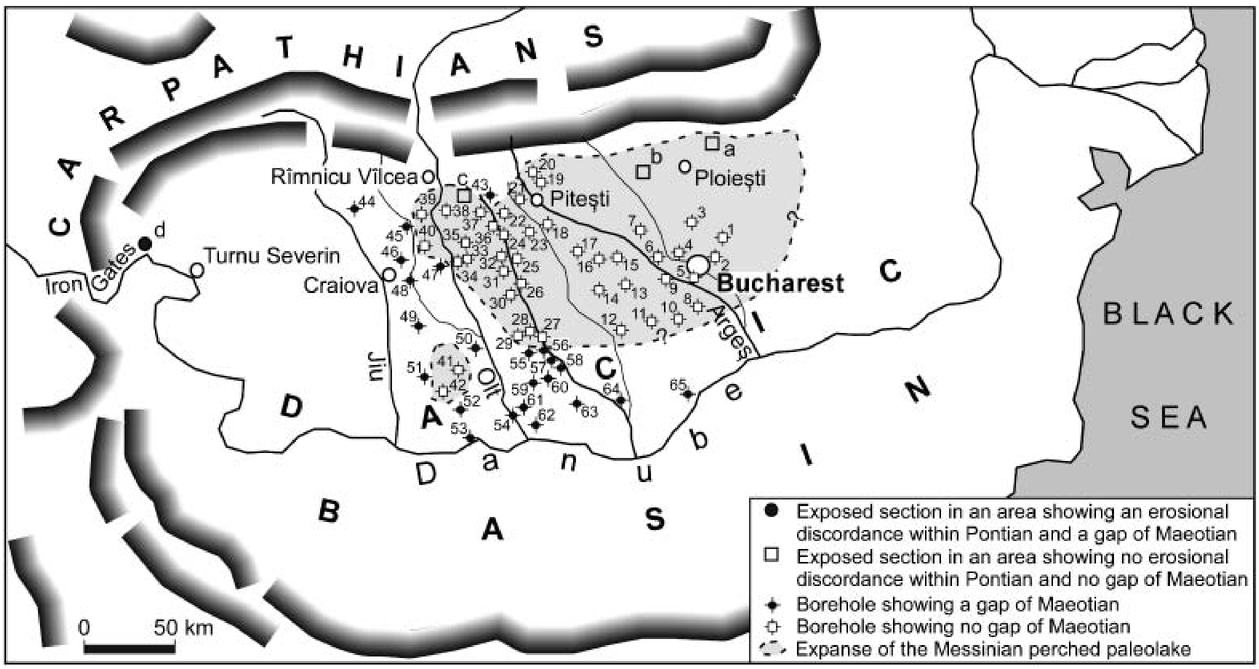

Fig. 11. Considered localities in the Dacic Basin. Exposed sections: a, Valea Vacii; b, Călugăreni; c, Badislava; d, Gura Văii. Boreholes: 1, Moara Vlăsiei; 2, Afumaţi; 3, Periş 909; 4, Flămanzeni 185; 5, Dumitrana 1483; 6, Potlogi 146; 7, Titu 1690; 8, Singureni 315; 9, Bălaria 590; 10, Ghimpaţi 2; 11, Videle 96; 12, Orbeasca 255; 13, Ciuperneci 400; 14, Ciolaneşti 155; 15, Petreşti 1600; 16, Visina 165; 17, Dumbrăveni 166; 18, Humele Buzoeşti 2046; 19, Coseşti 3275; 20, Mălureni 3300; 21, Gieşti-Pădureţi 75; 22, Spineri 4 and 5030; 23, Gocieşti 41; 24, Tatuleşti 5036; 25, Corbu 3; 26, Bîrla 70; 27, Văleni 7; 28, Boianu 48; 29, Boianu 45; 30, Ciureşti 67; 31, Priseaca 3026; 32, Mogoşeşti 921; 33, Priseaca 2222; 34, Brebeni 28; 35, Optaşi-Măgura 2; 36, Oporelu 3303; 37, Negreni 3014; 38, Priseaca 3025; 39, Doba 26; 40, Izvoru 39; 41, Caracal 2; 42, Dobroteşti 10; 43, Cotmeana 3205; 44, Ţicleni; 45, Monrunglav; 46, GerceŢşti 116; 47, Piatra Olt 101; 48, Malu; 49, Leu 105; 50, Caracal 490; 51, Mîrşani 31; 52, Caracal 499; 53, Caracal 433; 54, Giuvărăşti 16; 55, Stoicăneşti 43; 56, Stoicăneşti 44; 57, Bocăleşti 104; 58, Cârligaţi 2; 59, Plăviceni 8; 60, Plăviceni 44; 61, Lita; 62, Turnu Măргurele; 63, Puţineiu 3; 64, Alexandria; 65, Giurgiu.

Mediterranean nannoplankton influxes into the Central Paratethys are not restricted events because they are also recorded in the Azov Sea region, close to Kerc. Here, they correspond to an interval restricted to Zones NN11 and NN12 and are located in deposits of latest Pontian – earliest Kimmerian age (i.e. almost reaching the earliest Pliocene) (Semenenko & Lyuljeva, 1978; Semenenko & Pevzner, 1979; Semenenko & Olejnik, 1995). The influxes are sepa-

  Basin Research, doi: 10.1111/j.1365-2117.2005.00269.x

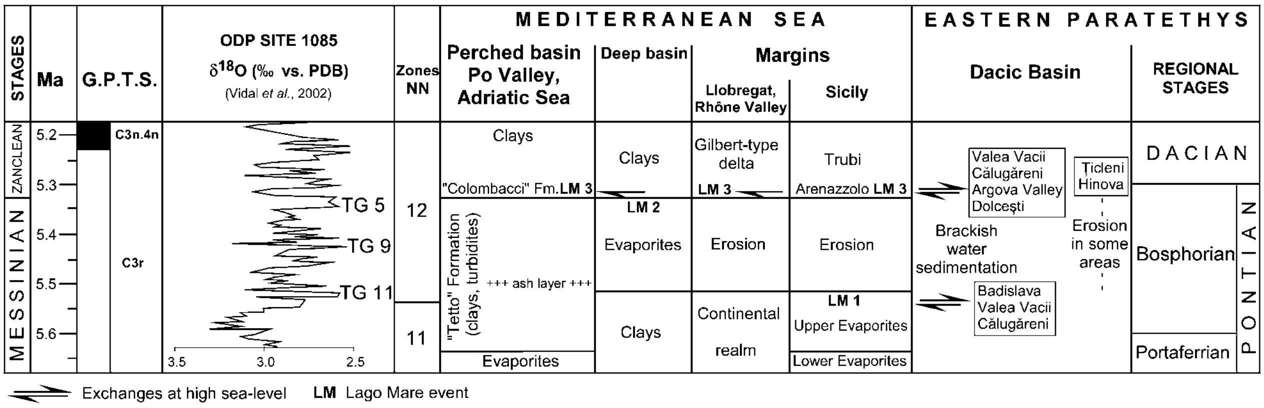

Fig. 12. Proposed evolution of selected basins in the Mediterranean Sea and the Eastern Paratethys during the late Messinian–early Zanclean. Chronological location of the three proposed Lago Mare events. Age of boundary between nannofossil Zones NN11 and NN12 is from Backman & Raffi (1997).

rated by a gap in the deposits that Semenenko (1995) considered as being because of widespread erosion in the northwstern Black Sea, recently confirmed by Gillet *et al.* (2003).

Paratethyan water influxes into the Mediterranean (latest Messinian–earliest Zanclean)

Two Lago Mare events can be distinguished in the Mediterranean realm, the first event occurs at the top of the Sicilian Upper Evaporites (i.e. at the end of the evaporitic phase on the Mediterranean margins; Clauzon *et al.*, 1996), and the second occurs at the beginning of the Zanclean flooding. We relate them to the two successive high Mediterranean sea levels (TG 11 and TG 5) which allowed exchanges of surface waters between the Mediterranean Sea and Paratethys, as supported by the presence of Paratethyan dinocysts (*Galecysta etrusca* for example) in the two successive Lago Mare events (Fig. 12).

We present a review of many selected Lago Mare Formation localities in the Mediterranean (Fig. 13), taking mainly into account Paratethyan mollusc, ostracod and dinocyst occurrences (Table 2). In this review, deep basinal localities (containing only ostracods) are distinguished from marginal ones, which are in turn subdivided into two categories according to the chronological assignment that we propose (late Messinian or earliest Zanclean).

The Messinian localities generally overlie marginal evaporites (*sensu* Clauzon *et al.*, 1996) and/or are overlain by the Messinian erosional surface; in some places, a nannofossil age (NN11) is known (Pasquasia: Cita *et al.*, 1973; Corfou: Vismara Schilling *et al.*, 1976). The calcareous nannofossil assemblages suggest an NN11 age for the Lago Mare Formation and an NN12 age for the Arenazzolo Formation, based on to the disappearance of *Discoaster quinqueramus* between them at Capo Rossello (Cita & Gartner, 1973) and Eraclea Minoa (Bizon *et al.*, 1978; A. Di Stefano, personal information) (Fig. 13). These two formations are separated by the Messinian erosional surface, most conspicuously expressed westward where the uppermost 5 m of the Lago Mare Formation are missing at the Eraclea Minoa reference section. Such data lead us to reject the classical stratigraphical position of the Arenazzolo Formation (Fig. 2) and to shift it into the earliest Zanclean (Fig. 12), a view previously implied by some authors (Brolsma, 1976; Butler *et al.*, 1995). In this section, cysts of *Galeacysta etrusca* have been recorded only during relative high sea levels (i.e. within the turbiditic layer preceding the last gypsum and within the Arenazzolo Formation) according both to the abundance of *Pinus* vs. halophyte pollen grains (Fauquette *et al.*, in press) and to a sequence stratigraphic analysis (Homewood *et al.*, 1992). It is clear that, at Eraclea Minoa, two successive influxes of Paratethyan elements are recorded in relation to relative high sea levels, respectively: (1) before the almost complete desiccation of the Mediterranean (marked by dinoflagellate cysts including *Galeacysta etrusca* and, at a relative lower sea level, by Congeria and ostracods) and (2) after the almost complete desiccation of the Mediterranean (marked by dinoflagellate cysts including *Galeacysta etrusca*). These influxes are separated by the Messinian erosional surface which corresponds to the deep desiccated basin evaporites (Clauzon *et al.*, 1996). Accordingly, these influxes can be respectively related to isotopic stages TG 11 (last occurrence of *Discoaster quinqueramus*, corresponding to the Lago Mare Formation in Sicily) and TG 5 (earliest Zanclean corresponding to the Arenazzolo Formation in Sicily), a gap in sedimentation of 190 kyr separating these two layers (Fig. 12). At Cava Serredi (Livorno, Italy), the uppermost 20 m of the Lago Mare facies are missing from the present-day quarry face at about 400-m north of the section described by Bossio *et al.* (1981). This suggests the presence of the Messinian erosional surface between Messinian and Zanclean deposits, and disputes the continuous deposition claimed by Bossio *et al.* (1981) and Corradini & Biffi (1988).

We distinguished some other earliest Zanclean localities because we observed them above the Messinian erosional surface, as suspected by some previous authors. These localities include Papiol (Almera, 1894; Gillet, 1965), localities from the Rhône Valley (Fontannes, 1883; Denizot, 1952; Ballesio, 1972) and Aleria in Corsica (Magné

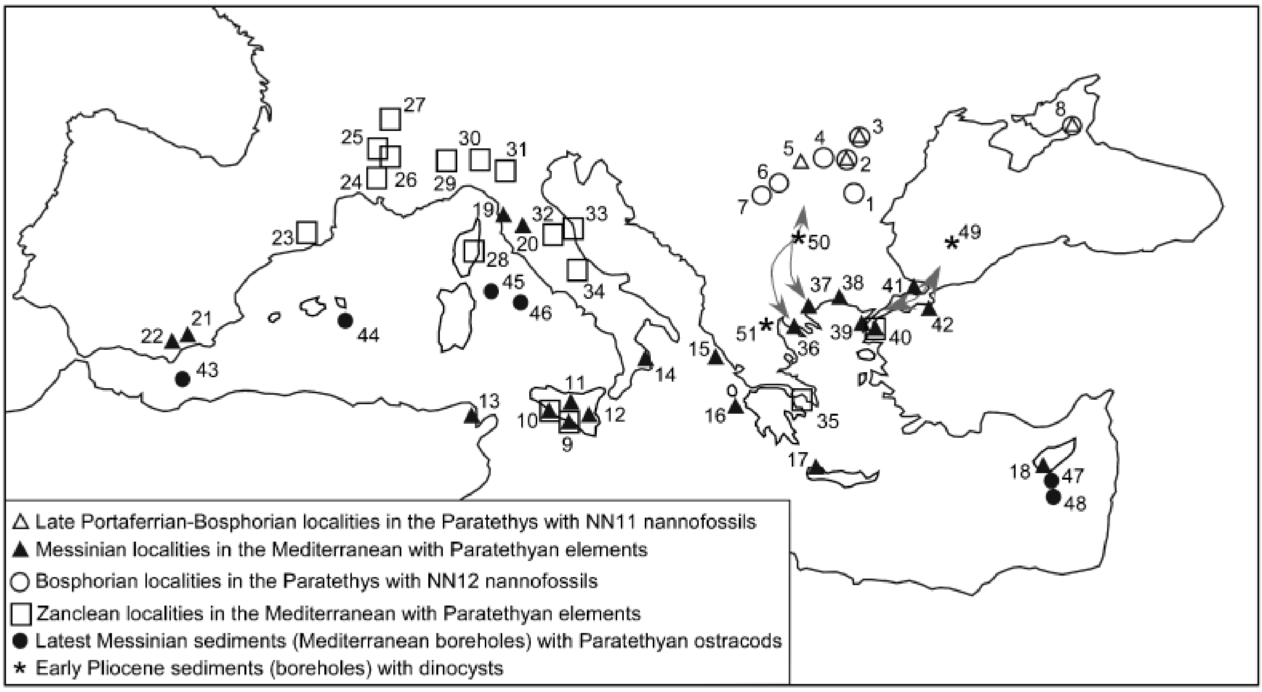

Fig. 13. Selected localities in the Mediterranean and Dacic basins used to propose three Lago Mare events from the late Messinian to earliest Zanclean. The discussed possible gateways between the Aegean Sea and the Eastern Paratethys are indicated by grey double arrows. Localities (some including several sections; references are given in Table 2) are as follows: 1, Argova Valley; 2, Călugăreni; 3, Valea Vacii; 4, Doiceşti; 5, Badislava; 6, Ţicleni; 7, Hinova; 8, Kerc (Azov Sea); 9, Capo Rossello; 10, Eraclea Minoa; 11, Pasquasia; 12, Vizzini; 13, Djebel Kechabta; 14, Zinga; 15, Corfou; 16, Zakynthos; 17, Khairetiana (Crete); 18, Pissouri and Polemi (Cyprus); 19, Cava Serredi; 20, Pomarance; 21, Vera; 22, Sorbas; 23, Papiol; 24, Théziers; 25, Saint-Marcel d'Ardèche; 26, Saint-Restitut; 27, Allex; 28, Aleria; 29, Alba; 30, Torre Sterpi; 31, Monteglino; 32, Maccarone; 33, Ancone; 34, Le Vicenne; 35, Souvala (Aegina); 36, Axios-Thermaikos Basin; 37, Strymon Basin; 38, Xanthi-Kometini Basin; 39, Gelibolu; 40, Intepe; 41, Ambarliköy; 42, Yalakdere; 43, Site 978A; 44, Site 975B; 45, Site 654; 46, Site 974B; 47, Site 968A; 48, Site 967A; 49, Site 380A; 50, Ravno Polé; 51, Ptolemais.

et al., 1977) (Fig. 13). In the Tyrrhenian Sea, the Messinian erosional surface can be followed offshore from Aleria to the basin where it cuts the Messinian evaporites (Aleria, 1980), that are demonstrated as being the marginal ones (Clauzon *et al.*, 1996).

We regard the Colombacci Formation of the Po Valley and the Adriatic realm, classically accepted as latest Messinian in age (Fig. 2), as earliest Zanclean for the following reasons. At Maccarone, this Formation with Paratethyan ostracods and dinoflagellate cysts (including *Galeacysta etrusca*: Bertini, 1992; Popescu, in progress; Table 2) represents a marine environment with planktonic and benthic foraminifers (Carloni *et al.*, 1974) and oceanic dinoflagellate cysts such as *Impagidinium aculeatum* (Bertini, 1992; Popescu, in progress) which began 44 m below the Colombacci Formation. It inevitably belongs to a relative high sea level. The occurrence of *in situ* foraminifers (Carloni *et al.*, 1974) points to a Zanclean age for the Colombacci Formation. This conclusion was previously reached in a confidential study for the TOTAL Company on the Montagna dei Fiori section (near Ascoli, Marche, Italy), an area where the Colombacci Formation is very thick (Selli, 1973; Bassetti *et al.*, 1994).

The age has been unclear for some localities from the Aegean Sea, with assignment to the Messinian (Rögl *et al.*, 1991; Syrides, 2000) or Zanclean (Karistineos & Georgiades-Dikeoulia, 1985–1986), such as in the Axios-Thermaikos Basin (Fig. 13). The significance of the incursion of Paratethyan waters is also discussed (Syrides, 2000), and the problem is perpetuated because most of the localities have no age control other than molluscan evidence. The matter is nonetheless crucial because these faunas are located in a possible gateway area between the Paratethys and the Mediterranean (Stankovic, 1960; Hsü *et al.*, 1977, 1978a; Kojumdgieva, 1987; Marinescu, 1992). Therefore, after several field investigations in the northern Aegean Sea, we established that localities of the Strymon, Xanthi-Kometini and Gelibolu basins that have Paratethyan elements (Fig. 13) were cut by the Messinian erosional surface (cutting in some places the marginal evaporites, a feature clearly seen also on seismic profiles of the Prinos Basin: Proedrou, 1979; Proedrou & Sidiropoulos, 1993), and overlain by Gilbert-type fan delta deposits showing bottomset beds belonging to nannofossil Zone NN12. A similar situation is suspected for the Ambarliköy area (Fig. 13) based on seismic investigations in the Black Sea (Gillet, 2004). We have recorded Mediterranean calcareous nannofossils continuously along the Intepe section at the western opening of the Dardanelles Strait (Fig. 13). This section belongs to the Messinian Alçitepe Formation

Table 2. Mediterranean Lago Mare localities and their fossil content

Localities	Congeria	Ostracods	Dinocysts
Alboran Sea:			
Vera (Cita *et al.*, 1980)		+	
Sorbas (Civis *et al.*, 1979; Ott d'Estevou & Montenat, 1990)	+	+	
Site 978A (Iaccarino & Bossio, 1999)		+	
Northwestern Mediterranean:			
Papiol (Gillet, 1960, 1965; Almera, 1894)	+	+	
Théziers, *Saint-Marcel d'Ardèche*, *Saint-Restitut*, *Allex* (*Rhône Valley*) (Fontannes, 1883; Ballesio, 1972; Archambault-Guezou, 1976; Carbonnel, 1978)	+	+	
Cava Serredi (Bossio *et al.*, 1981; Corradini & Biffi, 1988)	+	+	+
Pomarance (Bossio *et al.*, 1978)	+	+	
Aleria (*Corsica*) (Pilot *et al.*, 1975; Magné *et al.*, 1977)	+	+	+*
Site 975B (Iaccarino & Bossio, 1999)		+	
Site 654 (Cita *et al.*, 1990)		+	
Site 974B (Iaccarino & Bossio, 1999)		+	
Po Valley and Adriatic Sea:			
Alba (Cavallo & Repetto, 1988)	+		+*
Torre Sterpi (Corselli & Grecchi, 1984)	+	+	+*
Monteglino (Iaccarino & Papani, 1979)	+	+	
Monticino 1987 (Marabini & Vai, 1988; Bertini, 1992)	+		+
Ancone (Gillet, 1968)	+	+	
Maccarone (Carloni *et al.*, 1974; Bertini, 1992)		+	+*
Le Vicenne (Cipollari *et al.*, 1999; Gliozzi, 1999; Bertini, in progress)	+	+	+
Central Mediterranean:			
Vizzini (Di Geronimo *et al.*, 1989)	+		
Capo Rossello (Cita & Colombo, 1979; Bonaduce & Sgarrella, 1999)	+	+	+*
Eraclea Minoa (Decima & Sprovieri, 1973; Bonaduce & Sgarrella, 1999)	+	+	+*
Pasquasia (Colalongo, 1968; Cita *et al.*, 1973)		+	
Zinga (Selli, 1973; Martina *et al.*, 1979)		+	
Djebel Kechabta (Burollet, 1952; Benson, 1976)		+	
Ionian Sea:			
Corfou (Vismara Schilling *et al.*, 1976)		+	
Zakynthos (Kontopoulos *et al.*, 1997)			+
Aegean and Marmara seas:			
Khairetiana (Crete) (Sissingh, 1972)		+	
Souvala (Aegina) (Rögl *et al.*, 1991)	+	+	
Axios-Thermaikos Basin (Gillet, 1937; Gillet & Geissert, 1971; Syrides, 1998)	+		
Strymon Basin (Syrides, 1995, 1998)	+		
Xanthi-Komotini Basin (Syrides, 1998)	+		
Gelibolu (Gillet *et al.*, 1978; Görür *et al.*, 1997)		+	
Intepe (Gillet *et* al., 1978; Görür *et al.*, 1997)		+	
Ambarliköy (Gillet *et al.*, 1978; Görür *et al.*, 1997)		+	
Yalakdere (Gillet *et al.*, 1978; Görür *et al.*, 1997)		+	
Eastern Levantine Basin:			
Pissouri and **Polemi (Cyprus)** (Orszag-Sperber *et al.*, 1980; Di Stefano *et al.*, 1999; Rouchy *et al.*, 2001)	+	+	
Site 967 (Spezzaferri *et al.*, 1998)		+	
Site 968 (Blanc-Valleron *et al.*, 1998)		+	

A distinction is drawn between the deep basin localities and the marginal ones, and among the latter, between those referred to the late Messinian and those referred to the earliest Zanclean.
Normal characters: deep basin localities **Bold characters**: localities referred to Late Messinian *Italic characters*: localities referred to Early Zanclean.
*Our study.

(Görür *et al.*, 1997), and has two apparently conformable assemblages: the lower part of the succession is assignable to Zone NN11 (co-occurrence of *Triquetrorhabdulus rugosus*, *Reticulofenestra rotaria*, *Amaurolithus primus* and *A. delicatus*), and the the upper part is assignable to Zone NN12 (indicated by the appearance of *Ceratolithus armatus*/*C. acutus*, and the disappearance of *Triquetrorhabdulus rugosus*). Moreover, as in other Mediterranean and Atlantic regions

(Backman & Raffi, 1997; Castradori, 1998), the two abovementioned nannofossil events are not coincident: the extinction of *T. rugosus* is younger than the appearance of *C. armatus/C. acutus*. The two assemblages are separated by a lignite (5-cm thick), a sand (2-cm thick) and a shelly limestone (17-cm thick), which may express the discontinuity observed to the north at Yaylaköy (Gulf of Saros) where clayey bottomset beds belonging to Zone NN12 are nested within the Alçitepe Formation owing to the Messinian erosional surface. Presently, only two localities are of uncertain age: Trilophos (locality 36 on Fig. 13) is assigned to the late Messinian (Gillet & Geissert, 1971; Syrides, 1998) pending nannoplankton data (Fig. 13; Table 2); and Souvala, a locality of the Aegina Island (35 on Fig. 13), is ascribed to the earliest Zanclean (Fig. 13; Table 2) because nannoossils of Zone NN12 overlie beds containing Congeria, although there is no information on whether an erosional surface is present (Rögl *et al*., 1991). Hence, despite some missing information on the latter locality, we believe that the two high sea-level exchanges between the Mediterranean Sea and the Paratethys, occurring just before and just after the Mediteranean Sea desiccation, have been recorded in this area.

Re-examination of the Lago Mare localities suggests that two successive influxes of Paratethyan organisms enterred the Mediterranean Sea, firstly in the late Messinian and again in the earliest Zanclean. Such influxes were made of surface waters, these being able to transport Congeria and ostracod larvae and where dinoflagellates live in the photic zone. They necessarily correspond to the two opposite influxes of Mediterranean surface waters occurring at high sea level, transporting the calcareous nannoplankton characterizing Zones NN11 and NN12 (Fig. 12). Accordingly, these results suggest the existence of two relatively brief episodes of two-way exchange at high sea level between the Paratethys and the Mediterranean, the brackish to fresh Paratethyan waters exported at the surface, and the Mediterranean saline waters imported below surface (Fig. 12).

DISCUSSION

Two brief influxes of Mediterranean waters (with calcareous nannoplankton and dinoflagellates) have clearly occurred in the late Messinian–earliest Zanclean of the Eastern Paratethys (Dacic and Euxinian basins). They, respectively, belong to the calcareous nannofossil Zones NN11 and NN12. According to palaeomagnetic data in the northern Dacic Basin (Snel *et al*., in press), they immediately preceded and followed the Messinian salinity crisis. This timing is also attested by the presence of the Messinian erosional surface below the bottomset beds (assigned to Zone NN12) of the Gilbert-type fan delta of Turnu Severin. Because nannoplankton and dinoflagellates are mostly distributed in surface waters (the upper photic zone, i.e. the uppermost 90 m), it is realistic to correlate these influxes with the two successive high global sea levels illustrated by the isotope stages TG 11 and TG 5 of Shackleton *et al*. (1995) which respectively immediately predate (5.52 Ma) and postdate (5.33 Ma) the Messinian salinity crisis (Vidal *et al*., 2002; Warny *et al*., 2003) (Fig. 12). At the same time, brief reverse flows of Paratethyan waters will have entered the Mediterranean, explaining the arrival of Paratethyan elements (Congeria, ostracods and dinoflagellates) and causing the development of two successive Lago Mare facies in the Mediterranean. This scenario resolves the apparently discrepant chronology of this facies that is represented by localities underlying the Messinian erosional surface, but also localities overlying the same surface (Fig. 12). The present-day water exchanges between the Maramara and Black seas through the Bosphorus Strait occurs because brackish waters exit the Black Sea as a surface current that flows over a deeper reverse current of saline Mediterranean waters entering the Black Sea (Fortey, 2000). This presents a realistic analogue for the suggested water exchanges between the Mediterranean Sea and Eastern Paratethys during the Late Neogene. In some areas protected from erosion, the two successive exchanges at high sea level have been recorded within the same vertical section: in the Eastern Paratethys (northern Dacic Basin) and in the Mediterranean (Eraclea Minoa classical section, Intepe) (Fig. 13). In the Mediterranean (except the Po Valley and the Adriatic realm), fluvial erosion during the Mediterranean desiccation resulted in a nesting of Zanclean deposits within Miocene deposits that are generally considerably eroded. Therefore, only one of the two Lago Mare facies caused by high sea-level exchanges can be exposed in each locality, except near Eraclea Minoa and at Cava Serredi (Livorno) where relatively weak erosion occurred. The late Messinian Lago Mare sediments have been protected from erosion in some Mediterranean localities (Fig. 13), whereas the earliest Zanclean Lago Mare deposits are often poorly documented because of the difficulty in observing the oldest Zanclean sediments within the Messinian canyons. In the Po Valley and Adriatic realm, only the second influx (earliest Zanclean) seems documented, considering that, at Maccarone, it significantly postdates an ash bed dated at 5.51 ± 0.04 Ma ($^{40}Ar/^{39}Ar$: Odin *et al*., 1997; H. Maluski, personal information). Such an assumption can be extrapolated across the whole region considering that, for example, at Monticino, the second Lago Mare deposits unconformably overlie the marginal evaporites (Marabini & Vai, 1988); and at Torre Sterpi and Sioneri (near Alba), they overlie the reworked marginal evaporites. These data may support some uplift of the Otrante Sill during the episode that includes the first high sea-level exchange between the Eastern Paratethys and the Mediterranean (5.90–5.40 Ma) (Fig. 14). The connection of the Mediterranean Sea with the Eastern Paratethys at high sea level just before the salinity crisis provides a better explanation for the sea-level drop of the latter than by its drainage into the dried-up Mediterranean as proposed by Hsü *et al*. (1978a). Similar relationships at high sea level occurred repeatedly between the two realms before and after the time-window including

  Basin Research, doi: 10.1111/j.1365-2117.2005.00269.x

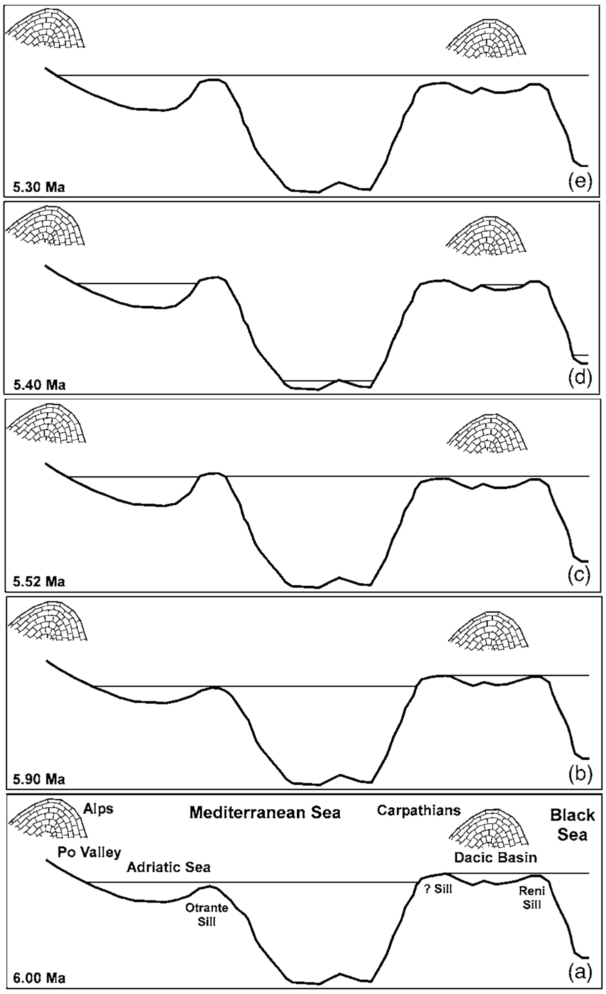

Fig. 14. Proposed sea-level changes in the Mediterranean Sea and the Eastern Paratethys between 6.00 and 5.30 Ma, and their brief connections during episodes of high sea level.

the Messinian salinity crisis as attested by Mediterranean nannofossil records in the Dacic Basin (Mărunţeanu & Papaianopol, 1998) and by the unusual presence of Paratethyan fauna in the Mediterranean, such as below the Crevillente 6 mammal level (Archambault-Guezou *et al.*, 1979) dated at about 6.1 Ma (Garcés *et al.*, 1998).

The significance of Paratethyan dinocyst influxes into the Mediterranean Basin is different from that of Congeria influxes, because they are not recorded simultaneously at some non-coastal localities, such as Eraclea Minoa for instance. At Eraclea Minoa, Paratethyan dinocysts are recorded in the following relatively high sea-level deposits: (1) a turbiditic layer underlying the last gypsum that represents a relative drop in sea level (Homewood *et al.*, 1992) and (2) the Arenazzolo Formation. These two relatively high sea-level deposits are separated by the Lago Mare Formation, which includes Congeria only. We believe that dinocyst and Congeria migrations have occurred at the same time (as recorded simultaneously in several coastal localities, Torre Sterpi for example). But in some distal localities, such as Eraclea Minoa, dinocysts owing to their greater abundance appear more reliable for identifying the exact influx level. Indeed, Congeria beds are a better signature for characterizing more coastal conditions and brackish-water lagoons along the shoreline.

Such exchanges at high sea-level between the Eastern Paratethys and the Mediterranean would correspond to episodic connections not only forced by rises in sea level but also controlled by palaeogeographic features such as very narrow and winding sills and marine currents. Where were such connections located? (Fig. 13). A proto-Dardanelles–Bosphorus gateway was considered by Archambault-Guezou (1976), Kojumdgieva (1987) and Marinescu (1992). The absence of Mediterranean nannofossils from the earliest Pliocene at Site 380A (Percival, 1978), relatively close to the present-day Bosphorus Strait, allows us to discard this hypothesis. An approximately 200-kyr delay in the arrival of Mediterranean diatoms and dinocysts at this site supports our decision (Schrader, 1978; Popescu, in press). According to Carbonnel (1980), a passage in the Black Sea area is untenable because no comparable ostracod faunas are known from wells of DSDP Leg 42B (Benson, 1978; Olteanu, 1978) (Fig. 1a). The morphology of Dacic Basin coccoliths supports a direct connection between the Dacic Basin and the Mediterranean, on the basis of difference in Crimean coccoliths that show some adaptation to Black Sea euxinic conditions because they probably reached this area later. The possibility of a passage through the Serres Basin into Bulgaria, already considered by Kojumdgieva (1987), is discarded according to recent results published by Zagorchev (2002). Nevertheless, a gateway through northern Greece, Macedonia and Bulgaria seems possible (Stankovic, 1960; Hsü *et al.*, 1977, 1978a) because the area was under prevalent extension at that time (Dabovski *et al.*, 2002). Such a possibility, already suggested by Marinescu (1992), should be explored. Assuming such a scenario, the Dacic Basin could have been directly connected to the Mediterranean Sea, being itself episodically connected to the Black Sea north of the Dobrogea horst through the Reni Strait (Semenenko, 1995) (Fig. 14). Such a gateway is supported by morphological adaptations of the dinocysts to the low salinity of the Dacic Basin, which seems to be less important at Hinova than at Cernat or at Site 380A, i.e. at an increased distance away from the connection. A passage through the Sofia Basin is supported by evidence of Mediterranean dinocysts in the Zanclean lacustrine facies from Ravno Polé borehole near Sofia (Drivaliari, 1993). In addition, the canyon of Mezdra to the north of Sofia is a reliable candidate for providing the outlet towards the Danube Plain. We suggest that the most reliable outlet of this gateway in the Aegean Sea is the area of Thessaloniki (i.e. the Axios-Thermaikos Basin) where Syrides (1998) found Paratethyan Congeria together with typical Mediterranean organisms (*Mactra*, *Abra*, *Parvivenus widhalmi*). This prospective gateway is also supported by the presence in the Zanclean lacustrine layers of Ptolemais, a nearby basin, of *Spiniferites cruciformis*, a typical dinocyst from the Paratethys (Kloosterboer-van Hoeve *et al.*, 2001) at a time when Mediterranean nannofossils of Zone NN13 also penetrated the Dacic Basin (Mărunţeanu &

Papaianopol, 1998). Hence, a passage through the region of Thessaloniki, Macedonia and the Basin of Sofia must be preferred (Fig. 13) and needs to be tested by future investigations.

The evolution of the Mediterranean region (including the Po Valley) and Eastern Paratethys during the interval 6.00–5.30 Ma, as forced by changes in Mediterranean sea level and relationships with the Atlantic Ocean, is summarized in Fig. 14. Some attention is given to the function of sills within the Mediterranean–Eastern Paratethys realm, which controlled exchanges between the basins or caused their isolation. Fig. 14b corresponds to the marginal evaporitic phase, and Fig. 14d to the deep basin desiccation. High sea levels in Fig. 14c (i.e. isotope stage TG 11) and 14 (i.e. isotope stage TG 5) would have produced exchanges between the Mediterranean Sea and Eastern Paratethys, i.e. the Lago Mare events in the Mediterranean realm and simultaneous nannoplankton-dinocyst influxes in the Dacic and Euxinian basins.

The northern part of the Dacic Basin has evolved as a perched basin disconnected both from the Black and Mediterranean seas (Figs 11 and 14), with residual brackish to fresh waters probably caused by the highly positive water budget of the area forced by climatic conditions and proximity of high reliefs. A similar evolution was envisioned for the Po Valley–Adriatic Basin which probably existed during the desiccation of the Mediterranean Sea as a perched freshwater basin (Fig. 14), continuously fed by waters from the Alpine and rising Apennine mountain ranges: during the salinity crisis, the area was characterized by almost continuous sedimentation (Corselli & Grecchi, 1984; Cita & Corselli, 1990; Clauzon *et al.*, 1997; Figs 2 and 12). This hypothesis is supported in the lower part of the Maccarone section by high percentages of certain subdesertic plants (such as *Lygeum*; Bertini, 1994, 2002) that are generally abundant in Sicily before and after the salinity crisis (Suc & Bessais, 1990; Bertini *et al.*, 1998). Subdesertic plants probably migrated northwards during the desiccation of the Mediterranean Sea because they could not persist within the evaporitic basin where such dry conditions prevailed (Fauquette *et al.*, in press). The upper part of the section (including the Colombacci Formation) deposited prior to the Zanclean clays has yielded planktonic foraminifers and ostracods that are considered not to be reworked (Carloni *et al.*, 1974), and oceanic dinocysts such as *Impagidinium aculeatum* (Bertini, 1992). We suggest these data indicate that the basin once again received marine waters from the Mediterranean before the officially defined beginning of the Pliocene. Simultaneously, a strong increase in bisaccate pollen grains occurs parallel to a manifold decrease in coastal plants (halophytes), which expresses the sudden establishment of offshore conditions (Bertini, 1994, 2002). This break is so abrupt that it cannot be explained by a tectonic event. We consider that water of the Po Valley–Adriatic lake was at the same level as the Mediterranean Sea, which was now able to overtop the uplifted Otrante Sill (Fig. 14) and introduce surface marine waters during Zanclean flooding, i.e. isotope stage TG 5.

The interpretation of ostracod layers is not easy in terms of invasion of the Mediterranean Basin by Paratethyan waters. There is no ambiguity for the more or less marginal localities where ostracods are generally associated with the other Paratethyan immigrants (Congeria, dinocysts): they really result from brackish water inflows (Fig. 13: localities 9–22 and 36–42 for the first influx, localities 9–10, 23–35 and 40 for the second influx) from the Eastern Paratethys (Table 2). More debatable is the interpretation of ostracod layers found, without any other marker of Paratethyan origin, at the top of the Messinian series in the deep Mediterranean Basin boreholes (Fig. 13: localities 43–48) (Table 2). These ostracods, accepted as being *in situ* because of their fragile carapaces, are thought to represent brackish- or freshwater lakes developed on the deep sea floor just after the desiccation of the Mediterranean Sea (Iaccarino & Bossio, 1999). Such deep deposits are considered to have occurred later than the marginal Lago Mare sediments (Iaccarino & Bossio, 1999, p. 538, Fig. 8). Nevertheless we believe that they result from different events as already suggested by Carbonnel (1980) who put forward the following arguments: the ostracod faunas revealed by deep sea boreholes are less diverse than the marginal ones, and some differences in carapace morphology exist. For us, the presence of lakes on the deep sea floor is incompatible with Mediterranean–Eastern Paratethys exchanges at high sea level. Hence, we consider that such lakes in the deep, almost desiccated Mediterranean Basin had developed immediately at the end of the desiccation or existed during longer periods in some intermediate basins (see ODP Site 652 in the Tyrrhenian Basin; Cita *et al.*, 1990). We suggest that local ecological conditions caused the appearance of *Cyprideis* group ostracods in these deep Mediterranean lakes, as suggested by Rouchy *et al.* (2001) for the southern Cyprus basins. In contrast, the marginal Lago Mare facies seem to have been caused by real influxes of Eastern Paratethys waters during cross exchanges at high sea level between the Mediterranean Sea and the Eastern Paratethys.

Finally, three Lago Mare events occurred in the Mediterranean Sea between 5.96 and 5.30 Ma: they are distinct not only chronologically but also in view of their origin. They have been labelled LM 1, LM 2, and LM 3 on Fig. 12:

- LM 1 occurred at 5.52 Ma and corresponds to isotope stage TG 11; LM 2 occurred at the end of the desiccation, i.e. just before 5.33; and LM 3 occurred at 5.33 Ma and corresponds to isotope stage TG 5;
- LM 1 and LM 3 result from exchanges at high sea level between the Mediterranean Sea and Eastern Paratethys and are characterized by Congeria, ostracods and dinocysts; LM 2 reflects ecological changes in the deep Mediterranean lagoons at the end of desiccation, and is marked only by the presence of ostracods.

As a consequence, we recommend restricting the term Lago Mare to a palaeoecological context, and discontinuing its use in chronostratigraphic applications.

Our results resolve the widespread confusion surrounding the old Lago Mare concept (Hsü *et al*., 1973, 1977; Cita *et al*., 1978b), which was implied by Fortuin *et al*. (1995, p. 198) in terms of stratigraphic relationships with the Messinian erosional surface, and by Iaccarino & Bossio (1999, p. 538, Fig. 8) as diachronism that we explain by differences between the Mediterranean margins and central basins.

Referring to the map on Fig. 13, LM 1 has a widespread geographic distribution across the Mediterranean margins. In contrast, LM 2 is restricted to the central Mediterranean basins. Lastly, LM 3 appears less widely distributed than LM 1, a feature that could be explained by the insufficient strength of the Paratethyan surface current to oppose the pressure of inflowing Atlantic water.

CONCLUSION

Some classical signatures of the Messinian salinity crisis in the Mediterranean Basin have been found in the Dacic Basin (Eastern Paratethys) in the area of Turnu Severin, close to the course of the modern Danube, namely:

- an erosional surface overlain by clay deposits belonging to calcareous nannofossil Zone NN12,
- an impressive Gilbert-type fan delta.

In addition to evaporite deposition and the presence of an erosional surface in the Black Sea, these new elements located at the outlet of the Iron Gates assert that the Eastern Paratethys was also severely affected by the Messinian salinity crisis.

Influxes of Mediterranean nannofloras and dinocysts penetrated the Dacic Basin and northwestern part of the Euxinian Basin during events corresponding to Zones NN11 and NN12, i.e., just before and just after the desiccation of the Mediterranean. Hence, new data on Mediterranean influxes into the Eastern Paratethys, and new field evidences from the Dacic Basin, suggest that the Mediterranean Sea and the Eastern Paratethys were connected at high sea level just before and just after the crisis, providing another explanation for Black Sea desiccation other than its drainage into the desiccated Mediterranean Basin. Our data suggest that high sea-level cross exchanges existed between the Mediterranean Sea and the Eastern Paratethys.

The Danube River appeared as an immediate consequence of the salinity crisis, and rapidly reached a course similar to its modern one over the Romanian Plain. The Messinian erosional surface developed along the Danube course and along its main tributaries whereas the northern part of the Dacic Basin remained as a perched lake, fed by Carpathian rivers owing to a regional positive hydrologic budget. This area endured continuous sedimentation, as was proposed for the Po Valley and the Adriatic realm.

Henceforth, the Lago Mare must be considered a triple event. Two events, LM 1 and LM 3, affected only the Mediterranean margins: one Paratethyan water incursion occurred just before the Mediterranean became desiccated, the other marking the Zanclean reflooding of the Mediterranean; they respectively correspond to isotope stages TG 11 (5.52 Ma) and TG 5 (5.33 Ma). They are only recorded in the marginal and perched satellite basins. They did not affect the deep Mediterranean Basin lakes (containing ostracods of the *Cyprideis* group) which we believe to have developed (LM 2 event) when the Mediterranean was dessiccated, just before the Zanclean infilling.

The gateways followed by these water exchanges are more clearly defined. A proto-Bosphorus Strait seems to be unnecessary, but a gateway through Macedonia and Bulgaria seems possible and is being explored.

ACKNOWLEDGMENTS

The following colleagues are acknowledged for discussions and for providing information: M.-P. Aubry, A. Di Stefano, C. Dinu, J.-L. Guendon, D. Jipa, L. Londeix, T. Nica, N. Panin, S.C. Rădan, M. Rădan, N. Ţicleanu, M.N. Çağatay and the late I. Papaianopol, C. Rădulescu and P.-M. Samson. W. Krijgsman has performed palaeomagnetic measurements at Hinova and Husnicioara and made some comments on the manuscript. TOTAL provided financial support for the field trip in 1998. PETROM has granted access to some subsurface data. Dr G. Udubaşa, Director of the Romanian Institute of Geology, has provided facilities and R. Maftei some assistance. I. Magyar has offered a fruitful critical review of the manuscript. We greatly appreciate the comments of the two referees, S. Iaccarino and R. Flecker whose suggestions resulted in a significantly improved manuscript. The final English version was edited by Dr Martin J. Head (University of Cambridge).

This work is a contribution to the CNRS ECLIPSE Project on The Messinian Salinity Crisis and to the EEDEN Programme of the European Science Foundation.

REFERENCES

Aleria (1980) Le canal de Corse et les bassins nord-tyrrhéniens au Miocène supérieur et terminal (Messinien); leur évolution plio-quaternaire. *Géol. Médit.*, **7**(1), 5–12.

Almera, J. (1894) *Descripción de los terrenos pliocénicos de la cuenca del Bajo Llobregat y Llano de Barcelona*. Mapa Geol. Prov, Barcelona.

Archambault-Guezou, J. (1976) Présence de Dreissenidae euxiniques dans les dépôts à Congéries de la vallée du Rhône et sur le pourtour du bassin méditerranéen. Implications biogéographiques. *Bull. Soc. Géol. France*, **18**(5, Ser. 7), 1267–1276.

Archambault-Guezou, J., Ilina, L.B., Keller, J.-P. & Montenat, C. (1979) Affinités euxiniques des mollusques messiniens d'Elche (Alicante, Espagne) et implications paléogéographiques. *Ann. Géol. Pays Hellén*, **1**(spec. issue), 27–37.

Backman, J. & Raffi, I. (1997) Calibration of Miocene nannofossil events to orbitally tuned cyclostratigraphies from ceara rise. In: *Leg 154* (Ed. by N.J. Shackleton & W.B. Curry, *et al.*) *Proc. Ocean Drill. Progr. Sci. Result*, **154**, 83–89.

Ballesio, R. (1972) Etude stratigraphique du Pliocène rhodanien. *Doc. Lab. Géol. Fac. Sci. Lyon*, **53**, 1–333.

Barber, P.M. (1981) Messinian subaerial erosion of the proto-Nile delta. *Mar. Geol.*, **44**(3–4), 253–272.

Bassetti, M.A., Ricci Lucchi, F. & Roveri, M. (1994) Physical stratigraphy of the Messinian post-evaporitic deposit in Central-Southern Marche area (Appennines, Central Italy). *Mem. Soc. Geol. It.*, **48**, 275–288.

Benson, R.H. (1976) Changes in the ostracodes of the Mediterranean with the Messinian salinity crisis. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **20**, 147–170.

Benson, R.H. (1978) Preliminary examination of the ostracodes of DSDP Leg 42B. In: *Leg 42B* (Ed. by D.A. Ross & Y.P. Neprochnov, *et al.*) *Init. Rep. Deep Sea Drill. Proj.* **42**(2), 1039–1040.

Berggren, W.A., Hilgen, F.J., Langereis, C.G., Kent, D.V., Obradovich, J.D., Raffi, I., Raymo, M.E. & Shackleton, N.J. (1995a) Late Neogene chronology: new perspectives in high-resolution stratigraphy. *Geol. Soc. Am. Bull.*, **107**(11), 1272–1287.

Berggren, W.A., Kent, D.V., Swisher, C.C. & Aubry, M.-P. (1995b) A revised Cenozoic geochronology and chronostratigraphy. In: *Geochronology Time Scales and Global Stratigraphic Correlation SEPM Spec. Publ.,* **54**, 141–212.

Bertini, A. (1992) *Palinologia ed aspetti ambientali del versante Adriatico dell'Appennino centro-settentrionale durante il Messiniano e lo Zancleano*. PhD Thesis, University of Florence.

Bertini, A. (1994) Palynological investigations on Upper Neogene and Lower Pleistocene sections in Central and Northern Italy. *Mem. Soc. Geol. Iter.*, **48**, 431–443.

Bertini, A. (2002) Palynological evidence of Upper Neogene environments in Italy. *Acta Univ. Carolinae, Geol.*, **46**(4), 15–25.

Bertini, A., Corradini, D. & Suc, J.-P. (1995) On *Galeacysta etrusca* and the connections between the Mediterranean and the Paratethys. *Rom. J. Stratigr.*, **76**(Suppl. 7), 141–142.

Bertini, A., Londeix, L., Maniscalco, R., Di stefano, A., Suc, J.-P., Clauzon, G., Gautier, F. & Grasso, M. (1998) Paleobiological evidence of depositional conditions in the Salt Member, Gessoso-Solfifera Formation (Messinian, Upper Miocene) of Sicily. *Micropaleontology*, **44**(4), 413–433.

Bizon, J.-J., Bizon, G. & Müller, C. (1978) Données tirées de l'étude des fomarinifères et des nannofossiles du Messinien en affleurement et dans le domaine marin. *Bull. Mus. Natn. Hist. Nat., Paris*, **518**(70, ser. 3), 123–135.

Blanc-valleron, M.-M., Rouchy, J.-M., Pierre, C., Badaut-trauth, D. & Schuler, M. (1998) Evidence of Messinian nonmarine deposition at Site 968 (Cyprus lower slope). In: *Leg 160* (Ed. by A.H.F. Robertson & K.-C. Emeis, *et al.*) *Proc. Ocean Drill. Progr. Sci. Results*, **160**, 437–445.

Bonaduce, G. & Sgarrella, F. (1999) Paleoecological interpretation of the latest Messinian sediments from southern Sicily (Italy). *Mem. Soc. Geol. Iter.*, **54**, 83–91.

Bossio, A., Esteban, M., Giannelli, L., Longinelli, A., Mazzanti, R., Mazzei, R., Ricci Lucchi, F. & Salvatorini, G. (1978) Some aspects of the Upper Miocene in Tuscany. In: *Messinian Seminar 4, Rome* (Ed. by Pacini), p. 88. IGCP Project 96 & CNR.

Bossio, A., Giannelli, L., Mazzanti, R., Mazzei, R. & Salvatorini, G. (1981) Gli strati alti del Messiniano, il passaggio Miocene–Pliocene e la sezione plio-pleistocenica di Nugola nelle colline a NE del Monti Livornesi. In: *9th Congress of Society of Paleontology, Italy* (Ed. by Pacini), p. 199. Società Paleontologica Italiana.

Brolsma, M.J. (1976) Discussion of the arguments concerning the palaeoenvironmental interpretation of the Arenazzolo in Capo Rossello and Eraclea Minoa (S. Sicily, Italy). *Mem. Soc. Geol. Iter.*, **16**, 153–157.

Burollet, P.F. (1952) *Porto Farina*. Carte géologique de la Tunisie au 1/50.000ème, **7**.

Busson, G. (1990) Le Messinien de la Méditerranée vingt après. *Géol. France*, **3–4**, 3–58.

Butler, R.W.H., Lickorish, W.H., Grasso, M., Pedley, H.M. & Ramberti, L. (1995) Tectonics and sequence stratigraphy in Messinian basins, Sicily: Constraints on the initiation and termination of the Mediterranean salinity crisis. *Geol. Soc. Am. Bull.*, **107**(4), 425–439.

Carbonnel, P. (1978) La zone à *Loxoconcha djaffarovi* SCHNEIDER (Ostracoda, Miocène supérieur) ou le Messinien de la vallée du Rhône. *Rev. Micropaléontol.*, **21**(3), 106–118.

Carbonnel, P. (1980) L'ostracofaune du Messinien: une preuve de la vidange de la Paratéthys. *Géol. Médit.*, **7**(1), 19–24.

Carloni, G., Francavilla, F., Borsetti, A.M., Cati, F., D'Onofrio, S., Mezzetti, R. & Savelli, C. (1974) Ricerche stratigrafiche sul limite Miocene–Pliocene nelle Marche centro-meridionali. *Giorn. Geol.*, **39**(2, Ser. 2), 363–392.

Castradori, D. (1998) Calcareous nannofossils in the basal Zanclean of the Eastern Mediterranean Sea: remarks on paleoceanography and sapropel formation. In: *Leg 180* (Ed. by A.H.F. Robertson, K.-C. Emeis, C. Richter & A. Camerlenghi), *Proc. Ocean Drill. Progr., Sci. Res.*, **180**, 113–123.

Cavallo, O. & Repetto, G. (1988) Un nuovo giacimento della facies a Congerie nell'Albese. *Riv. Piemont. Stor. Nat.*, **9**, 43–62.

Chumakov, I. (1973) Geological history of the Mediterranean at the end of the Miocene-the beginning of the Pliocene according to new data. In: *Leg 13* (Ed. by W.B.F. Ryan & K.J. Hsü, *et al.*) *Init. Rep. Deep Sea Drill. Proj.*, **13**(2), 1241–1242.

Cipollari, P., Cosentino, D., Esu, D., Girotti, O., Gliozzi, E. & Praturlon, A. (1999) Thrust-top lacustrine-lagoonal basin development in accretionary wedges: late Messinian (Lago-Mare) episode in the central Apennines (Italy). *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **151**, 149–166.

Cita, M.B. (1991) Development of a scientific controversy. In: *Controversies in Modern Geology* (Ed. by D.W. Muller, J.A. McKenzie & H. Weissert), pp. 13–23. Academic Press. Limited, London.

Cita, M.B. & Colombo, L. (1979) Sedimentation in the latest Messinian at Capo Rossello (Sicily). *Sedimentology*, **26**, 497–522.

Cita, M.B. & Corselli, C. (1990) Messinian paleogeography and erosional surfaces in Italy: an overview. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **77**, 67–82.

Cita, M.B. & Gartner, S. (1973) Studi sul Pliocene e sugli strati di passaggio dal Miocene al Pliocene. IV. The stratotype Zanclean foraminiferal and nannofossil biostratigraphy. *Riv. Ital. Paleont.*, **79**(4), 503–558.

Cita, M.B., Racchetti, S., Brambilla, R., Negri, M., Colombaroli, D., Morelli, L., Ritter, M., Rovira, E., Sala, P., Bertarini, L. & Sanvito, S. (1999) Changes in sedimentation rates in all Mediterranean drillsites document basin evolution and support starved basin conditions after early Zanclean flood. *Mem. Soc. Geol. Iter.*, **54**, 145–159.

Cita, M.B., Ryan, W.B.F. & Kidd, R.B. (1978a) Sedimentation rates in Neogene deep sea sediments from the Mediterranean and geodynamic implications of their changes. In: *Leg 42A* (Ed. by K.J. Hsü & L. Montadert, *et al.*) *Init. Rep. Deep Sea Drill. Proj.*, **42**(1), 991–1002.

Cita, M.B., Santambrogio, S., Melillo, B. & Rogate, F. (1990) Messinian paleoenvironments: new evidence from the

Tyrrhenian Sea (ODP Leg 107). In: *Leg 107* (Ed. by K.A. Kastens & J. Mascle, *et al.*) *Init. Rep. Deep Sea Drill. Proj.*, Sci. Res., **107**, 211–227.

CITA, M.B., STRADNER, H. & CIARANFI, N. (1973) Studi sul Pliocene e sugli strati di passagio dal Miocene al Pliocene. III. Biostratigraphical investigations on the Messinian stratotype and on the overlying "Trubi" Formation. *Riv. Ital. Paleont.*, **79**(3), 393–446.

CITA, M.B., VISMARA SCHILLING, A. & BOSSIO, A. (1980) Studi sul Pliocene e sugli strati di passagio dal Miocene al Pliocene. XII. Stratigraphy and paleoenvironment of the Cuevas del Almanzora section (Vera basin). A re-interpretation. *Riv. Ital. Paleont.*, **86**(1), 215–240.

CITA, M.B., WRIGHT, R.C., RYAN, W.B.F. & LONGINELLI, A. (1978b) Messinian paleoenvironments. In: *Leg 42A* (Ed. by K. Hsü & L. Montadert, *et al.*) *Init. Rep. Deep Sea Drill. Proj.*, *Sci. Res.*, **42**(1), 1003–1025.

CIVIS, J., MARTINELL, J. & DE PORTA, J. (1979) Presencia de *Cyprideis pannonica pseudoagrigentina* DECIMA en el Miembro Zorreras (Sorbas, Almeria). *Studia Geol.*, **15**, 57–62.

CLAUZON, G. (1973) The eustatic hypothesis and the pre-cutting of the Rhone Valley. In: *Leg 13* (Ed. by W.B.F. Ryan & K.J. Hsü, *et al.*) *Init. Rep. Deep Sea Drill. Proj.*, **13**(2), 1251–1256.

CLAUZON, G. (1978) The Messinian Var canyon (Provence, Southern France). Paleogeographic implications. *Mar. Geol.*, **27**(3–4), 231–246.

CLAUZON, G. (1979) Le canyon messinien de la Durance (Provence, France): une preuve paléogéographique du bassin profond de dessiccation. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **29**(1–2), 15–40.

CLAUZON, G. (1982) Le canyon messinien du Rhône: une preuve décisive du "desiccated deep-basin model" (Hsü, Cita et Ryan, 1973). *Bull. Soc. Géol. France*, **24**(3, Ser. 7), 597–610.

CLAUZON, G. (1990) Restitution de l'évolution géodynamique néogène du bassin du Roussillon et de l'unité adjacente des Corbières d'après les données écostratigraphiques et paléogéographiques. *Paléobiol. Cont.*, **17**, 125–155.

CLAUZON, G. (1996) Limites de séquence et évolution géodynamique. *Géomorphologie*, **1**, 3–22.

CLAUZON, G. (1997) Detailed morpho-sedimentary recording of the Messinian events in the betic basin in the light of the two phase model of the Salinity Crisis. In: *Neogene Basins of the Mediterranean Region: Controls and Correlation in Space and Time* (Ed. by E. Dilibento, A. Di Stefano & R. Maniscalco) . R.C.M.N.S. Inter.-Coll., Catania, *Program Abstracts*, 40–42.

CLAUZON, G. (1999) L'impact des variations eustatiques du bassin de Méditerranée occidentale sur l'orogène alpin depuis 20 Ma. *Et. Géogr. Phys.*, **28**, 1–8.

CLAUZON, G., RUBINO, J.-L. & CASERO, P. (1997) Regional modalities of the Messinian Salinity Crisis in the framework of a two phases model. In: *Neogene Basins of the Mediterranean Region: Controls and Correlation in Space and Time* (Ed. by E. Dilibento, A. Di Stefano & R. Maniscalco) . R.C.M.N.S. Inter.-Coll., Catania, *Program Abstracts*, 44–46.

CLAUZON, G., RUBINO, J.-L. & SAVOYE, B. (1995) Marine Pliocene Gilbert-type fan deltas along the French Mediterranean coast. Field Trip Guide Book, 16th IAS regional meeting of Sedimentology. *Publ. Ass. Séd. Fr.*, **23**, 143–222.

CLAUZON, G. & SUC, J.-P. (1998) Peut-on appliquer au couple Mer Noire – Danube le modèle dévolution du bassin de Méditerranée occidentale – Rhône lors de la crise de salinité messinienne? Rapport TOTAL – Conventions TEP/DEG-1546-1551, 62pp.

CLAUZON, G., SUC, J.-P., GAUTIER, F., BERGER, A. & LOUTRE, M.-F. (1996) Alternate interpretation of the Messinian salinity crisis: controversy resolved? *Geology*, **24**(4), 363–366.

COLALONGO, M.L. (1968) Ostracodi del neostratotipo del Messiniano. *Giorn. Geol.*, **35**(2, Ser. 2), 67–72.

CORNÉE, J.-J., SAINT-MARTIN, J.-P., CONESA, G., MUNCH, P., ANDRE, J.-P., SAINT-MARTIN, S. & ROGER, S. (2004) Correlations and sequence stratigraphic model for Messinian carbonate platforms of the western and central Mediterranean. *Int. J. Earth Sci.*, **93**, 621–633.

CORRADINI, D. & BIFFI, U. (1988) Etude des dinokystes à la limite Messinien-Pliocène dans la coupe Cava Serredi, Toscane, Italie. *Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine*, **12**(1), 221–236.

CORSELLI, C. & GRECCHI, G. (1984) The passage from hypersaline to hyposaline conditions in the Mediterranean Messinian: discussion of the possible mechanisms triggering the "lago-mare" facies. *Paléobiol. Cont.*, **14**(2), 225–239.

DABOVSKI, C., BOYANOV, I., KHRISCHEV, K., NIKOLOV, T., SAPOUNOV, I., YANEV, Y. & ZAGORCHEV, I. (2002) Structure and Alpine evolution of Bulgaria. *Geol. Balcanica*, **32**(2–4), 9–15.

DECIMA, A. & SPROVIERI, R. (1973) Comments on late Messinian microfaunas in several sections from Sicily. In: *Messinian Events in the Mediterranean* (Ed. by C.W. Drooger), *Kon. Ned. Akad. Wetenschappen*, *Geodynam. Sci. Rep.* **7**, 229–234.

DELRIEU, B., ROUCHY, J.-M. & FOUCAULT, A. (1993) La surface d'érosion fini-messinienne en Crète centrale (Grèce) et sur le pourtour méditerranéen: rapports avec la crise de salinité méditerranéenne. *C. R. Acad. Sci. Paris*, **316**(ser. 2), 527–533.

DENIZOT, G. (1952) Le Pliocène dans la vallée du Rhône. *Rev. Géogr. Lyon*, **27**(4), 327–357.

DI GERONIMO, I., ESU, D. & GRASSO, M. (1989) Gli strati a "Congerie" del Messiniano superiore del margine nord-occidentale Ibleo. Caratteristiche faunistiche e possibli implicazioni paleogeografiche e paleoclimatiche. *Atti Acad. Peloritana dei Pericolanti*, **67**(Suppl. 1), 129–150.

DRIVALIARI, A. (1993) Images polliniques et paléoenvironnements au Néogène supérieur en Méditerranée orientale. Aspects climatiques et paléogéographiques d'un transect latitudinal (de la Roumanie au delta du Nil). PhD Thesis, University of Montpellier 2.

DRIVALIARI, A., ŢICLEANU, N., MARINESCU, F., MARUNŢEANU, M. & SUC, J.-P. (1999) A Pliocene climatic record at Ţicleni (Southwestern Romania). In: *The Pliocene: Time of Change* (Ed. by J.H. Wrenn, J.-P. Suc & S.A.G. Leroy), pp. 103–108. Amer. Ass. Stratigr. Palynologists Foundation.

FAUQUETTE, S., SUC, J.-P., BERTINI, A., POPESCU, S.-M., WARNY, S., BACHIRI TAOUFIQ, N., PEREZ VILLA, M.-J., CHIKHI, H., SUBALLY, D., FEDDI, N., CLAUZON, G. & FERRIER, J. (in press) How much did the climate force the Messinian salinity crisis? Quantified climatic conditions from pollen records in the Mediterranean region. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*

FONTANNES, F. (1883) Note sur l'Extension et la Faune de la mer pliocène dans le sud-est de la France. *Bull. Soc. Géol. France*, **11**(Ser. 3), 103–142.

FORTEY, R. (2000) La mer Noire, fille du Déluge? *La Recherche*, **327**, 54–57.

FORTUIN, A.R., KELLING, J.M.D. & ROEP, TH.B. (1995) The enigmatic Messinian-Pliocene section of Cuevas del Almanzora (Vera Basin, SE Spain) revisited – erosional features and strontium isotope ages. *Sedim. Geol.*, **97**, 177–201.

Garcés, M., Krijgsman, W. & Agusti, J. (1998) Chronology of the late Turolian deposits of the Fortuna basin (SE Spain): implications for the Messinian evolution of the eastern Betics. *Earth Planet. Sci. Lett.*, **163**, 69–81.

Gautier, F., Clauzon, G., Suc, J.-P., Cravatte, J. & Violanti, D. (1994) Age et durée de la crise de salinité messinienne. *C. R. Acad. Sci. Paris*, **318**(ser. 2), 1103–1109.

Gillet, H. (2004) La stratigraphie tertiaire et la surface d'érosion messinienne sur les marges occidentales de la Mer Noire: Stratigraphie sismique haute résolution. PhD Thesis, University of Bretagne Occidentale (Brest).

Gillet, H., Lericolais, G., Rehault, J.-P. & Dinu, C. (2003) La stratigraphie oligo-miocène et la surface d'érosion messinienne en mer Noire, stratigraphie sismique haute résolution. *C. R. Geosciences*, **335**, 907–916.

Gillet, S. (1937) Sur la présence du Pontien *s. str.* Dans la région de Salonique. *C. R. Acad. Sci. Paris*, **205**, 1243–1245.

Gillet, S. (1960) Observations sur de jeunes coquilles de Mollusques du Pliocène saumâtre du Llobregat (Barcelone). *Bull. Soc. Géol. France*, **1**(Ser. 7), 731–733.

Gillet, S. (1965) Los Limnocardidos del Plioceno de Papiol (Barcelona). *Mem. y Commun.*, **1**(Ser. 2), 3–81.

Gillet, S. (1968) La faune messinienne des environs d'Ancona. *Giorn. Geol.*, **36**(Ser. 2), 69–100.

Gillet, S. & Geissert, F. (1971) La faune de mollusques du Pontien de Trilophos (SW de Thessaloniki). *Ann. Géol. Pays Hellén.*, **23**(Ser. 1), 123–164.

Gillet, S., Gramann, F. & Steffens, P. (1978) Neue biostratigraphische Ergebnisse aus dem brackischen Neogen an Dardanellen und Marmara-Meer (Türkei). *Newslett. Stratigr.*, **7**(1), 53–64.

Gliozzi, E. (1999) A late Messinian brackish water ostracod fauna of Paratethyan aspect from Le Vicenne Basin (Abruzzi, central Apennines, Italy). *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **151**, 191–208.

Gorini, C., Le Marrec, A. & Mauffret, A. (1993) Contribution to the structural and sedimentary history of the Gulf of Lions (western Mediterranean), from the ECORS profiles, industrial seismic profiles and well data. *Bull. Soc. Géol. France*, **164**(3), 353–363.

Görür, N., Cagatay, N., Sakinc, M., Sumengen, M., Senturk, K., Yaltirak, C. & Tchapalyga, A. (1997) Origin of the Sea of Marmara deduced from Neogene to Quaternary paleogeographic evolution of its frame. *Int. Geol. Rev.*, **39**, 342–352.

Haq, B.U., Hardenbol, J. & Vail, P.R. (1987) Chronology of fluctuating sea levels since the Triassic. *Science*, **235**, 1156–1167.

Homewood, P., Guillocheau, F., Eschard, R. & Cross, T.A. (1992) Corrélations haute résolution et stratigraphie génétique: une démarche intégrée. *Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine*, **16**, 357–381.

Hsü, K.J., Cita, M.B. & Ryan, W.B.F. (1973) The origin of the Mediterranean evaporites. In: *Leg 13* (Ed. by W.B.F. Ryan & K.J. Hsü, *et al.*) *Init. Rep. Deep Sea Drill. Proj.* **13**, 1203–1231.

Hsü, K.J. & Giovanoli, F. (1979) Messinian event in the Black Sea. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **29**(1–2), 75–94.

Hsü, K.J., Montadert, L., Bernoulli, D., Cita, M.B., Erickson, A., Garrison, R.E., Kidd, R.B., Melieres, F., Muller, C. & Wright, R. (1977) History of the Mediterranean salinity crisis. *Nature*, **267**, 399–403.

Hsü, K.J., Montadert, L., Bernoulli, D., Cita, M.B., Erickson, A., Garrison, R.E., Kidd, R.B., Melieres, F., Muller, C. & Wright, R. (1978a) History of the Mediterranean salinity crisis. In: *Leg 42A* (Ed. by K.J. Hsü & L. Montadert, *et al.*) *Init. Rep. Deep Sea Drill. Proj.*, **42**(1), 1053–1078.

Hsü, K.J. & Montadert, L., *et al* (eds.) (1978b) *Leg 42A. Init. Rep. Deep Sea Drill. Proj.*, **42**, 1.

Iaccarino, S. & Bossio, A. (1999) Paleoenvironment of uppermost Messinian sequences in the Western Mediterranean (Sites 974, 975, and 978). In: *Leg 161* (Ed. by R. Zahn, M.C. Comas & A. Klaus), *Proc. Ocean Drill. Progr., Sci. Results*, **161**, 529–541.

Iaccarino, S. & Papani, G. (1979) Il Messiniano dell'Appennino settentrionale dalla Val d'Arda alla Val Secchia: stratigrafia e rapporti con il substrato e il Pliocene. In: *Volume Dedicato a Sergio Venzo* (Ed. by G. Step), pp. 15–46. University of Parma.

Jipa, D. (1997) Late Neogene – Quaternary evolution of Dacian Basin (Romania). An analysis of sediment thickness pattern. *Geo-Eco-Marina*, **2**, 127–134.

Karistineos, N.K. & Georgiades-Dikeoulia, E. (1985–86) The marine transgression in the Serres Basin. *Ann. Géol. Pays Hellén.*, **33**(1), 221–232.

Kloosterboer-Van hoeve, M.L., Steenbrink, J. & Brinkhuis, H. (2001) A short-term cooling event, 4.205 million years ago, in the Ptolemais Basin, Northern Greece. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **173**, 61–73.

Kojumdgieva, E. (1987) Evolution géodynamique du bassin égéen pendant le Miocène supérieur et ses relations à la Paratéthys Orientale. *Geol. Balcanica*, **17**(1), 3–14.

Kontopoulos, N., Zelilidis, A., Piper, D.J.W. & Mudie, P.J. (1997) Messinian evaporites in Zakynthos, Greece. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **129**, 361–367.

Krijgsman, W., Hilgen, F.J., Raffi, I., Sierro, F.J. & Wilson, D.S. (1999a) Chronology, causes and progression of the Messinian Salinity Crisis. *Nature*, **400**, 652–655.

Krijgsman, W., Hilgen, F.J., Marabini, S. & Vai, G.B. (1999b) New paleomagnetic and cyclostratigraphic age constraints on the Messinian of the Northern Apennines (Vena del Gesso Basin, Italy). *Mem. Soc. Geol. It.*, **54**, 25–33.

Letouzey, J., Gonnard, R., Montadert, L., Kristchev, K. & Dorkel, A. (1978) Black Sea: geological setting and recent deposits distribution from seismic reflection data. In: *Leg 42B* (Ed. by D.A. Ross & Y.P. Neprochnov, *et al.*) *Init. Rep. Deep Sea Drill. Proj.*, **42**(2), 1077–1084.

Lofi, J. (2002) La Crise de Salinité Messinienne: Conséquences directes et différées sur l'évolution sédimentaire de la marge du Golfe du Lion. PhD Thesis, University of Sciences et Techniques. Lille.

Lofi, J., Rabineau, M., Gorini, C., Berne, S., Clauzon, G., De Clarens, P., Dos Reis, T., Mountain, G.S., Ryan, W.B.F., Steckler, M. & Fouchet, C. (2003) Plio-Quaternary prograding clinoform wedges of the Western Gulf of Lions continental margin (NW Mediterranean) after the Messinian Salinity Crisis. *Mar. Geol.*, **198**, 289–317.

Lourens, L.J., Antonarakou, A., Hilgen, F.J., Van Hoof, A.A.M., Vergnaud Grazzini, C. & Zachariasse, W.J. (1996) Evaluation of the Pliocene to early Pleistocene astronomical time scale. *Paleoceanography*, **11**, 391–413.

Magné, J., Orszag-Sperber, F. & Pilot, M.-D. (1977) Nouvelles données sur le Pliocène de Corse: le problème de la limite Miocène-Pliocène. *Bull. Bur. Rech. Géol. Min.*, **3**(Ser. 2, sect. 1), 209–218.

Magyar, I., Geary, D.H. & Müller, P. (1999) Paleogeographic evolution of the Late Miocene Lake Pannon in Central Europe. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **147**, 151–167.

Marabini, S. & Vai, G.B. (1988) Geology of the Monticino Quarry, Brisighella, Italy. Stratigraphic implications of its late Messinian mammal fauna. In: *Fossil Vertebrates in the Lamone Valley, Romagna Apennines – Field Trip Guidebook* (Ed. by C. De Giuli & G.B. Vai), pp. 39–57. Faenza.

Marinescu, F. (1978) *Stratigrafia Neogenului Superior Din Sectorul Vestic Al Bazinului Dacic*. Edit. Acad. R.S.R., Bucharest.

Marinescu, F. (1992) Les bioprovinces de la Paratéthys et leurs relations. *Paleontologia i Evolució*, **24–25**, 445–453.

Marinescu, F., Ghenea, C. & Papaianopol, I. (1981) Stratigraphy of the Neogene and the Pleistocene Boundary. Guide Excursion A6, Guidebook ser. 20, 12th Congr. Carpatho-Balkan, Inst. Geol. Geophys. Bucharest, p. 111.

Marinescu, F., Marunţeanu, M., Papaianopol, I. & Popescu, G. (1998) Tables with the correlations of the Neogene deposits in Romania. *Rom. J. Stratigr.*, **78**, 181–186.

Martina, E., Casati, P., Cita, M.B., Gersonde, R., D'Onofrio, S. & Bossio, A. (1979) Notes on the Messinian stratigraphy of the Crotone basin, Calabria (Italy). *Ann. Géol. Pays. Hellén.*, **2**(spec. issue), 755–765.

Mărunţeanu, M. (1992) Distribution of the Miocene calcareous nannofossils in the Intra- and Extra-Carpathian areas of Romania. *Knikovnicka ZPN*, **14b**(2), 247–261.

Mărunţeanu, M. & Papaianopol, I. (1995) The connection between the Dacic and Mediterranean Basins based on calcareous nannoplankton assemblages. *Rom. J. Stratigr.*, **76**(7), 169–170.

Mărunţeanu, M. & Papaianopol, I. (1998) Mediterranean calcareous nannoplankton in the Dacic Basin. *Rom. J. Stratigr.*, **78**, 115–121.

Müller, P., Geary, D.H. & Magyar, I. (1999) The endemic molluscs of the Late Miocene Lake Pannon: their origin, evolution, and family-level taxonomy. *Lethaia*, **32**, 47–60.

Nastaseanu, S. & Bercia, I. (1968) *Baia de Arama. Carte géologique de Roumanie au 1/200.000*, **Vol. 32**. Institut géologique, Bucharest.

Nesteroff, W.D. (1973) Un modèle pour les évaporites messiniennes en Méditerranée, des bassins peu profonds avec des dépôts d'évaporites lagunaires. In: *Messinian events in the Mediterranean* (Ed. by C.W. Drooger), *Kon. Ned. Akad. Wetensch.*, *Geodynam. Sci. Rep.*, **7**, 68–81.

Odin, G.S., Ricci LUCCHI, F., Tateo, F., Cosca, M. & Hunziker, J.C. (1997) Integrated stratigraphy of the Maccarone section, Late Messinian (Marche region, Italy). In: *Miocene Stratigraphy – An Integrated Approach* (Ed. by A. Montanari, G.S. Odin & R. Coccioni), pp. 529–544. Elsevier, Amsterdam.

Olteanu, R. (1978) Ostracoda from DSDP Leg 42B. In: *Leg 42B* (Ed. by D.A. Ross & Y.P. Neprochnov, *et al.*) *Init. Rep. Deep Sea Drill. Proj.*, **42**(2), 1017–1038.

Orszag-Sperber, F., Rouchy, J.-M., Bizon, G., Bizon, J.-J., Cravatte, J. & Muller, C. (1980) La sédimentation messinienne dans le bassin de Polemi (Chypre). *Géol. Médit.*, **7**(1), 91–102.

Orszag-Sperber, F., Rouchy, J.-M. & Blanc-Valleron, M.-M. (2000) La transition Messinien-Pliocène en Méditerranée orientale (Chypre): la période du *Lago-Mare* et sa signification. *C. R. Acad. Sci. Paris., Earth Planet. Sci.*, **331**, 483–490.

Ott D'estevou, P. & Montenat, C. (1990) Le bassin de Sorbas –Tabernas. *Doc. et Trav. IGAL*, **12–13**, 101–128.

Papaianopol, I. & Mărunţeanu, M. (1993) Biostratigraphy (molluscs and calcareous nannoplankton) of the Sarmatian and Meotian in Eastern Muntenia (Dacic basin – Romania). *Zemni plyn a nafta*, **38**(1), 9–15.

Percival Jr, S.F. (1978) Indigenous and reworked coccoliths from the Black Sea. In: *Leg 42B* (Ed. by D.A. Ross & Y.P. Neprochnov, *et al.*) *Init. Rep. Deep Sea Drill. Proj.*, **42**(2), 773–781.

Pilot, M.-D., Brebion, P. & Lauriat-Rage, A. (1975) Les gisements fossilifères du Néogène recent et du Quaternaire de la region d'Aléria-Vadina. *Bull. Soc. Sc. Hist. Nat. Corse*, 61–77.

Popescu, S.-M. (2001) Repetitive changes in Early Pliocene vegetation revealed by high-resolution pollen analysis: revised cyclostratigraphy of southwestern Romania. *Rev. Palaeobot. Palynol.*, **120**, 181–202.

Popescu, S.-M. (in press) Upper Miocene and Lower Pliocene environments in the southwestern Black Sea region from high-resolution palynology of DSDP site 380A (Leg 42B). *Palaeogeogr. Palaeoclimatol. Palaeoecol*.

Popescu, S.-M., Krijgsman, W., Suc, J.-P., Clauzon, G. & Mărunţeanu, M. (in press) Early Pliocene integrated stratigraphy and high-resolution chronology of the Dacic Basin (Southwestern Romania). *Palaeogeogr. Palaeoclimatol. Palaeoecol*.

Proedrou, P. (1979) The evaporites formation in the Nestos-Prinos graben in the Northern Aegean Sea. *Ann. Géol. Pays Hellén.*, **2**(spec. issue), 1013–1020.

Proedrou, P. & Sidiropoulos, T. (1993) Prinos Field – Greece, Aegean Basin. In: *Treatise of Petrolum Geology, Atlas of Oil and Gas Fields* (Ed. by N.H. Foster & E.A. Beaumont), pp. 275–291. American Association of Petroleum Geologists, Tulsa.

Rădulescu, C., Samson, P.-M., Sen, S., Stiuca, E. & Horoi, V. (1997) Les micromammifères pliocènes de Drănic (Bassin Dacique, Roumanie). In *BiochroM'97* (Ed. by J.-P. Aguilar, S. Legendre & J. Michaux), *Mém. Trav. E.P.H.E., Inst. Montpellier*, **21**, 635–647.

Riding, R., Braga, J.C., Martin, J.M. & Sanchez-Almazo, I.M. (1998) Mediterranean Messinian Salinity Crisis: constraints from a coeval marginal basin. Sorbas, SE Spain. *Mar. Geol.*, **146**, 1–20.

Rizzini, A., Vezzani, F., Cococcetta, V. & Milad, G. (1978) Stratigraphy and sedimentation of a Neogene-Quaternary section in the Nile delta area (A.R.E.). *Mar. Geol.*, **27**, 327–348.

Rögl, F., Bernor, R.L., Dertmizakis, M.D., Muller, C. & Stancheva, M. (1991) On the Pontian correlation in the Aegean (Aegina Island). *Newslett. Stratigr.*, **24**(3), 137–158.

Rögl, F. (1996) Stratigraphic correlation of the Paratethys Oligocene and Miocene. *Mitt. Ges. Geol. Bergbaustud. Österr.*, **41**, 65–73.

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

Rögl, F. & Steininger, F.F. (1983) Vom Zerfall der Tethys zu Mediterran uns Paratethys. Die neogene Paläogeographie und Palinspastik des zirkul-mediterranen Raumes. *Ann. Naturhist. Mus. Wien*, **85**(A), 135–163.

Ross, D.A. & Neprochnov, Y.P., *et al*. (eds.) (1978) *Leg 42B*. *Init. Rep. Deep Sea Drill. Proj.*, **42**, 2.

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

ROUCHY, J.-M. & SAINT-MARTIN, J.-P. (1992) Late Miocene events in the Mediterranean as recorded by carbonate-evaporite relations. *Geology*, **20**, 629–632.

RUGGIERI, G. (1967) The Miocene and later evolution of the Mediterranean Sea. In: *Aspects of Tethyan Biogeography* (Ed. by C.G. Adams & D.V. Ager), *Syst. Assoc. Publ.*, **7**, 283–290.

RYAN, W.B.F. & CITA, M.B. (1978) Messinian erosional surfaces in the Mediterranean. *Mar. Geol.*, **27**(3–4), 193–230.

RYAN, W.B.F. & HSÜ, K.J., *et al* (eds.) (1973) *Leg 13. Init. Rep. Deep Sea Drill. Proj.*, **13**.

SACCHI, M., HORVATH, F., MAGYAR, I. & MÜLLER, P. (1997) Problems and progress in establishing a Late Neogene chronostratigraphy for the Central Paratethys. *Neogene Newsletter*, **4**, 37–46.

SARJEANT, W.A.S. (1974) *Fossil and Living Dinoflagellates*. Academic Press, London.

SAVOYE, B. & PIPER, D.J.W. (1991) The Messinian event on the margin of the Mediterranean Sea in the Nice area, southern France. *Mar. Geol.*, **97**, 279–304.

SAVU, H. & GHENEA, C. (1967) Turnu Severin. Carte géologique de Roumanie au 1/200.000, 40, Institut géologique, Bucharest.

SCHRADER, H.-J. (1978) Quaternary through Neogene history of the Black Sea, deduced from the paleoecology of Diatoms, Silicoflagellates, Ebridians, and Chrysomonads. In: *Leg 42B* (Ed. by D.A. Ross & Y.P. Neprochnov, *et al.*) *Init. Rep. Deep Sea Drill. Proj.*, **42**(2), 789–901.

SELLI, R. (1973) An outline of the Italian Messinian. In: *Messinian Events in the Mediterranean* (Ed. by C.W. Drooger), *Kon. Ned. Akad. Wetensch., Geodynam. Sci. Rep.*, **7**, 150–171.

SEMENENKO, V.N. (1995) Geological events at the Miocene/Pliocene boundary in the Eastern Paratethys. *Geol. Soc. Greece*, **4**(Spec Publ.), 264–268.

SEMENENKO, V.N., ILJINA, L.B. & LYULJEVA, S.A. (1995) About zonal correlation of the Meotian stage of the Eastern Paratethys. *Rom. J. Stratigr.*, **76**(7), 115–116.

SEMENENKO, V.N. & LYULJEVA, S.A. (1978) Opît priamoi korelaţii moi-plioţena Vostocinogo Paratetisa i Tetisa. Stratigrafia Kainozoia Severnogo Pricernomoria i Krima. *Nauk. Trud.*, **2**, 95–105.

SEMENENKO, V.N. & OLEJNIK, E.S. (1995) Stratigraphic correlation of the Eastern Paratethys Kimmerian and Dacian stages by molluscs, dinocyst and nannoplankton data. *Rom. J. Stratigr.*, **76**(7), 113–114.

SEMENENKO, V.N. & PEVZNER, M.A. (1979) Correlation of Miocene and Pliocene of the Ponto-Caspian on the biostratigraphic and paleomagnetic data. *Proc. USSR Acad. Sci., Geol. Ser.*, **1**, 5–15.

SENEŠ, J. (1973) Correlation hypotheses of the Neogene Tethys and Paratethys. *Giorn. Geol.*, **39**(2), 271–286.

SHACKLETON, N.J., HALL, M.A. & PATE, D. (1995) Pliocene stable isotope stratigraphy of Site 846. In: *Leg 138* (Ed. by K. Sondra), *Proc. Ocean Drill. Progr., Sci. Results*, **138**, 337–355.

SISSINGH, W. (1972) Late Cenozoic ostracoda of the South Aegean island arc. *Utrecht Micropaleontol. Bull.*, **6**, 1–187.

SNEL, E., MARUNŢEANU, M., MACALET, R., MEULENKAMP, J.E. & VAN VUGT, N. (in press) Late Miocene to Early Pliocene chronostratigraphic framework for the Dacic Basin, Romania. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*

SPEZZAFERRI, S., CITA, M.B. & MCKENZIE, J. (1998) The Miocene/Pliocene boundary in the Eastern Mediterranean: results from Sites 967 and 969. In: *Leg 160* (Ed. by A.H.F. Robertson & K.-C. Emeis, *et al.*) *Proc. Ocean Drill. Progr., Sci. Results*, **160**, 9–28.

SPROVIERI, M., SACCHI, M. & ROHLING, E.J. (2003) Climatically influenced interactions between the Mediterranean and the Paratethys during the Tortonian. *Paleoceanography*, **18**(2), 1–10.

STANKOVIC, S. (1960) *The Balkan Lake Ohrid and its Living World. Monographiae Biologiae*, **Vol. 9**. Uitgeverij Dr W. Junk, The Hague, p. 357.

STEVANOVIĆ, P.M., NEVESSKAYA, L.A., MARINESCU, F., SOKAC, A. & JAMBOR, A (eds.) (1990) *Chronostratigraphie und Neostratotypen, Neogen der Westlivhen ("Zentrale") Paratethys*, **Vol. 8** (pp. 1–952. Jazu and Sanu, Zagreb-Belgrad, Pontien.

STOFFERS, P. & MÜLLER, G. (1978) Mineralogy and lithofacies of Black Sea sediments, Leg 42B Deep Sea Drilling Project. In: *Leg 42B* (Ed. by D.A. Ross & Y.P. Neprochnov, *et al.*) *Init. Rep. Deep Sea Drill. Proj*. **42**(2), 373–390.

SUC, J.-P. & BESSAIS, E. (1990) Pérennité d'un climat thermoxérique en Sicile, avant, pendant, après la crise de salinité messinienne. *C. R. Acad. Sci. Paris*, **310**(ser. 2), 1701–1707.

SÜTÖNÉ SZENTAI, M. (1989) Microplankton flora of the Pannonian sequence of the Szentlorinc-XII structure exploratory well. *Földtani Közlöny*, **119**, 31–43.

SYRIDES, G.E. (1995) Neogene mollusk faunas from Strymon basin, Macedonia, Greece. First results for biochronology and palaeoenvironment. *Geobios*, **18**(sp. issue), 381–388.

SYRIDES, G.E. (1998) Paratethyan mollusc faunas from the Neogene of Macedonia and Thrace, Northern Greece. *Rom. J. Stratigr.*, **78**, 171–180.

SYRIDES, G.E. (2000) Neogene marine cycles in Strymon basin, Macedonia, Greece. *Geol. Soc. Greece*, **9**(sp. publ.), 217–225.

ŢICLEANU, N. & DIACONIŢA, D. (1997) The main coal facies and lithotypes of the Pliocene coal Basin, Oltenia, Romania. In: *European Coal Geology and Technology* (Ed. by R. Gayer & J. Pesek), *Geol. Soc. Sp. Publ.*, **125**, 131–139.

VIDAL, L., BICKERT, T., WEFER, G. & ROHL, U. (2002) Late Miocene stable isotope stratigraphy of SE Atlantic ODP Site 1085: Relation to Messinian events. *Mar. Geol.*, **180**, 71–85.

VISMARA SCHILLING, A., STARDNER, H., CITA, M.B. & GAETANI, M. (1976) Stratigraphic investigations on the late Neogene of Corfou (Greece) with special reference to the Miocene/Pliocene boundary and to its geodynamic significance. *Mem. Soc. Geol. Iter.*, **16**, 279–317.

WARNY, S., BART, P.J. & SUC, J.-P. (2003) Timing and progression of climatic, tectonic and glacioeustatic influences on the Messinian Salinity Crisis. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **202**, 59–66.

WINTER, A., JORDAN, R.W. & ROTH, P.H. (1994) Biogeography of living coccolithophores in ocean waters. In: *Coccolithophores* (Ed. by A. Winter & W.G. Siesser), pp. 161–177. Cambridge University Press, Cambridge.

ZAGORCHEV, I. (2002) Neogene fluviolacustrine systems in the Northern Peri-Aegean region. *Geol. Balcanica*, **32**(2–4), 139–144.

Manuscript received 8 May 2002; Manuscript accepted 10 May 2005.