

Paleoenvironmental reconstruction of the Middle Eocene Trieste-Pazin basin (Croatia) from benthic foraminiferal assemblages

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ABSTRACT: Foraminiferal assemblages from four stratigraphic sections of the Trieste-Pazin basin in central Istria, Croatia (southwestern Tethyan realm) were investigated to reconstruct paleoenvironmental conditions and to determine the age of these deposits. The following five Middle Eocene planktonic foraminiferal zones were identified from the range and frequency of foraminiferal species: *Globigerinatheka kugleri*/*Morozovella aragonensis* Zone (E9), *Acarinina topilensis* Zone (E10), *Morozovelloides lehneri* Zone (E11), *Orbulinoides beckmanni* Zone (E12), and *Morozovelloides crassatus* Zone (E13). A data set of benthic foraminifera relative frequency has been subjected to R- and Q-mode cluster analyses to demonstrate the linkage between taxa distribution and paleoenvironmental gradients. Benthic foraminiferal biofacies indicate that the environment evolved from an initially mesotrophic upper bathyal slope setting towards a deeper, more oligotrophic, middle bathyal setting influenced by turbidity currents. The oligotrophy was a result of the deepening processes, and a consequential decrease in organic flux. The documented short-term periods of eutrophic to mesotrophic conditions within the deeper oligotrophic regime might represent a paleoceanographic influence of water-masses from an adjacent basin to the northwest, thus recording its paleogeographic connection with the Trieste-Pazin basin during the Middle Eocene (Lutetian).

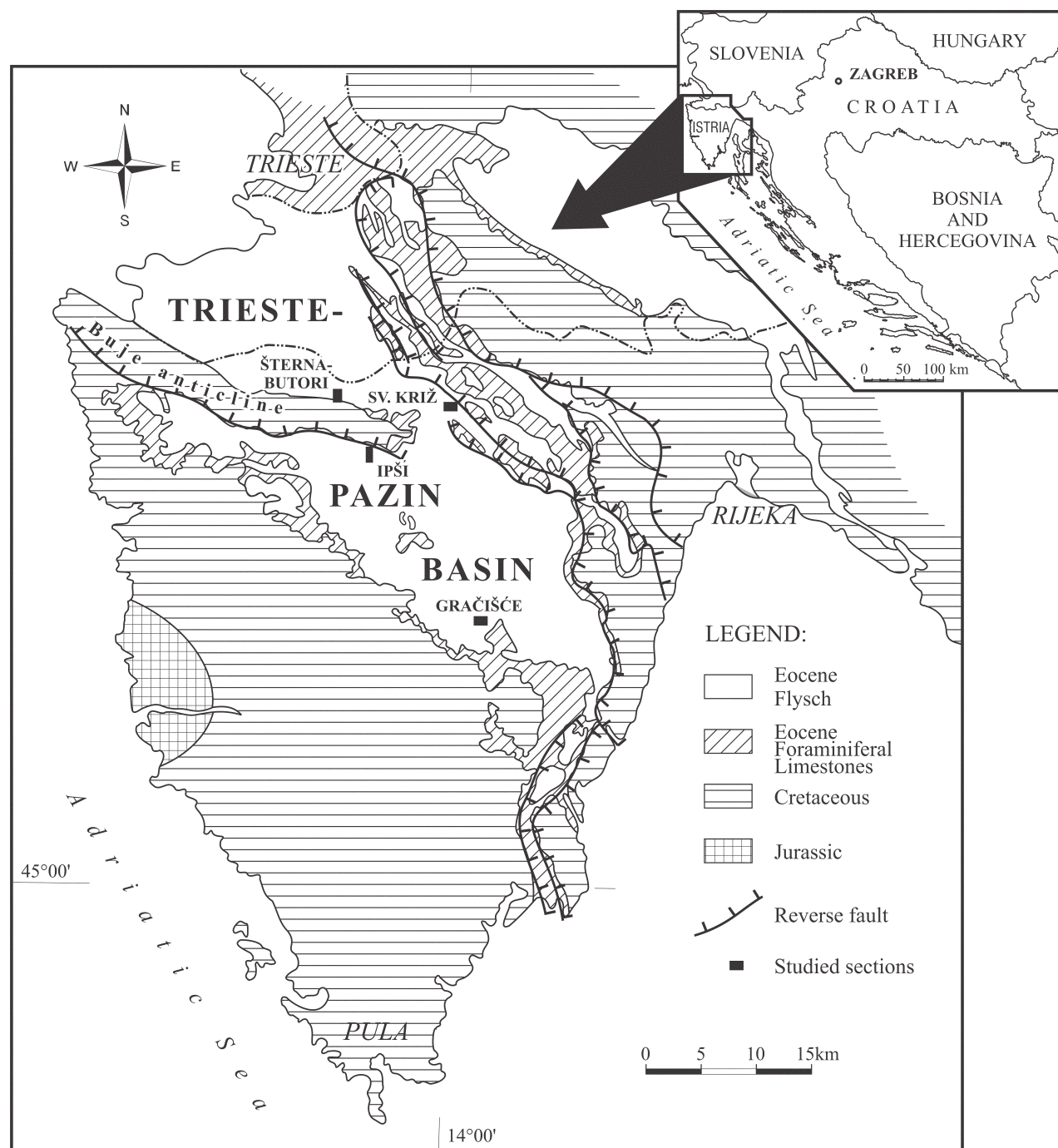
INTRODUCTION

The Middle Eocene deposits of the Alpine Tethys region are of great interest because they represent the final phase of a wide-spread and long-lasting, predominantly shallow marine sedimentation (Upper Triassic through Cretaceous), that resulted in 3500 to 5000m-thick carbonate platform deposits. During the Late Cretaceous and Early Paleogene, the collisional processes of the Adria plate and European plate led to the disintegration of the Adriatic Carbonate Platform producing both emerged (tilted) blocks with subaerial exposure and deep water siliciclastic deposition in localized small foreland basins. Very little is known, however, about paleoenvironmental conditions and paleogeographic settings of many of these individual foreland basins. The present study focuses on one such basin of the southwestern Tethyan realm, the Trieste-Pazin basin of central Istria, Croatia (text-fig. 1), because of the availability of well exposed outcrops and potential for examining thick, more or less continuous stratigraphic sections. Previous studies of these Middle Eocene clastic strata have mostly focused on provenance analyses and paleocurrent reconstructions that revealed hemipelagic *Globigerina* Marls overlain by proximal and distal Flysch facies (e.g., Schubert 1905; Magdalenic 1972), deposited in depths estimated to be greater than 1000m (e.g., Gohrbandt et al. 1960, 1962), with longitudinal and transverse paleotransport directions (e.g., Marjanac 1991; Orehek 1991). New paleobiogeographic interpretations are now possible because of the ever increasing knowledge about benthic foraminifera from deep-sea deposits and their potential in paleoceanographic reconstructions. Benthic foraminiferal assemblages from the Middle Eocene clastic sediments were analyzed here to gain insights into paleoenvironmental and paleogeographic reconstruction of the Trieste-Pazin basin. Faunal analyses were conducted on four stratigraphic sections in different parts of the basin. These sections represent different

parts of the Middle Eocene stratal succession because the sedimentation commenced and ended at different times in various parts of the basin, depending on its evolution.

Paleoenvironmental reconstructions stem from biofacies interpretations, which are based on a cluster analysis of the relative frequency data combined with the quantitative parameters of the foraminiferal assemblages (diversity, dominance, percentage of epifaunal vs. infaunal foraminifera, and percentage of agglutinated foraminifera). These paleoenvironmental indicators were used to evaluate possible variations in the main influences on the benthic foraminiferal faunas in different parts of the Trieste-Pazin basin at different times. The influences interpreted from the biofacies analyses include paleobathymetry, organic matter flux and the type of organic matter, and oxygen levels in bottom waters. These controlling factors were placed within the biostratigraphic framework to provide paleogeographic implications for this marginal narrow basin. Additionally, multi-faceted paleobathymetric determinations carried out in this study led to a revision of water depth interpretations for the deposition of part of the Middle Eocene succession from this region.

Previous studies of the Middle Eocene clastic successions from Istria focused mostly on planktonic foraminifera in order to biostratigraphically define the age of these deposits (Schubert 1904; Gohrbandt et al. 1960, 1962; Muldini-Mamužić 1964; Krašeninnikov et al. 1968; Piccoli and Proto Decima 1969; Šikic et al. 1973). In some of these studies only a few benthic foraminifera were identified from larger fractions (Schubert 1904; Gohrbandt et al. 1960, 1962; Muldini-Mamužić 1960; Krašeninnikov et al. 1968). Ostracod faunal analyses were also conducted (Gohrbandt et al. 1960, 1962), and nannoplankton analyses were subsequently carried out to locate the youngest



TEXT-FIGURE 1

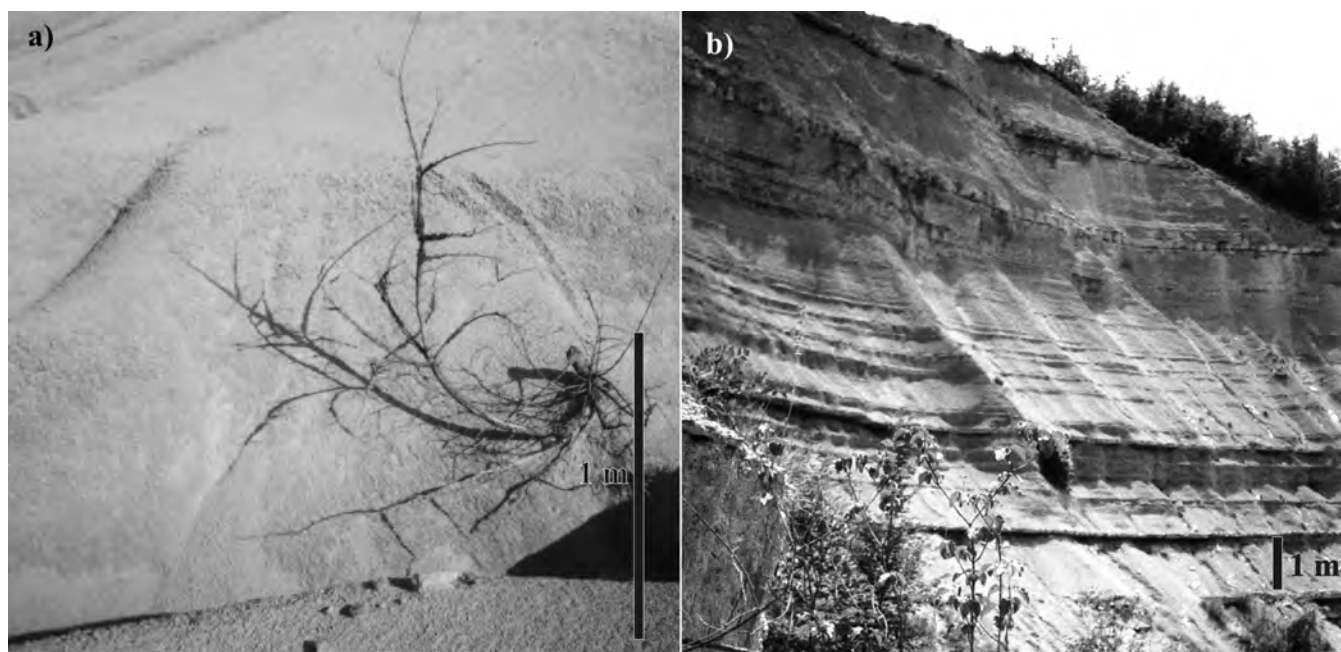
Geological map of Istria showing localities of the sections studied within the Trieste-Pazin basin. Simplified after Polšak and Šikic (1973), Šikic and Polšak (1973), Polšak (1967), Magaš (1968), Plenčar et al. (1974), Šikic et al. (1973), and Šikic et al. (1975).

sediments in the Trieste-Pazin basin, which were determined to be in the *Chiastmolithus oamaruensis* Zone (NP 18) of the Late Eocene (Benic 1991). The first detailed analyses of the benthic foraminiferal assemblages from the Middle Eocene clastic deposits of the Trieste-Pazin flysch basin were conducted by Živković (1996) and Živković and Babić (2003), and expanded in Živković (2004). These studies led to the first systematic reconstruction of trophic conditions and paleoenvironmental variability during the Middle to Late Eocene in the Trieste-

Pazin basin of Croatia. The results of this reconstruction are presented here because they provide new insights into important paleoceanographic characteristics of the southwestern Tethyan realm.

LOCATION AND STRATIGRAPHY OF THE STUDY AREA

The Trieste-Pazin basin is a foreland basin of Alpine type. Such basins are commonly dominated by marine flysch and pelagic



TEXT-FIGURE 2

Field photographs of the Eocene deposits from the Trieste-Pazin basin examined in this study: a) *Globigerina* marls; b) Flysch deposits.

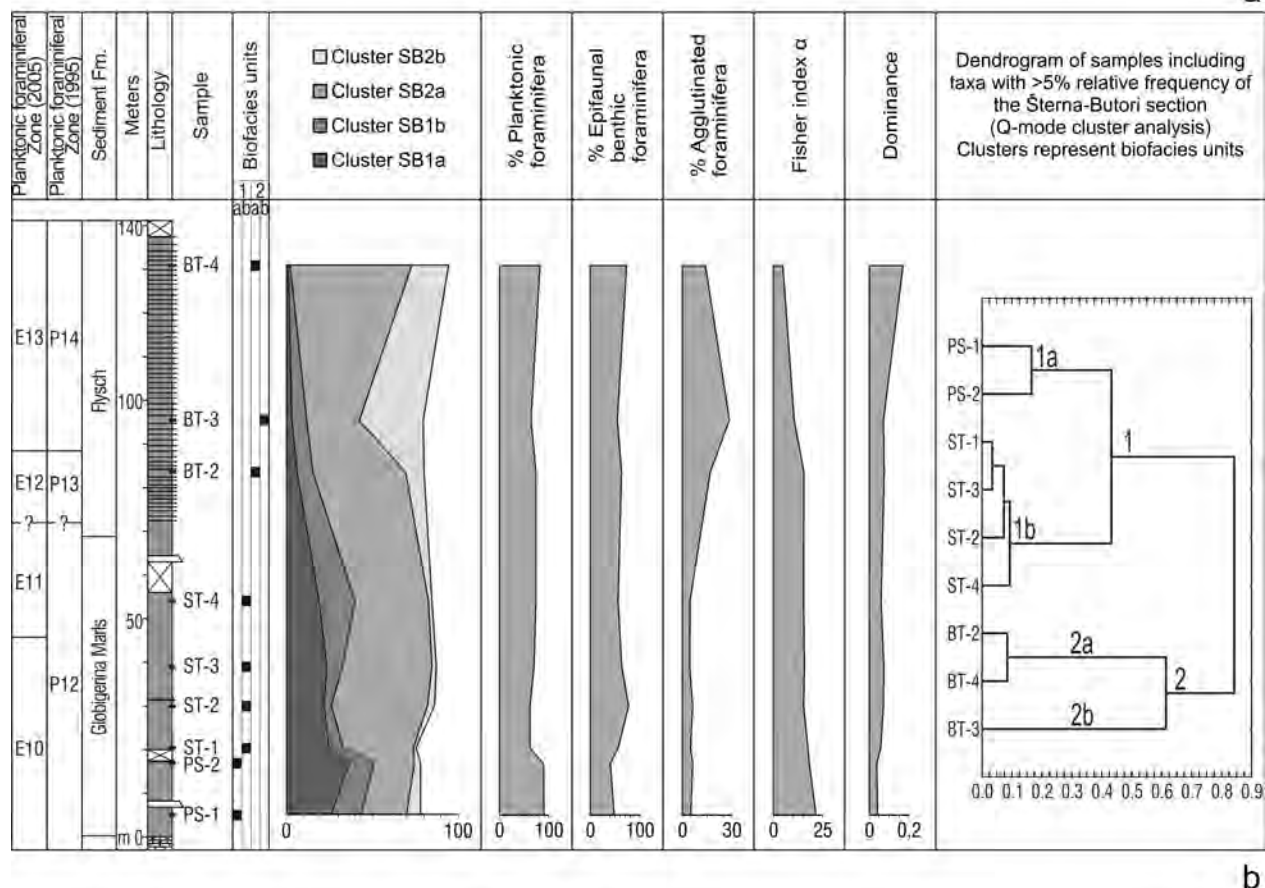
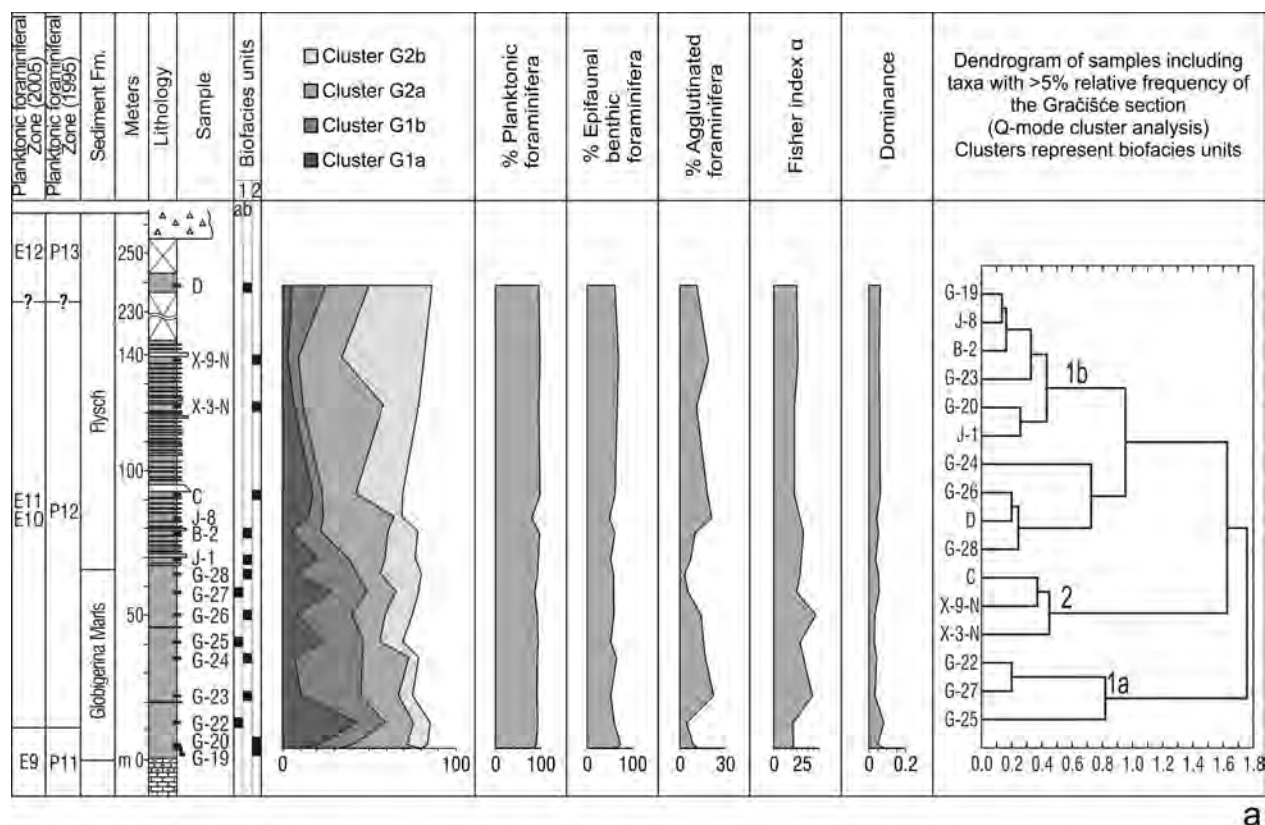
deposits (Ricci-Lucchi 2003). The Trieste-Pazin basin formed as a consequence of the subduction and closure of the Tethys ocean followed by a continent-continent collision between the European Plate and the Adria microplate beginning in the Cretaceous (Sissingh 2001). This basin was formed in the Middle Eocene, when Mesozoic carbonate platforms of the Tethys region, such as the Adriatic-Dinaridic Carbonate Platform (which separated from the Apenninic and Apulian platforms in the Lower Jurassic; Pamic et al. 1998, 2000; Vlahovic et al. 2005), became tectonically disintegrated due to intense collisional tectonics. The depositional settings gradually changed from shallow ramp-type carbonate platform deposition to deep basin flysch/turbidite deposition mainly controlled by intense synsedimentary tectonics (e.g., Vlahovic et al. 2005). The Lower to Middle Eocene carbonate platform deposits, known locally as the Foraminiferal Limestones, contain common large benthic foraminifera such as *Alveolina*, *Nummulites* and *Discocyclina*. These limestones are overlain by the so-called Transitional Beds (i.e., transitional to Flysch). The lowermost few meters of marly limestones from the Transitional Beds are commonly referred to as the “Marls with Crabs” and interpreted to reflect the gradual deepening from shelf to bathyal environments (Schubert 1904, 1905; Drobne 1977; Juracic 1979; Cosovic et al. 2004, 2006). The upper part of the Transitional Beds consists of several tens of meters of hemipelagic *Globigerina* Marls (text-fig. 2a), which are conformably overlain by coarser detrital deposits known as the Flysch or Flysch-like Beds (text-fig. 2b). These Flysch Beds consist of hemipelagic marls interbedded with calcarenites, sandstones, and carbonate breccias of gravity-flow origin (Magdalenic 1972).

Both the *Globigerina* Marls and the hemipelagic marls capping the turbidite sequences of the Flysch Beds (text-fig. 2) were the focus of this research at four locations within the Trieste-Pazin basin (text-fig. 1). This large Tertiary basin trends NW to SE

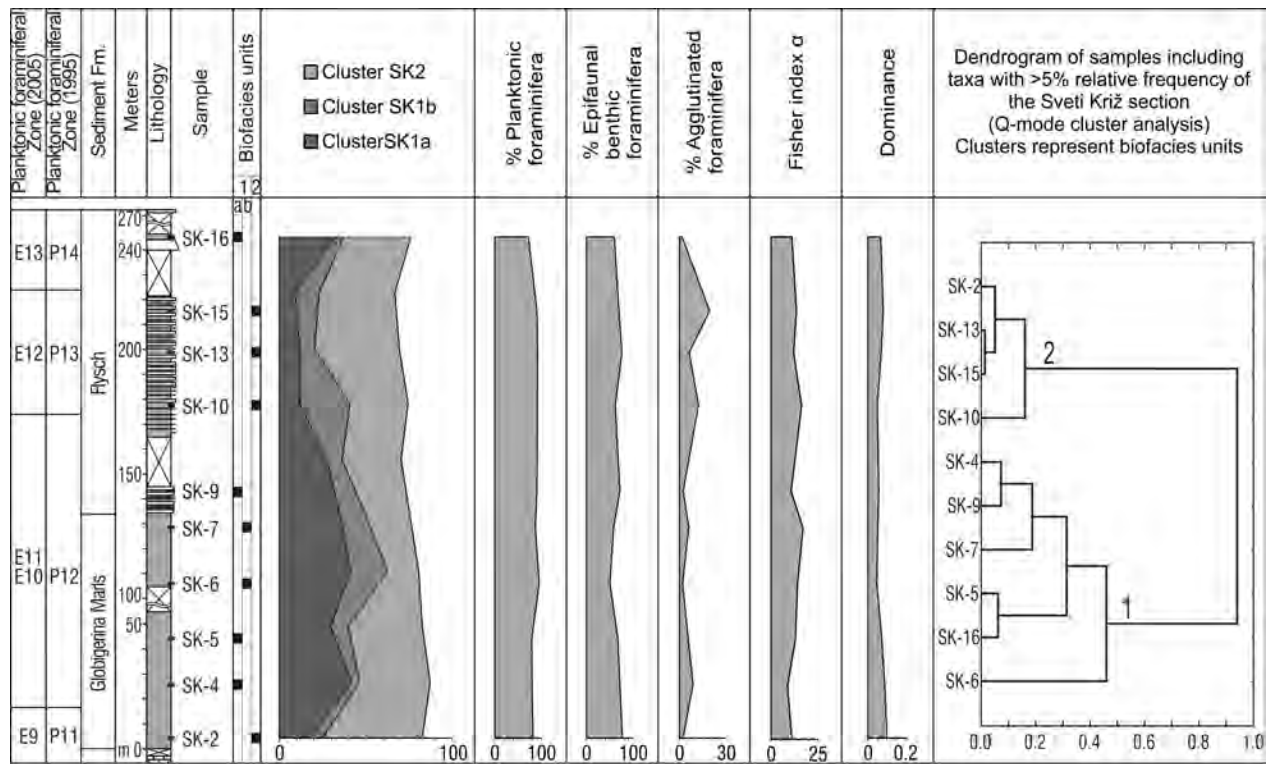
and is divided by a narrow neotectonic structure, known as the Buje anticline, into two parts: the Trieste basin to the north, and the Pazin basin to the south (Maticec 1994; text-fig. 1). Of the exposures studied, the Gracisce and Ipši sections are located in the Pazin basin, the Sveti Križ section in the eastern part of the Trieste-Pazin Basin, and the Šterna-Butori section in the southernmost part of the Trieste basin (text-fig. 1). The sections are 50 to 300m thick and include several tens of meters of the *Globigerina* Marls and/or more than 50m of decimeter-scale alternating hemipelagic marls and turbidite deposits (text-fig. 3). Planktonic foraminifera and calcareous nannoplankton determinations indicate that the investigated deposits are late Lutetian to early Priabonian in age (Krašeninnikov et al. 1968; Piccoli and Proto Decima 1969; Benic 1991; Živkovic 1996; Šparica et al. 2000; Živkovic and Babic 2003; Živkovic 2004). The compressional tectonics that took place by the end of the Late Eocene-Early Oligocene resulted in the closure of the entire Dinaridic Tethys (Pamic et al. 1998, 2000) whereas the flysch deposition in the Trieste-Pazin basin ended by the end of the Middle Eocene.

MATERIALS AND METHODS

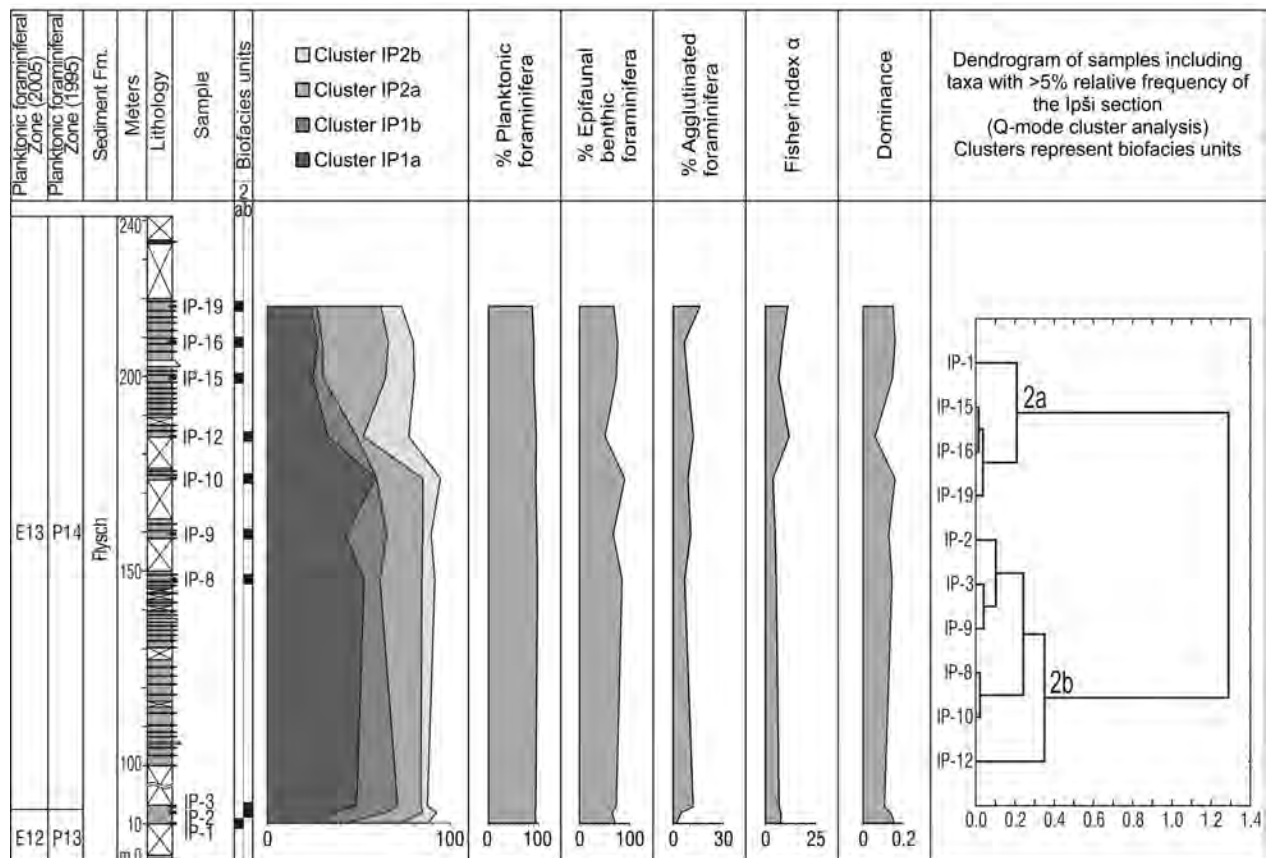
Samples examined in this study were collected from four sections (text-fig. 1). In the homogenous *Globigerina* Marls, samples were taken from the uniform and massive parts of the succession (text-fig. 2a). In the Flysch deposits (text-fig. 2b) samples were taken from the hemipelagic marls capping the turbiditic sequences. These marls are interpreted as hemipelagic because they contain <35% CaCO₃ as compared with up to 75% CaCO₃ in turbiditic mudstones overlying the calcarenitic intervals of the basal turbiditic sequences from the flysch deposits (Magdalenic 1972). Sampling frequency in the Flysch was lower than in the *Globigerina* Marls because of denser vegetation cover and incomplete exposure along less accessible steep cliffs (text-fig. 2b).



TEXT-FIGURE 3a, b
Results of the quantitative and paleoecological analyses of the benthic foraminiferal assemblages from the Eocene deposits of the Trieste-Pazin basin and the Q-mode cluster analysis dendrograms representing biofacies units from: a) the Gradišće section; b) the Šterna-Butori section.



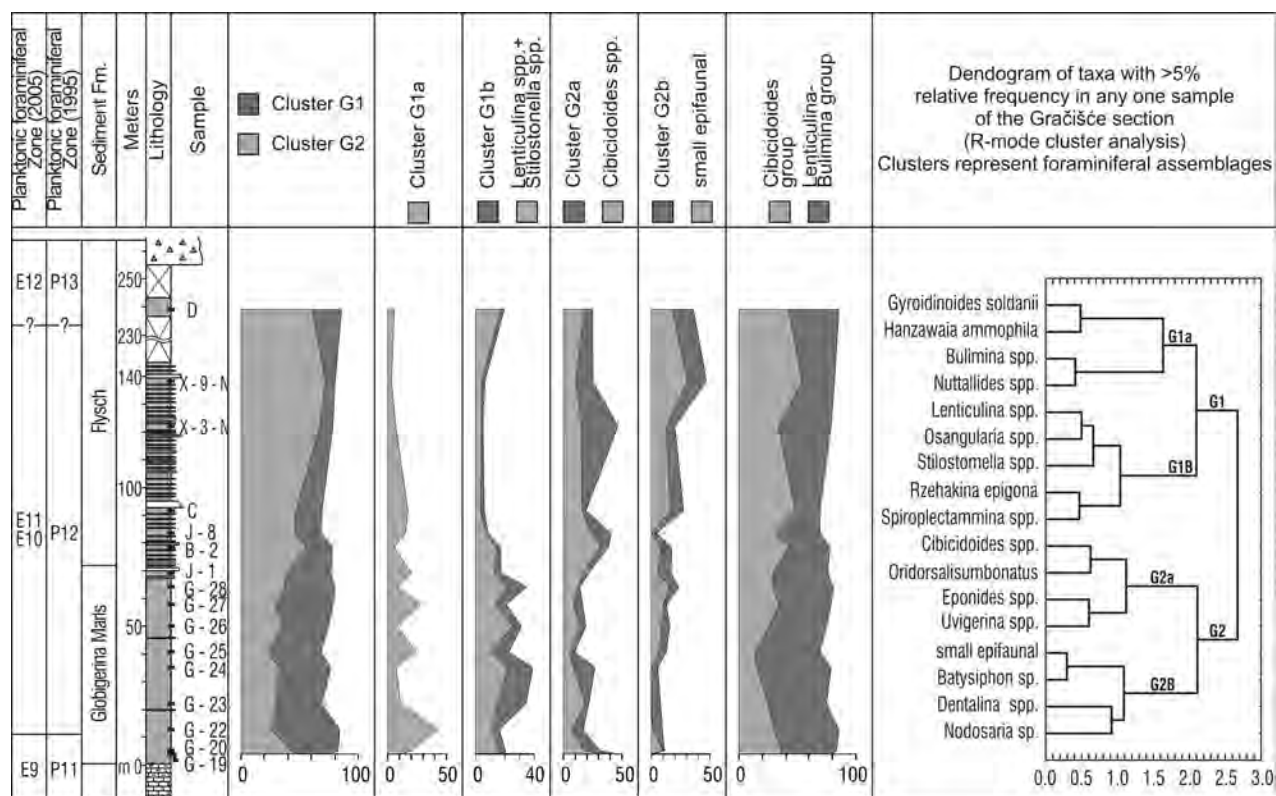
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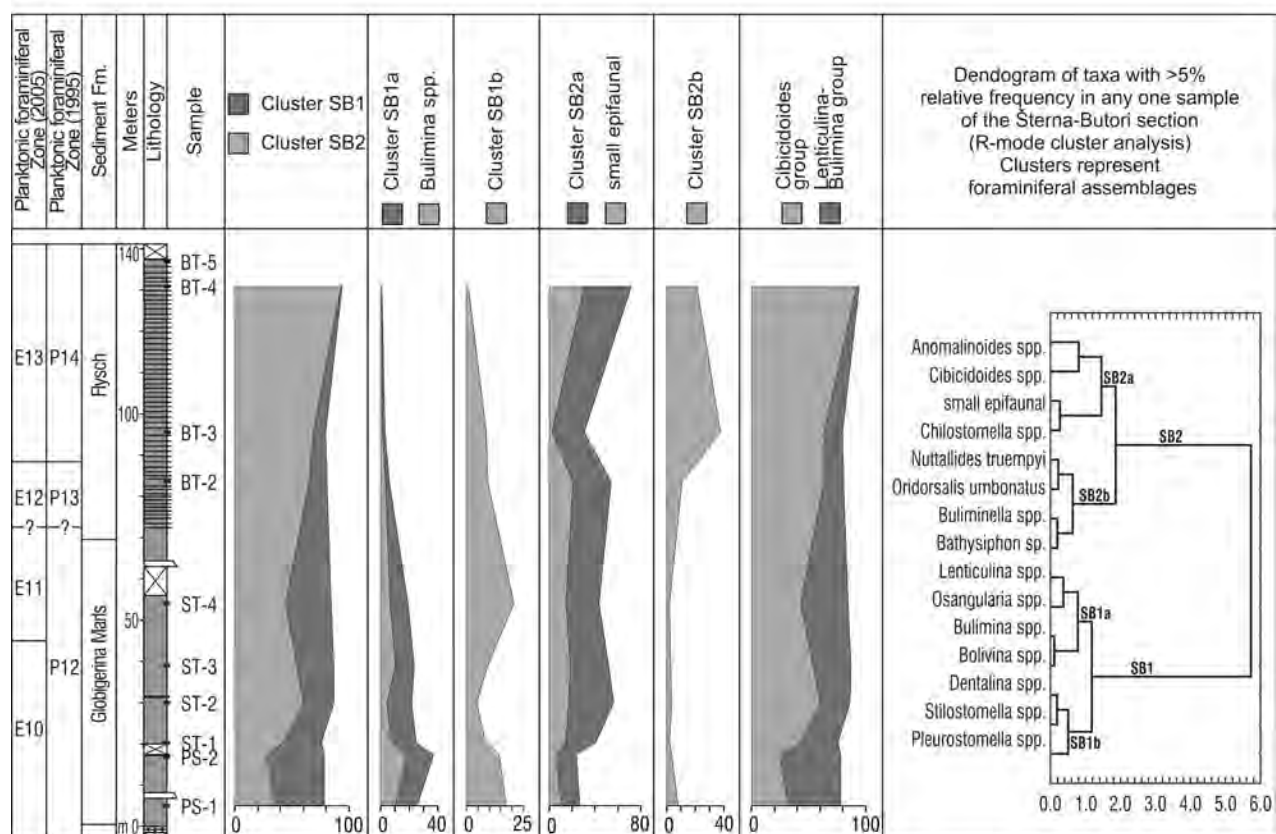
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TEXT-FIGURE 3c, d

Results of the quantitative and paleoecological analyses of the benthic foraminiferal assemblages from the Eocene deposits of the Trieste-Pazin basin and the Q-mode cluster analysis dendrograms representing biofacies units from: c) the Sveti Križ section; d) the Ipš section.



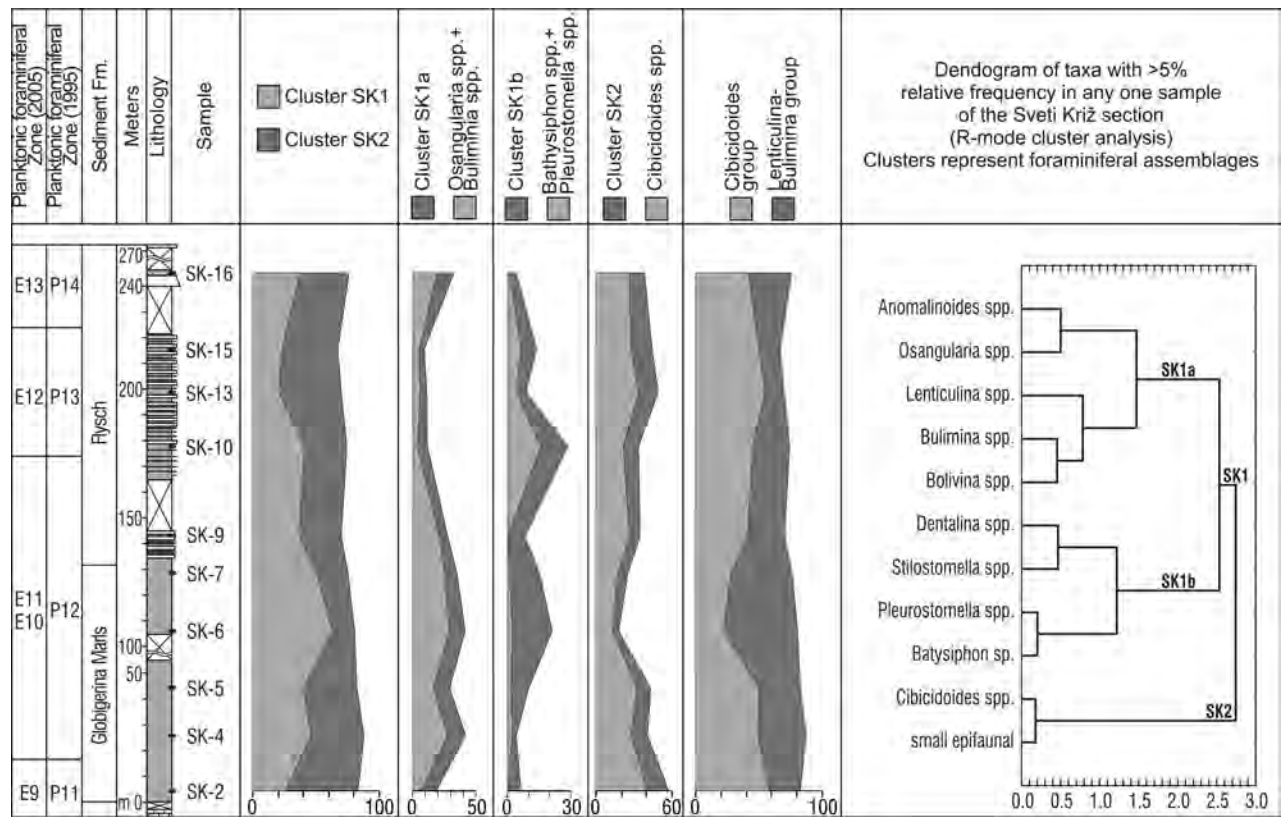
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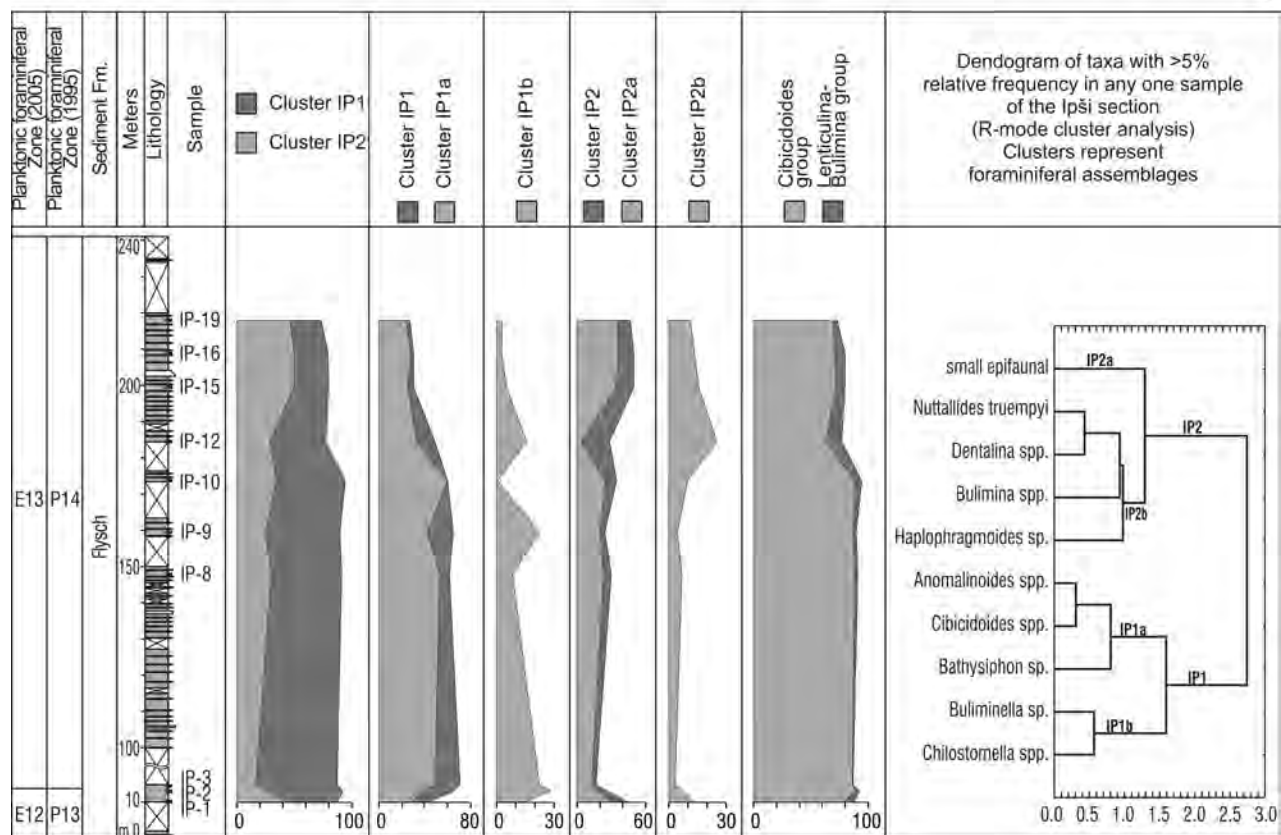
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TEXT-FIGURE 4a, b

Results of the R-mode cluster analysis on foraminiferal assemblages from: a) the Gračišće section; b) the Šterna-Butori section.



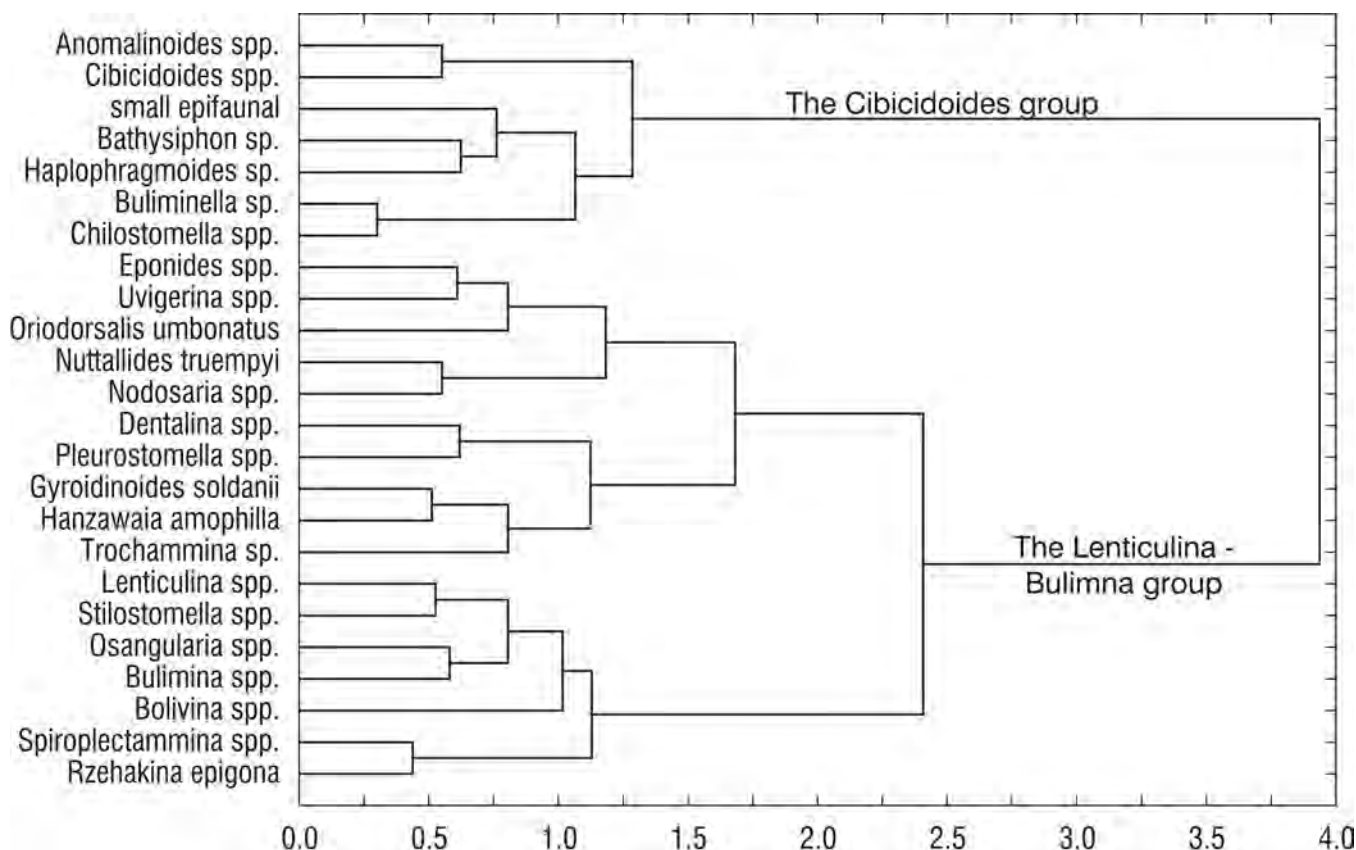
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d

TEXT-FIGURE 4c, d

Results of the R-mode cluster analysis on foraminiferal assemblages from: c) the Sveti Križ section; d) the Ipš section.



TEXT-FIGURE 5a
Cluster analysis dendrograms for the data from all samples from all four sections: a) Q-mode cluster analysis dendrogram.

All the samples collected were crushed, soaked in solution of hydrogen peroxide for 24 hours, washed over the 1000 and 63µm sieves, and dried. The coarser fraction was stored because it did not contain any foraminifera. The finer-grained fraction was split on a Retsch microsplitter to prepare suitable splits with approximately 200-400 benthic foraminifera. After determining the planktonic/benthic ratio in a sample (i.e., percentage of planktonic foraminifera), 100 planktonic and all benthic foraminifera were picked, identified and stored in Franke slides (which are part of the collection of the senior author). Most benthic taxa were identified at the species level and counted, although many individuals of small and juvenile trochospiral foraminifera were often described as “small epifaunal foraminifera” because they could not be identified even on a generic level due to their small size. Total counts of benthic and planktonic species determined in this way are presented in Appendices A-D.

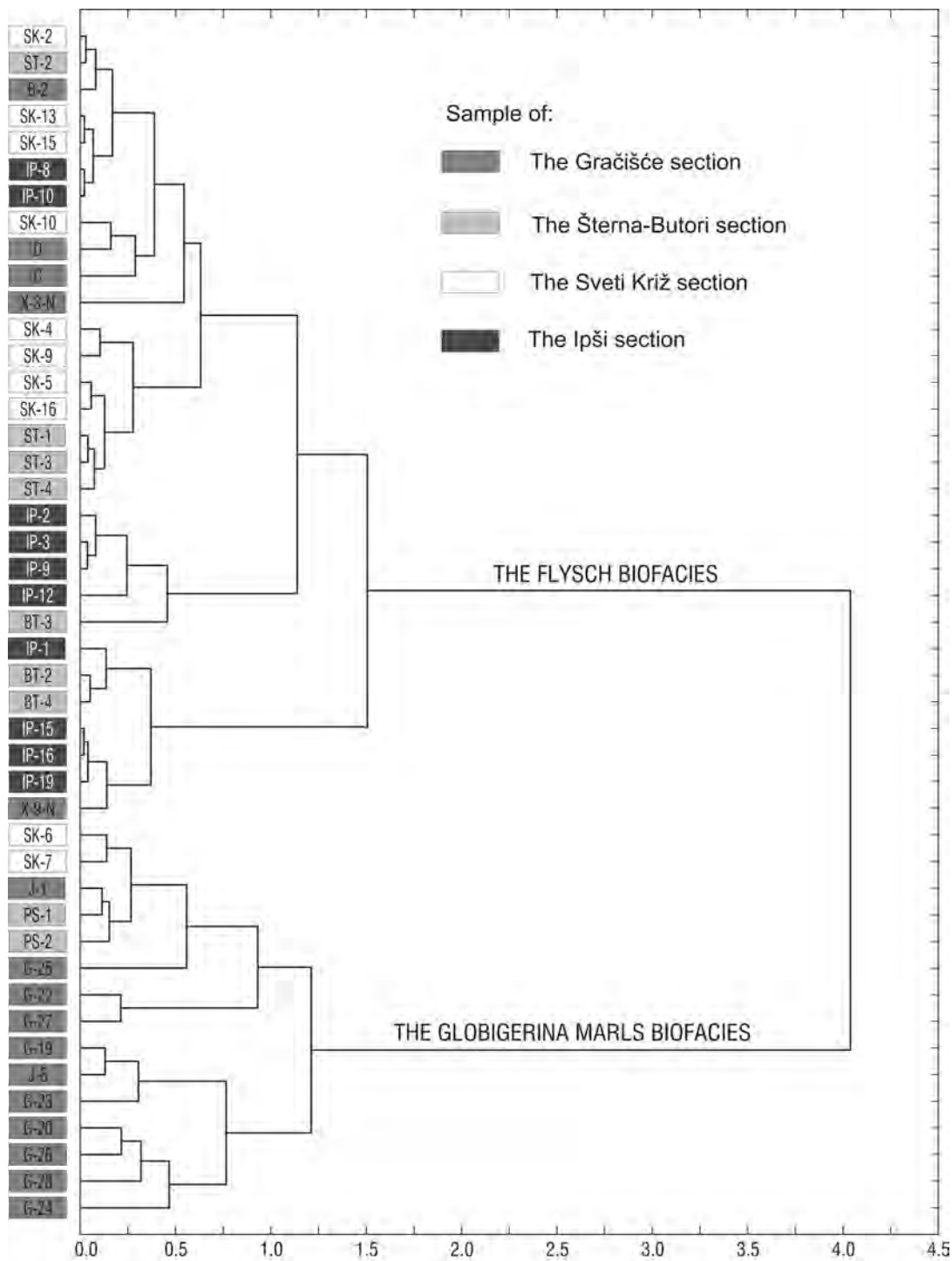
Calcareous benthic foraminiferal tests are more resistant to post mortem dissolution than planktonic tests (Berger 1979; for review see also Douglas and Woodruff 1981). As juvenile tests of both planktonic and benthic foraminifera are particularly vulnerable to dissolution (Premoli Silva and Boersma 1988), the rich and well-preserved planktonic foraminiferal assemblages, as well as the large number of juveniles within the benthic assemblages, testify to good preservation of the foraminiferal association in the samples examined here (Apps. A-D). Most of the tests are filled with carbonate mud and cement. Such infilling of the tests increased their chances for preservation.

Taxonomic determination of planktonic foraminifera was based on Toumarkine and Luterbacher (1985), Bolli and Saunders (1985), Premec-Fucek (1995), Premec-Fucek et al. (1998), Pearson et al. (2006) and Premoli Silva and Petrizzo (2006). Biostratigraphic zonation based on planktonic foraminifera followed the work of Berggren and Pearson (2005, 2006) (“E” zones), but the correlation to the “P” zones of Berggren et al. (1995) is also provided for direct comparison. If zonal markers were absent, then zone boundaries were placed following the criteria of Pearson et al. (2006) and Premoli Silva and Petrizzo (2006).

Quantitative parameters used in the analysis of benthic associations (diversity expressed by Fisher index α and dominance, text-fig. 3) were calculated using PAST software (Hammer 2002). The percentages of planktonic foraminifera in samples and the abundances of agglutinated foraminifera in benthic assemblages were also calculated (text-fig. 3).

Determination of paleobathymetry involved the commonly used ratio between planktonic and benthic foraminifera (expressed as percentage of planktonic foraminifera) and the occurrence, abundance, and upper depth limits of depth-restricted species (Table 1). Bathymetric divisions were used as defined by Van Morkhoven et al. (1986): neritic (0-200m), upper bathyal (200-600m), middle bathyal (600-1000m), and lower bathyal (1000-2000m).

To infer probable microhabitat preferences of benthic foraminifera, they were allocated to epifaunal and infaunal



TEXT-FIGURE 5b

Cluster analysis dendrograms for the data from all samples from all four sections: b) R-mode cluster analysis dendrogram.

morphogroups following Corliss (1985, 1991), Jones and Charnock (1985), and Corliss and Chen (1988) (Table 2). Trochospiral (rounded trochospiral, plano-convex trochospiral, and biconvex trochospiral) and milioline test morphologies, as well as tubular and branching, coiled flattened and streptospiral tests of agglutinated foraminifera, have been related to epifaunal microhabitats (Table 2). Although *Lenticulina* spp. has a planispiral coiling mode, it was placed in the biconvex

trochospiral category because of its well-defined biconvex shape and the lack of surface pores (following the work of Corliss and Chen 1988). On the other hand, calcareous foraminifera with rounded planispiral, tapered/cylindrical, flattened tapered, spherical/globose or flattened ovoid tests with pores covering the entire surface, and agglutinated forms with elongate multilocular, flattened trochospiral and globular tests, have all been associated with infaunal microhabitats (Table 2; Corliss

1985, 1991; Jones and Charnock 1985; Corliss and Chen 1988). This division is in general agreement with most published information dealing with benthic foraminiferal microhabitats, although there are some exceptions (e.g., Corliss 1985, 1991; Gooday 1986; Mackensen and Douglas 1989; Barmawidjaja et al. 1992; Buzas et al. 1993; Widmark 1995; De Stigter et al. 1998; Alegret et al. 2003). The association of test morphologies with the microhabitat preferences seems to be confirmed by studies in the California Borderland (Bernhard 1992), the Adriatic Sea (De Stigter 1996), and Sagami Bay, Japan (Ohga and Kitazato 1997). There are, however, some notable exceptions: the connection between test morphology and microhabitat was not observed in the studies of Bernhard (1986), Sen Gupta and Machain-Castillo (1993), and Alve and Bernhard (1995). Even though microhabitats have often been extrapolated from data on other similar taxa (e.g., Jorissen 1999), particularly in the case of extinct species, the connection between test morphology and microhabitat of infaunal taxa may be accurate in about 75% of the cases (Buzas et al. 1993; Jorissen 1999). The abundance of benthic foraminifera with tests considered as epifaunal was calculated (text-fig. 3), because food availability alone (e.g., Lutze and Coulbourn 1984; Shirayama 1984; Corliss 1985; Corliss and Chen 1988; Mackensen and Douglas 1989; Altenbach 1992) or in conjunction with oxygen levels, has been suggested as a controlling factor on benthic microhabitat distribution in a number of studies (e.g., Douglas and Woodruff 1981; Gooday 1986; Corliss and Chen 1988; Mackensen and Douglas 1989; Corliss and Emerson 1990; Rosoff and Corliss 1992; Barmawidjaja et al. 1992; Jorissen et al. 1992, 1995; Rathburn and Corliss 1994; Gooday and Rathburn 1999). The ability of individual taxa to change their microhabitat preference to obtain optimal food and oxygen levels (e.g., Jorissen 1988; Corliss and Emerson 1990; Barmawidjaja et al. 1992), however, presents additional difficulty in interpreting ancient microhabitats from benthic foraminiferal distribution.

A statistical evaluation was performed on the relative frequency data by means of R-mode and Q-mode cluster analysis (Ward's method, 1-Pearson r coefficient). Many species were grouped at the genus level, such as *Lenticulina* spp., *Bulimina* spp., *Dentalina* spp., *Pleurostomella* spp., *Stilostomella* spp., *Cibicidoides* spp., *Bolivina* spp., *Osangularia* spp., *Anomalinoides* spp., *Spiroplectammina* spp., *Eponides* spp., *Uvigerina* spp., *Chilostomella* spp., and *Buliminella* spp. To avoid having extremely large data sets only those genera and individual species of foraminifera with frequencies exceeding 5% in at least one sample of the particular section were considered. Statistical evaluation was performed for each section separately and for all four sections together. In the data set for all sections, all of the taxa included in all four sections were plotted to reveal assemblage differences between sections. R-mode clustering was utilized to define foraminiferal assemblages (text-fig. 4), and Q-mode clustering was used to characterize biofacies units (text-fig. 3). Biofacies units, together with species distribution, abundance, diversity patterns as well as epi- and infaunal abundances, were used to indicate changes in environmental parameters such as general trophic and oxic characteristics of the paleoenvironment.

RESULTS

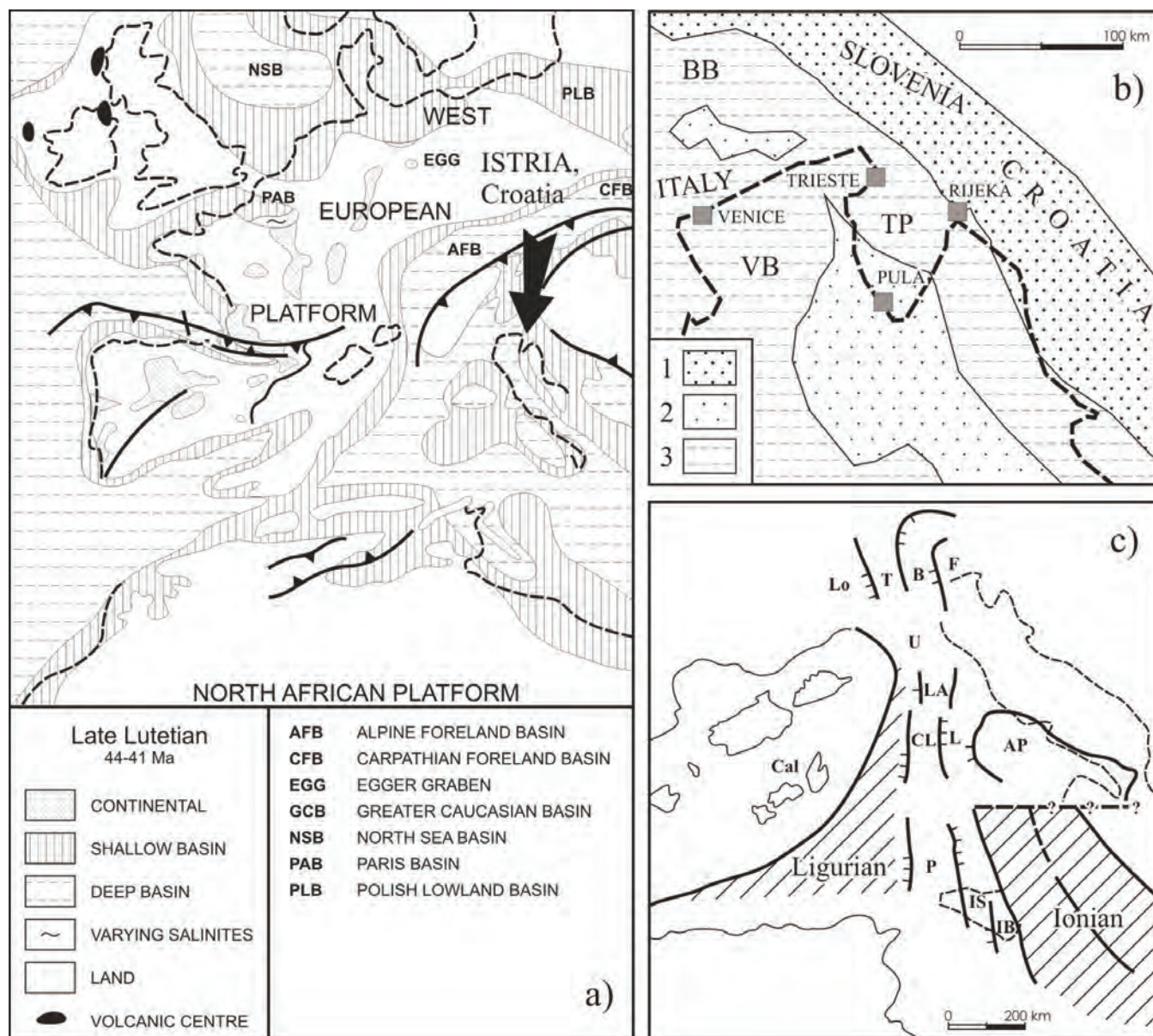
Biostratigraphy

The observed range and frequency of planktonic foraminiferal species in the four investigated sections enabled the recognition of five Middle Eocene planktonic foraminiferal zones of

Berggren and Pearson (2005, 2006). These are: *Globigerinatheka kugleri*/*Morozovella aragonensis* Zone (E9), *Acarinina topilensis* Zone (E10), *Morozovelloides lehneri* Zone (E11), *Orbulinoides beckmanni* Zone (E12), and *Morozovelloides crassatus* Zone (E13) (text-figs. 3 and 4).

The Concurrent-range Zone *Globigerinatheka kugleri*/*Morozovella aragonensis* (E9) is represented in the Gradišće and Sveti Križ sections by the rich and well preserved planktonic foraminiferal assemblage containing abundant *Morozovella aragonensis* (Nuttall 1930) (Pl. 1, fig. 1), *Acarinina bullbrooki* (Bolli 1957), *A. punctocarinata* Fleisher 1974 (Pl. 1, fig. 2), *Globigerinatheka subconglobata* (Shuskaya 1958), *Gk. mexicana* (Cushman 1925), *Turborotalita carcoselleensis* (Toumarkine and Bolli 1970), *Subbotina eocaena* (Guembel 1868), *S. hagni* (Gohrbandt 1967), *Turborotalia frontosa* (Subbotina 1953) (Pl. 1, fig. 3), and *T. possagnoensis* (Toumarkine and Bolli 1970) (Pl. 1, fig. 4; Apps. A and C). The upper Zone boundary was placed above the highest occurrence of the zonal marker *Morozovella aragonensis* in the Gradišće section (App. A), whereas in the Sveti Križ section, where this zonal marker was not found, the upper Zone boundary was placed approximately above the highest occurrence of *Igorina broedermanni* (Cushman and Bermúdez 1949) (Pearson et al. 2006; Premoli Silva and Petrizzo 2006; App. C).

The Partial-range Zone *Acarinina topilensis* (E10) has been defined in the Gradišće, Sveti Križ and Šterna-Butori sections (but see also Šparica et al. 2000 and Tarlao et al. 2005 for different biostratigraphic interpretations). The upper Zone boundary in the Šterna-Butori section was placed above the highest occurrence of *Guembelitrioides nuttalli* (Hamilton 1953) (Pearson et al. 2006) (text-figs. 3 and 4; App. B). This marker species is not present in the Gradišće and Sveti Križ sections and therefore the E10 and E11 Zone interval corresponding to the *Morozovella lehneri* Zone (P12) of Berggren et al. (1995), has not been subdivided. The assemblages of planktonic foraminifera in Zones E10 and E11 are characterized by the rich association of *Acarinina bullbrooki*, *A. punctocarinata* (see Pl. 1), *Globigerinatheka subconglobata*, *Gk. mexicana*, *Turborotalita carcoselleensis*, *Pseudohastigerina micra* (Cole 1927), *Subbotina hagni*, *S. eocaena*, *S. linaperta* (Finlay 1957), *S. senni* (Beckmann 1953), *Turborotalia frontosa* (see Pl. 1), *T. possagnoensis* (see Pl. 1), and *T. pomeroli* (Toumarkine and Bolli 1970) (App. B). The upper boundary of the *Morozovelloides lehneri* (E11) Partial-range Zone in the Gradišće and Sveti Križ sections has been placed below the lowest occurrence of *Orbulinoides beckmanni* (Saito 1962) (Pl. 1, fig. 5; Apps. A and C). In the Šterna-Butori section, because of the absence of zonal markers, the upper Zone boundary was placed below the first occurrences of *Turborotalia cerroazulensis* (Cole 1970), which appears in the *Orbulinoides beckmanni* Zone in the Mediterranean region (Berggren and Pearson 2005). This Zone boundary approximately corresponds to the highest occurrences of *Turborotalia frontosa* and *T. possagnoensis* (see Pl. 1; App. B) (Pearson et al. 2006; Premoli Silva and Petrizzo 2006) as recorded in the Šterna-Butori section. The planktonic foraminiferal assemblages in Zone E11 are characterized by *Acarinina bullbrooki*, *A. punctocarinata* (see Pl. 1), *Morozovelloides crassatus* (Cushman 1927), *Subbotina linaperta*, *S. yeguaensis* (Weinzierl and Applin 1929) (Pl. 1, fig. 6), *S. corpulenta* (Subbotina 1953), *Globigerina praebulloides occlusa* (Blow and Banner 1962), *G. officinalis* Subbotina 1953, *Turborotalita carcoselleensis*, *Globigerinatheka luterbacheri* Bolli 1972, *Gk. subconglobata*, *Pseudohastigerina*



TEXT-FIGURE 6

Paleogeographic reconstructions of the study area in Istria, Croatia: a) Paleogeographic map of the western Tethys region showing Istria as a narrow, shallow basin between a deep basin to the west and the land to the east during the Late Lutetian (from Meulenkamp and Sissingh 2003); b) Paleogeographic map of the Adriatic region during the Lutetian (Zone E9) showing location of the Trieste-Pazin basin (TP) and adjacent Belluno (BB) and Venetian (VB) basins (from Jenko and Bisticic 1978, and Tarla et al. 2005). Symbol explanation: 1-land, 2-submerged platform, 3-basin; c) Paleogeography of the central Mediterranean region during the Paleogene showing Istria as a part of the Friuli-Istria platform (F) adjacent to the Belluno basin (B) of northern Italy (from Muttoni et al. 2001). Lo-Lombard basin, U-Umbria-Marche basin, LA-Laziale-Abruzzese platform, CL-Campano-Lucana platform, L-Lagonegro basin, T-Trento Plateau, AP-Apulia-Gargano platform, P-Panormide platform, IS-Imerese-Sicani basins, IB-Iblei platform, Cal-Calabria block.

micra, *Turborotalia frontosa* (see Pl. 1), *T. possagnoensis* (see Pl. 1), and *T. pomeroli* (App. B).

The Taxon-range Zone *Orbulinoides beckmanni* (E12) was recognized in the Gracišće, Sveti Križ, Šterna-Butori, and Ipši sections (text-figs. 3 and 4). The zonal marker *Orbulinoides beckmanni* (see Pl. 1) has been found in very low numbers in the assemblages of the Gracišće and Sveti Križ sections (Apps. A and C). In the Gracišće section, the *O. beckmanni* Zone repre-

sents the top of the section. In the Sveti Križ section the last occurrence of *O. beckmanni* defines the upper boundary of the E12 Zone. In the Šterna-Butori section, because of the absence of zonal marker, the upper Zone boundary was approximately placed above the highest occurrence of *Globigerinatheka euganea* Proto Decima and Bolli 1970 and the lowest occurrence of *Gk. luterbacheri* (Pearson et al. 2006; Premoli Silva and Petrizzo 2006) (App. B). In the Ipši section, the Zone E12 is present in the lowermost part of the section and its upper bound-

TABLE 1

Paleobathymetric assignments of species and their upper depth limits with the sources of information.

Depth related species	Upper depth limit	Common distribution
<i>Anomalinoidea capitatus</i>	600m (1)	upper bathyal (2)
<i>Aragonia aragonensis</i>	200m (1)	primarily bathyal and abyssal form (2)
<i>Bathysiphon</i> spp.		lower slope (4)
<i>Bulimina corrugata</i>		bathyal (3)
<i>Bulimina jarvisi</i>	1000m (1)	primarily lower bathyal and abyssal (2)
<i>Bulimina tuxapamensis</i>	500m (1)	
<i>Cassidulina</i> spp.		middle bathyal (3)
<i>Cibicidoides alazanensis</i>	100m (1)	primarily upper and middle bathyal (2)
<i>Cibicidoides barnetti</i>	200m (1)	lower-middle bathyal (2)
<i>Cibicidoides eocaenus</i>	100m (1)	middle to lower neritic and uppermost bathyal (2)
<i>Cibicidoides grimsdalei</i>	1000 m (1)	primarily lower bathyal and abyssal taxon (2)
<i>Cibicidoides laurissae</i>	600 m (1)	
<i>Cibicidoides micrus</i>	100m (1)	
<i>Cibicidoides praemundulus</i>	600-1000m (1)	primarily lower bathyal and abyssal taxon (2)
<i>Cibicidoides</i> spp.		outer neritic to bathyal (3)
<i>Dentalina</i> spp.		outer neritic to bathyal (3)
<i>Eponides</i> spp.		outer neritic to bathyal (3)
<i>Gyroldinoides</i> spp.		upper bathyal to deeper (3)
<i>Hanzawaia ammophila</i>	100m (1)	outer neritic to upper bathyal (2)
<i>Haplophragmoides</i> spp.		lower slope (4)
<i>Lenticulina</i> spp.		outer neritic to bathyal (3), bathyal (7)
<i>Loxostomoides applinae</i>	30m (1)	epicontinental facies, neritic-upper bathyal (2)
<i>Marsonella oxycona</i>		middle slope (5)
<i>Melonis</i> spp.		middle bathyal (3)
<i>Nuttallides truempyi</i>	500m (1)	middle bathyal-abyssal (7)
<i>Osangularia plummerae</i>		neritic-upper bathyal (6)
<i>Rectuvigerina mexicana</i>	200m (1)	bathyal (2)
<i>Rzehakina epigona</i>	200m (1)	bathyal and abyssal (2)
<i>Spiroplectammina</i> spp.		middle bathyal (3)
<i>Textularia adalta</i>		bathyal (3)
<i>Uvigerina havaensis</i>	600m (1)	primarily middle bathyal (2)
<i>Uvigerina mexicana</i>	100m (1)	outer neritic and bathyal (2)

(1) Van Morkhoven et al. 1986, foldout; (2) Van Morkhoven et al. 1986, text and figures; (3) McDougal 1980, pp. 12, 29; (4) Kaminski et al. 1988; (5) Nyong and Olsson 1984; (6) Berggren and Aubert 1975; (7) Tjalsma and Lohmann 1983

ary, due to absence of the nominate taxon, was placed approximately above the last occurrence of *Globigerinatheka kugleri* (Bolli, Loeblich, and Tappan 1957) (Pl. 1, fig. 7; App. D) (Pearson et al. 2006; Premoli Silva and Petrizzo 2006). The typical Zone E12 association contains numerous specimens of *Subbotina* and *Globigerinatheka*, *Acarinina rohri* (Brönnimann and Bermúdez 1953), *Morozovelloides crassatus*, *Turborotalita carcoselleensis*, *Pseudohastigerina micra*, and *Planorotalites capdevilensis* (Cushman and Bermúdez 1949) (Apps. A-D).

The Highest-occurrence Zone *Morozovelloides crassatus* (E13) is marked by the rich association of *Pseudohastigerina micra*,

Subbotina eocaena, *S. hagni*, *S. linaperta*, *S. yeguanensis* (see Pl. 1), *Globigerina officinalis*, *Dentoglobigerina venezuelana* Hedberg 1937 (Pl. 1, fig. 8), *D. pseudovenezuelana* Blow and Banner 1962 (Pl. 1, fig. 9), *Globorotaloides quadrocameratus* Olsson, Pearson and Huber 2006 (Pl. 1, fig. 10), *Catapsydrax globiformis* (Blow and Banner 1962) (Pl. 1, fig. 11), *A. medizai* (Toumarkine and Bolli 1975) (Pl. 1, fig. 12), and *Turborotalia cerroazulensis* (see Pl. 1; Apps. B, C, and D). The upper Zone boundary has not been established in any of the three sections comprising the E13 Zone.

Quantitative and paleoecological analyses of the benthic foraminiferal assemblages

All biotic variables show large fluctuations within the successions examined. The Fisher index α is highly variable, ranging between 3.1 and 33.9 (text-fig. 3). It has the highest values in the E10, E11 and E12 Zones, decreases at the beginning of the E13 Zone, and increases slightly in the upper part of the E13 Zone. Dominance values vary between 0.05 and 0.23, reaching their peaks in the upper parts of the E13 Zone in the Šterna-Butori and Ipši sections (text-fig. 3).

Epifaunal foraminifera are generally more common than infaunal; only a few samples contain predominately infaunal forms (text-fig. 3). The proportion of agglutinated foraminifera ranges from 2 to 29% and is highly variable in all sections (text-fig. 3).

Cosmopolitan calcareous genera comprise most of the benthic assemblages in all sections (Apps. A-D). The most common calcareous species are *Cibicidoides eocaenus* (Guembel 1868) (Pl. 2, fig. 1), *C. alazanensis* (Nuttall 1932) (Pl. 2, fig. 2), *C. praemundulus* Berggren and Miller 1986 (Pl. 2, fig. 3), *Nuttallides truempyi* (Nuttall 1930) (Pl. 2, fig. 4), *Oridorsalis umbonatus* (Reuss 1851) (Pl. 2, fig. 5), *Gyroldinoides soldanii* (d'Orbigny 1826), *Osangularia pteromphalia* (Guembel 1868), *Stilostomella nuttalli* (Cushman and Jarvis 1934) (Pl. 2, fig. 6), *Lenticulina arcuatostrata* (Hantken 1975), *L. inornata* (d'Orbigny 1846), and *Bulimina tuxapamensis* Cole 1928 (Pl. 2, fig. 7). Dominant calcareous species groups include *Cibicidoides* spp., *Lenticulina* spp., and *Bulimina* spp. Common calcareous groups include *Anomalinoidea* spp., *Eponides* spp., *Dentalina* spp., *Nodosaria* spp., *Pleurostomella* spp., *Stilostomella* spp., *Uvigerina* spp., and *Bolivina* spp. The agglutinated foraminiferal assemblages are dominated by tubular and elongated taxa. Common agglutinated species and species groups identified from all sections are *Bathysiphon* sp. (Pl. 2, fig. 8), *Rhabdammina robusta* (Grzybowski 1898) (Pl. 2, fig. 9), *Spiroplectammina dalmatina* (de Witt Puyt 1941) (Pl. 2, fig. 10), *Cylindroclavulina rudis* (Costa 1855) (Pl. 2, fig. 11), *Clavulina parisiensis* d'Orbigny 1826, *Textularia* spp., *Ammodiscus incertus* (d'Orbigny 1954) (Pl. 2, fig. 12), *Karrerella subglabra* (Guembel 1868) (Pl. 2, fig. 13), *K. bradyi* (Cushman 1911), *Rzehakina epigona* (Rzehak 1895) (Pl. 2, fig. 14), and *Haplophragmoides* sp.

Benthic assemblages

The Gracišće section

R-mode clustering of the benthic foraminiferal assemblages resulted in two main clusters (text-fig. 4a, Table 3). Cluster G1 groups taxa that are important constituents of the lower part of Zone E10/E11, and of Zone E12. These constituents also generally decrease upwards in abundance. Within this cluster, sub-cluster G1a (including *Nuttallides truempyi* and *Bulimina*

TABLE 2

Morphogroup assignments according to Corliss (1985, 1991), Jones and Charnock (1985) and Corliss and Chen (1988).

EPIFAUNAL CALCAREOUS	
Rounded trochospiral	Milioline
<i>Anomalinoidea capitatus</i>	<i>Quinqueloculina</i> sp.
<i>Anomalinoidea</i> sp.	<i>Sigmoilina</i> sp.
<i>Cibicidoides alazanensis</i>	<i>Sigmoilinita tenuis</i>
<i>Gavelinella limbata</i>	
Plano-convex trochospiral	EPIFAUNAL AGGLUTINATED
<i>Gyroidinoides soldanii</i>	Tubular or branching
<i>Cibicidoides eocaenus</i>	<i>Batysiphon</i> sp.
<i>Cibicidoides grimsdalei</i>	<i>Rhabdammina abyssorum</i>
<i>Cibicidoides laurissae</i>	<i>Rhabdammina robusta</i>
<i>Cibicidoides</i> sp.	
<i>Eponides haeringensis</i>	Coiled flattened and streptos
<i>Hanzawaia ammophila</i>	<i>Ammodiscus incertus</i>
<i>Planularia georgiana</i>	<i>Ammodiscus cretaceous</i>
<i>Planulina renzi</i>	<i>Rzehakina epigona</i>
<i>Planulina</i> sp.	
Biconvex trochospiral	INFAUNAL CALCAREOUS
<i>Cibicidoides barnetti</i>	Rounded planispiral
<i>Cibicidoides micrus</i>	<i>Pullenia quinqueloba</i>
<i>Cibicidoides praemundulus</i>	<i>Melonis</i> sp.
<i>Eponides plummerae</i>	
<i>Eponides</i> sp.	Tapered/cylindrical
<i>Lenticulina arcuatostriata</i>	<i>Bulimina alsatica</i>
<i>Lenticulina cultrata</i>	<i>Bulimina brevis</i>
<i>Lenticulina degolyeri</i>	<i>Bulimina corrugata</i>
<i>Lenticulina helena</i>	<i>Bulimina inflata</i>
<i>Lenticulina iljini</i>	<i>Bulimina jarvisi</i>
<i>Lenticulina inornata</i>	<i>Bulimina macillenta</i>
<i>Lenticulina midwayensis</i>	<i>Bulimina tuxapamensis</i>
<i>Lenticulina subpapillosa</i>	<i>Bulimina</i> sp.
<i>Lenticulina</i> cf. <i>pilulifera</i>	<i>Buliminella</i> sp.
<i>Lenticulina</i> cf. <i>trinitatensis</i>	<i>Chilostomella oolina</i>
<i>Lenticulina</i> sp.	<i>Chilostomella cylindroides</i>
<i>Lenticulina</i> sp. 1	<i>Chrysalogonium eocenicum</i>
<i>Lenticulina</i> sp. 4	<i>Chrysalogonium longiscatum</i>
<i>Lenticulina</i> sp. 5	<i>Chrysalogonium obliquatum</i>
<i>Lenticulina</i> sp. 6	<i>Dentalina adalta</i>
<i>Lenticulina</i> sp. 7	<i>Dentalina advena</i>
<i>Lenticulina</i> sp. 8	<i>Dentalina basiplanata</i>
<i>Lenticulina</i> sp. 9	<i>Dentalina bicornis</i>
<i>Lenticulina</i> sp. 10	<i>Dentalina californica</i>
<i>Lenticulina</i> sp. 11	<i>Dentalina cocoaensis</i>
<i>Lenticulina</i> sp. 12	<i>Dentalina communis</i>
<i>Lenticulina</i> sp. 13	<i>Dentalina consobrina</i>
<i>Lenticulina</i> sp. 14	<i>Dentalina dusenburyi</i>
<i>Lenticulina</i> sp. 15	<i>Dentalina</i> sp.
<i>Nuttallides truempyi</i>	<i>Ellipsonodosaria exilis</i>
<i>Osangularia plummerae</i>	<i>Nodosaria longiscata</i>
<i>Osangularia pteromphalia</i>	<i>"Nodosaria" vertebralis</i>
<i>Osangularia</i> sp.	<i>Nodosaria</i> sp.
	<i>Pleurostomella acuta</i>
	<i>Pleurostomella bellardi</i>
	<i>Pleurostomella brevis</i>
	<i>Pleurostomella</i> cf. <i>incrassata</i>
	<i>Pleurostomella</i> sp.
	<i>Praeglobobulimina pupoides</i>
	<i>Rectuvigerina mexicana</i>
	<i>Stilostomella adolphina</i>
	<i>Stilostomella advena</i>
	<i>Stilostomella curvatura</i>
	<i>Stilostomella gracillima</i>
	<i>Stilostomella haueriana</i>
	<i>Stilostomella midwayensis</i>
	<i>Stilostomella nuttalli</i>
	<i>Stilostomella pyrula</i>
	<i>Stilostomella verneuilli</i>
	<i>Stilostomella</i> sp.
	<i>Trifarina</i> sp.
	<i>Uvigerina havaensis</i>
	<i>Uvigerina hispidocostata</i>
	<i>Uvigerina mexicana</i>
	<i>Uvigerina</i> sp.
	Flattened tapered
	<i>Aragonia aragonensis</i>
	<i>Astacolus</i> sp.
	<i>Bolivina antegressa dentata</i>
	<i>Bolivina midwayensis</i>
	<i>Bolivina nobilis</i>
	<i>Bolivina</i> sp.
	<i>Fronicularia</i> sp.
	<i>Loxostomoides applinae</i>
	<i>Marginulina propinqua</i>
	<i>Marginulina subullata</i>
	<i>Marginulina</i> sp.
	<i>Marginulinopsis fragaria</i>
	<i>Marginulinopsis</i> sp.
	<i>Saracenaria latiformis</i>
	<i>Saracenaria triangularis</i>
	<i>Saracenaria tunesiana</i>
	<i>Vaginulinopsis asperula</i>
	Spherical/globose
	<i>Ellipsoglandulina cubensis</i>
	<i>Globocassidulina inexculta</i>
	<i>Globulina</i> sp.
	<i>Grigelis</i> sp.
	<i>Lagena acuticosta</i>
	<i>Lagena basi-striatula</i>
	<i>Lagena becki</i>
	<i>Lagena ellipsoidalis</i>
	<i>Lagena hexagona</i>
	<i>Lagena laevis</i>
	<i>Lagena schvageriana</i>
	<i>Lagena sphaerica</i>
	<i>Lagena striata</i>
	<i>Lagena</i> sp.
	<i>Oolina simplex</i>
	<i>Oolina</i> sp.
	<i>Polymorphina gracilis</i>
	Flattened ovoid
	<i>Fissurina carinata</i>
	<i>Fissurina orbignyana</i>
	<i>Fissurina</i> sp.
	<i>Cassidulina laevigata</i>
	Biconvex trochospiral
	<i>Oridorsalis umbonatus</i>
	INFAUNAL AGGLUTINATED
	Elongate multilocular
	<i>Clavulina parisiensis</i>
	<i>Cylindroclavulina colomi</i>
	<i>Cylindroclavulina eocaena</i>
	<i>Cylindroclavulina rudis</i>
	<i>Dorothia</i> sp.
	<i>Hormosina</i> sp.
	<i>Karrerella gaudryoides</i>
	<i>Karrerella siphonella</i>
	<i>Karrerella subglabra</i>
	<i>Karrerella brady</i>
	<i>Marsonella indentata</i>
	<i>Marsonella oxycona</i>
	<i>Plectina dalmatina</i>
	<i>Spiroplectammina dalmatina</i>
	<i>Spiroplectammina clotho</i>
	<i>Spiroplectammina</i> cf. <i>cubensis</i>
	<i>Spiroplectammina navarroana</i>
	<i>Spiroplectammina spectabilis</i>
	<i>Textularia adalta</i>
	<i>Textularia dibollensis</i>
	<i>Textularia</i> sp.
	<i>Tritaxia jarvisi</i>
	<i>Tritaxia szabo</i>
	<i>Tritaxilina hantkeni</i>
	<i>Tritaxilina pupa</i>
	<i>Vulvulina haeringensis</i>
	<i>Vulvulina spinosa</i>
	Flattened trochospiral
	<i>Haplophragmoides</i> sp.
	<i>Trochammina</i> sp.
	<i>Trochamminoides irregularis</i>
	<i>Usbekistania charoides</i>
	Globular
	<i>"Trochammina"</i> sp.

spp.) shows a few peaks within the *Globigerina* Marls and the lowermost part of the Flysch deposits (text-fig. 4a). Sub-cluster G1b (including *Lenticulina* spp., *Osangularia* spp. and *Stilostomella* spp.) is the important element of the *Globigerina* Marls and strongly decreases in the Flysch.

Cluster G2 groups species that are more common in the Flysch, i.e. in the middle part of Zone E10/E11. Sub-cluster G2a (e.g., *Cibicidoides* spp., *Uvigerina* spp.) becomes increasingly abundant in the Flysch. Sub-cluster G2b mainly groups small epifaunal specimens, *Dentalina* spp., and *Bathysiphon* sp., which make up an important part of the Flysch assemblages (App. A).

The Šterna-Butori section

The benthic foraminiferal assemblages of this section are divided into two main groups by R-mode cluster analysis (text-fig. 4b, Table 3). Cluster SB1 groups foraminifera that are common in the *Globigerina* Marls of Zones E10 and E11, but decrease in abundance in the Flysch deposits and almost completely disappear in the uppermost part of the section. In most of the *Globigerina* Marls, sub-cluster SB1a (*Bulimina* spp., *Bolivina* spp., *Lenticulina* spp., and *Osangularia* spp.) is a more important constituent of cluster SB1 than sub-cluster SB1b (*Stilostomella* spp., *Dentalina* spp. and *Pleurostomella* spp.). Sub-cluster SB1b becomes the more important component of cluster SB1 in the uppermost *Globigerina* Marls and in the lower part of the Flysch (text-fig. 4c).

Cluster SB2 groups foraminifera that become increasingly important upsection. This cluster dominates in the Flysch deposits of Zones E12 and E13 making up more than 80% of the assemblage. Sub-cluster SB2a (e.g., *Cibicidoides* spp. and small epifaunal foraminifera) mainly constitute cluster SB2 in the *Globigerina* Marls, whereas sub-cluster SB2b (e.g., *Nuttallides truempyi*, *Buliminella* spp. and *Trochammina* sp.) becomes an increasingly important part of cluster SB2 in the Flysch Beds (text-fig. 4c).

The Sveti Križ section

R-mode clustering of the benthic foraminiferal assemblages also resulted in two main clusters (text-fig. 4c, Table 3). Cluster SK1 is separated into two important sub-clusters: SK1a and SK1b. Sub-cluster SK1a groups foraminifera that make up the largest part of the assemblages in the *Globigerina* Marls and in the lowermost part of the Flysch deposits (e.g., *Bulimina* spp. and *Osangularia* spp.) of Zone interval E10/E11 and substantially decrease in abundance in the Flysch (text-fig. 4c). Sub-cluster SK1b groups species that are common in the upper part of the *Globigerina* Marls in Zone interval E10/E11 and in the lower part of the Flysch (e.g., *Dentalina* spp. and *Stilostomella* spp.) in the lower part of Zone E12. Cluster SK2 groups epifaunal *Cibicidoides* spp. and small epifaunal foraminifera that are important constituents of the assemblages throughout the section, but dominate the benthic record in Zones E9, E12 and E13.

The Ipšič section

R-mode cluster analysis of the benthic foraminiferal assemblages from this section also resulted in two main clusters (text-fig. 4d, Table 3). Cluster IP1 dominates the composition of the assemblages in most of the section but becomes less important in the uppermost parts of the section. Sub-cluster IP1a mainly consists of *Cibicidoides* spp., which is the major compo-

nent of cluster IP1. Sub-cluster IP1b (*Buliminella* sp. and *Chilostomella* spp.) makes up an important part of the assemblage in the lower part of the section (uppermost E12 and lowermost E13 Zones), peaks in the middle part of Zone E13, and diminishes in abundance in the uppermost part of the section (text-fig. 4d). Cluster IP2 groups foraminifera that are significant components of the assemblages throughout the section (e.g., small epifaunal foraminifera, *Dentalina* spp. and *Nuttallides truempyi*), but dominate over cluster IP1 only in the lowermost and in the upper parts of the section.

Benthic foraminiferal assemblages of all sections

R-mode clustering of all species and species groups (text-fig. 5a) of all four sections clustered into two main groups that more or less correspond to the clusters for each individual section (see comparison in Table 3). The two main clusters are here referred to as the *Lenticulina-Bulimina* group, and the *Cibicidoides* group (text-fig. 5a, Table 3). The *Lenticulina-Bulimina* group includes several species and species groups that in some stratigraphic sections cluster with the *Cibicidoides* group foraminifera when clustered for that particular section (indicated as highlighted in Table 3). In the Ipšič section, the foraminiferal taxa from the *Lenticulina-Bulimina* group are present in very low abundances (with exception of *Bolivina* spp. and *Dentalina* spp.), and were therefore not used in the individual analysis of the Ipšič section (highlighted in Table 3). The abundances of each group in the foraminiferal assemblages for each of the four sections are presented in text-figure 4.

Biofacies succession

The benthic assemblage data, paleoecological characteristics, and Q-mode clustering of the data set for each section were used to define biofacies units (text-fig. 3). These units were then used to interpret paleoenvironmental history of the successions within the Trieste-Pazin basin.

The Gradišće section

Biofacies 1 is characterized by variable and moderately diverse assemblages dominated by the *Lenticulina-Bulimina* group (text-figs. 3a and 4a). This biofacies is present in the lower part of the section and is divided into two sub-facies (text-fig. 3a). Cluster G1 (e.g., *Lenticulina* spp., *Bulimina* spp., *Osangularia* spp., *Nuttallides truempyi*), together with sub-cluster G2a (e.g., *Cibicidoides* spp. and *Oridorsalis umbonatus*), makes up the main part of the foraminiferal assemblages in this biofacies (text-fig. 4a), comprising the *Globigerina* Marls and the lowermost Flysch. Here the *Lenticulina-Bulimina* group prevails, mostly consisting of outer neritic to upper bathyal taxa, with a few representatives of deeper water species (e.g., *Uvigerina havanensis* Cushman and Bermúdez 1936, *Cibicidoides praemundulus*, and *Anomalinoidea capitatus* (Guembel 1868); Table 1; App. A). Some samples contain abundant *Nuttallides truempyi* as a representative of upper to middle bathyal depth. Sub-facies 1a is present in a few samples from the *Globigerina* Marls, and is characterized by moderately diversified assemblages of moderate dominance (text-figs. 3a and 4a). These assemblages are characterized by peaks of sub-cluster G1a (e.g., *Nuttallides truempyi*, *Bulimina* spp.) with lower proportions of sub-cluster G1b (*Lenticulina* spp., *Stilostomella* spp.) and cluster G2 (e.g., *Cibicidoides* spp.; text-figs. 3a and 4a). Sub-facies 1b is present in the remainder of the *Globigerina* Marls, and in the lower and the uppermost parts of the Flysch (text-fig. 3a). This sub-facies is characterized by common cluster G1 with the prevalence of sub-cluster G1b and significant proportions of

TABLE 3

Comparison of the main benthic foraminiferal assemblages based on cluster analysis for each section alone and for all four sections together. Note: the highlighted taxa clustered in different assemblages when clustered for a particular section as opposed to the overall analysis of data from all four sections.

	Clusters for the Gračišće section	Clusters for the Šterna-Butori section	Clusters for the Sveti Križ section	Clusters for the Ipši section	Clusters for all four sections
Cibicidoides group	<i>Cibicidoides</i> spp. Small epifaunal <i>Bathysiphon</i> sp. <i>Dentalina</i> spp. <i>Nodosaria</i> spp. <i>Oridorsalis umbonatus</i> <i>Eponides</i> spp. <i>Uvigerina</i> spp.	<i>Cibicidoides</i> spp. Small epifaunal <i>Anomalinoidea</i> spp. <i>Bathysiphon</i> sp. <i>Buliminella</i> sp. <i>Chilostomella</i> spp. <i>Nuttallides truempyi</i> <i>Oridorsalis umbonatus</i>	<i>Cibicidoides</i> spp. Small epifaunal <i>Anomalinoidea</i> spp. <i>Osangularia</i> spp.	<i>Cibicidoides</i> spp. Small epifaunal <i>Anomalinoidea</i> spp. <i>Bathysiphon</i> sp. <i>Buliminella</i> sp. <i>Chilostomella</i> spp. <i>Haplophragmoides</i> sp. <i>Nuttallides truempyi</i> <i>Dentalina</i> spp.	<i>Cibicidoides</i> spp. Small epifaunal <i>Anomalinoidea</i> spp. <i>Bathysiphon</i> sp. <i>Buliminella</i> sp. <i>Chilostomella</i> spp. <i>Haplophragmoides</i> sp.
Lenticulina-Bulimina group	<i>Lenticulina</i> spp. <i>Osangularia</i> spp. <i>Bulimina</i> spp. <i>Stilostomella</i> spp. <i>Nuttallides truempyi</i> <i>Rzehakina epigona</i> <i>Spiroplectammina</i> spp. <i>Gyroidinoides soldanii</i> <i>Hanzawaia ammophila</i>	<i>Lenticulina</i> spp. <i>Osangularia</i> spp. <i>Bulimina</i> spp. <i>Bolivina</i> spp. <i>Stilostomella</i> spp. <i>Pleurostomella</i> spp. <i>Dentalina</i> spp.	<i>Lenticulina</i> spp. <i>Bulimina</i> spp. <i>Bolivina</i> spp. <i>Stilostomella</i> spp. <i>Pleurostomella</i> spp. <i>Dentalina</i> spp. <i>Bathysiphon</i> sp.		<i>Lenticulina</i> spp. <i>Osangularia</i> spp. <i>Bulimina</i> spp. <i>Bolivina</i> spp. <i>Stilostomella</i> spp. <i>Nuttallides truempyi</i> <i>Pleurostomella</i> spp. <i>Dentalina</i> spp. <i>Rzehakina epigona</i> <i>Trochammina</i> sp. <i>Spiroplectammina</i> spp. <i>Gyroidinoides soldanii</i> <i>Hanzawaia ammophila</i> <i>Oridorsalis umbonatus</i> <i>Eponides</i> spp. <i>Uvigerina</i> spp.

cluster G2 (text-fig. 3a). In the lower part of the Flysch, sub-clusters G1b and G2b diminish upsection, whereas sub-cluster G2a increases in abundance. In most assemblages of sub-facies 1b, epifaunal foraminifera slightly predominate over infaunal.

Biofacies 2 is characterized by moderately diverse benthic assemblages, dominated by the *Cibicidoides* group, corresponding to cluster G2, and by a very low proportion of cluster G1, which further decreases in abundance upsection (text-figs. 3a and 4a). This biofacies is present in the Flysch deposits, with the assemblages characterized by high proportions of epifaunal and agglutinated foraminifera. The most important characteristics of Biofacies 2 are increased abundance of small epifaunal population, lowered *Cibicidoides* spp. proportions, and, in some samples, higher abundance of *Dentalina* spp., *Eponides* sp., *Uvigerina* spp., *Nuttallides truempyi* and tubular agglutinated taxa (App. A). Deep-water foraminifera are more abundant in Biofacies 2 (e.g., *Cibicidoides praemundulus*, *Uvigerina havanensis*, *U. hispidocostata* Cushman and Todd 1945), and indicate middle bathyal depths (Table 1; App. A).

The Šterna-Butori section

The foraminiferal assemblages from the Šterna-Butori section show a decrease in diversity (from high to low), and an increase in dominance upsection (text-fig. 3b). The infaunal population predominates at the base of the section, but epifaunal proportions increase upwards and dominate throughout the rest of the interval.

Biofacies 1 is characterized by highly diverse assemblages of benthic foraminifera, with low dominance and low proportions of agglutinated foraminifera (text-fig. 3b). This biofacies is present in the *Globigerina* Marls (Zones E10 and E11), and is divided into two sub-facies (text-fig. 3b). Sub-facies 1a, present in the lowermost part of the *Globigerina* Marls, displays dominance of infaunal forms and prevalence of the *Lenticulina-Bulimina* group in the highly diverse assemblage (text-figs. 3 and 4). This sub-facies is characterized by mainly outer shelf to upper bathyal assemblage. In sub-facies 1a cluster SB1 species (e.g., *Bulimina* spp., *Bolivina* spp., and *Dentalina* spp.) predominate over cluster SB2 (*Cibicidoides* spp., small epifaunal foraminifera; text-figs. 3b and 4b). In sub-facies 1b, present in the remainder of the *Globigerina* Marls (Zones E10 and E11), the assemblages are moderately diverse with increased proportions of epifaunal taxa and the prevalence of the *Cibicidoides* group foraminifera (text-figs. 3 and 4). Representatives of middle bathyal setting (*C. laurissae* (Mallory 1959), *C. praemundulus*, *A. capitatus*, *C. grimsdalei* (Nuttall 1930) and *U. havanensis*) start to appear in low numbers but increase in abundance upwards, indicating increasing paleodepths (Table 1; App. B). In the lower part of sub-facies 1b, sub-cluster SB1a (e.g., *Bulimina* spp., *Bolivina* spp.) is significantly more common than sub-cluster SB1b (*Dentalina* spp., *Stilostomella* spp.), whereas in the uppermost part of sub-facies 1b, sub-cluster SB1b increases in importance and predominates over sub-cluster SB1a (text-figs. 3b and 4b). Sub-cluster SB2a (*Cibicidoides* spp., small epifaunal foraminifera) reaches higher values upsection, whereas sub-cluster SB2b (e.g., *Nuttallides truempyi*, *Oridorsalis umbonatus*) is relatively rare throughout

Biofacies 1. The epifaunal population decreases in the uppermost part of this sub-facies.

Biofacies 2 is present in the Flysch deposits and its main characteristic, compared to Biofacies 1, is that the abundance of cluster SB1 foraminifera is strongly reduced and further decreases upsection (text-figs. 3b and 4b). Diversity also decreases upsection, from moderate to low, while dominance increases. The assemblage is characterized by the dominance of epifaunal foraminifera, by the appearance of *Chilostomella cylindroides* Reuss 1851 and *Ch. oolina* Schwager 1878, and by high values of *Trochammina* sp., *Bathysiphon* sp., and *Buliminella* cf. *elegantissima* d'Orbigny 1839. Almost all buliminids and bolivinids disappear. The abundance of sub-cluster SB2a species generally increases in the Flysch, and sub-cluster SB2b becomes a more important constituent of cluster SB2 (text-fig. 4b). A sample from the middle part of the Flysch displays highly increased abundances of sub-cluster SB2b (*Nuttallides truempyi*, *Trochammina* sp. and *Oridorsalis umbonatus*) and substantially decreased proportions of sub-cluster SB2a (i.e., very low proportions of small epifaunal foraminifera). This assemblage is therefore considered as sub-facies 2b (text-figs. 3b and 4b).

The Sveti Križ section

Biofacies 1 is present in the *Globigerina* Marls (except in its lowermost part) and in the lowermost and the uppermost parts of the Flysch (text-fig. 3c). This biofacies is characterized by assemblages of intermediate to low diversity, with abundant *Osangularia* spp. and *Bulimina* spp., and by common but never abundant *Lenticulina* spp., together with abundant *Cibicidoides* spp. and small epifaunal forms. Biofacies 1 is characterized by the prevalence of cluster SK1 species (e.g., *Osangularia* spp., *Bulimina* spp., *Stilostomella* spp., *Dentalina* spp.) in most samples (text-figs. 3c and 4c). The abundance of cluster SK1 decreases upwards, resulting in an assemblage characteristic of upper bathyal depths with many deep-water forms (*Cibicidoides praemundulus*, *Nuttallides truempyi* and *Anomalinoidea capitatus*; Table 1; App. C). Cluster SK2 (*Cibicidoides* spp., small epifaunal foraminifera) becomes increasingly important upsection (text-figs. 3 and 4). Sub-facies 1a in the lower part of the *Globigerina* Marls and in the Flysch is characterized by the prevalence of *Cibicidoides* group foraminifera, whereas sub-facies 1b in the upper part of the *Globigerina* Marls is characterized by the *Lenticulina-Bulimina* group (text-figs. 3c and 4c).

Biofacies 2 is dominated by cluster SK2 foraminifera (*Cibicidoides* spp., small epifaunal foraminifera). This biofacies is present in the lowermost part of the *Globigerina* Marls and in most of the Flysch (text-fig. 3c), and is characterized by the dominance of *Cibicidoides* group species, by abundant cluster SK2 assemblages, and by a high epifaunal population in most samples (text-fig. 3c). Biofacies 2 is also characterized by increased abundance of small epifaunal foraminifera and agglutinated tubular taxa. Such changes may imply increasing paleodepths to deeper parts of the upper or even middle bathyal, and a more distal setting. The foraminiferal assemblage from the base of Zone E12 shows a prevalence of cluster SK1 species, but because of the low abundance of cluster SK1a species (*Lenticulina* spp., *Osangularia* spp., *Bulimina* spp.) and the more numerous cluster SK2 species, this assemblage has been assigned to biofacies 2 (text-figs. 3c and 4c).

The Ipšič section

The assemblages from the Ipšič section differ significantly from those in other sections because of the absence of the *Globigerina* Marls and of typical *Lenticulina-Bulimina* group faunas. In the samples from the Ipšič section, lenticulinids, osangulariids, and buliminids are very rare or absent. The turbidite layers are thin and represent deeper and more distal facies. To facilitate the comparison between all the sections examined, the label "biofacies 1", characteristic mainly of the *Globigerina* Marls, was not employed in this context, and only the label "biofacies 2", characteristic of the Flysch deposits in other sections (text-fig. 3), is used in interpretations.

Biofacies 2 (text-fig. 3d) is represented by an assemblage of moderate to low diversity and high dominance, characterized by high epifaunal abundances with prevalent *Cibicidoides* group foraminifera throughout the section. Sub-facies 2a, present in the lowermost and upper parts of the Ipšič section, displays moderate diversity. This sub-facies is characterized by similar abundances of clusters IP1 and IP2. The assemblage composition is dominated by sub-cluster IP2a (small epifaunal specimens) that predominate over IP1a (e.g., *Cibicidoides* spp.). In the lowermost part of the section sub-cluster IP1b (*Buliminella* sp., *Chilostomella* spp.) is characterized by abundant *Buliminella* sp., accompanied by several other infaunal taxa (*Dentalina* spp., *Bolivina* spp.), and by the absence of *Chilostomella* spp. (text-figs. 3d and 4d, App. D). In the uppermost part of Zone E12 and the lower part of Zone E14 the abundances of both *Buliminella* sp. and *Chilostomella* spp. are high, but significantly decrease in the upper part of the section (App. D). The upper part of sub-facies 2a, in the uppermost part of the section, is characterized by common lower bathyal indicators (e.g., *Cibicidoides grimsdalei*).

Sub-facies 2b exhibits low diversity except in the uppermost part of sub-facies 2b where diversity is high and dominance is low (text-fig. 3d). In this sub-facies, cluster IP1a is more common than sub-cluster IP2a. Sub-cluster IP1b makes up most of the infaunal population but decreases in abundance upsection with the increasing importance of other infaunal taxa. In the uppermost part of sub-facies 2b, sub-cluster IP2a declines in abundance, while sub-cluster IP2b (*Nuttallides truempyi*, *Dentalina* spp., *Bolivina* spp.) becomes more common (Table 1; App. D).

Biofacies of the Trieste-Pazin basin

The Q-mode clustering of all samples from all four sections grouped most of the samples from the *Globigerina* Marls and the lower Flysch deposits of the Gradišće section, the lowermost samples from the Šterna-Butori section, and two samples from the upper part of the *Globigerina* Marls of the Sveti Križ samples into the *Globigerina* Marls biofacies (text-fig. 5a). This biofacies is generally characterized by the presence of *Lenticulina-Bulimina* group foraminifera, reflecting outer shelf to upper bathyal depths. The exceptions within the *Globigerina* Marls are the lowermost samples of the Gradišće and Sveti Križ sections, characterized by the dominance of the *Cibicidoides* group in the assemblages. The second cluster, containing all other samples, is characteristic of the Flysch deposits from the upper E10/E11, E12 and E13 Zones, and is therefore named the Flysch biofacies. This biofacies is generally characterized by the *Cibicidoides* group with typical *Cibicidoides* spp., small epifaunal foraminifera, *Dentalina* spp. and *Uvigerina* spp., as well as *Buliminella* sp. and *Chilostomella* spp. in the central part of the Trieste-Pazin basin (the Šterna-Butori and Ipšič sections).

PALEOBATHYMETRIC DETERMINATION

Relevant data

The hemipelagic *Globigerina* Marls in the Gracišće, Sveti Križ and Šterna-Butori area yield rich and moderately to highly diverse foraminiferal assemblages dominated by planktonic forms. The percentage of planktonic foraminifera varies between 62 and 97%. In the Gracišće, Sveti Križ and Ipši sections this percentage is generally around 90%, but in the middle part of the Šterna-Butori section the values range between 62 and 74% (text-fig. 4). The diverse planktonic foraminiferal fauna includes both juvenile and adult specimens (Živkovic 1996, 2004; Živkovic and Babic 2003), indicating open marine conditions and good connection to the Tethys Ocean.

The benthic assemblages from the *Globigerina* Marls are characterized by calcareous genera *Lagena*, *Osangularia*, *Stilostomella* (see Pl. 2), *Lenticulina*, *Nodosaria*, *Bulimina*, *Osangularia*, *Stilostomella*, *Eponides*, *Dentalina*, *Oridorsalis*, and by *Rectuvigerina mexicana* (Cushman 1926), *Uvigerina mexicana* Nuttall 1932, *Aragonia aragonensis* (Nuttall 1930), and *Cibicidoides eocaenus* (see Pl. 2). Agglutinated foraminifera are also present in all sections, including *Cylindroclavulina* (see Pl. 2), *Clavulina*, *Bathysiphon* (see Pl. 2), *Rhabdammina* (see Pl. 2), *Cyclammina*, *Vulvulina*, *Textularia*, *Trochammina*, *Ammodiscus* (see Pl. 2), *Rzehakina* (see Pl. 2), *Haplophragmoides*, *Spiroplectammina* (see Pl. 2), and *Dorothia* (Apps. A-D). These forms are indicative of outer shelf or bathyal depths (McDougal 1980; Grünig and Herb 1980; Tjalsma and Lohmann 1983; Van Morkhoven et al. 1986; Nocchi et al. 1988; Kaminski et al. 1988; Müller-Merz and Oberhänsli 1991; Gebhard 1999; and others). Some of the species present have limited depth ranges indicative of middle and lower bathyal depositional environments (e.g., *Nuttallides truempyi*, *Cibicidoides grimsdalei*, and *C. praemundulus*; see Table 1). The co-occurrence of typical deep-sea taxa and neritic to upper bathyal taxa indicates deposition at depths of 300-500m.

In the Flysch deposits, neritic species are much less common and bathyal species predominate; the presence of deep sea taxa indicates deepening to middle bathyal during the Late Lutetian. Typical representatives of these taxa are *Cibicidoides grimsdalei*, *C. laurissae*, *Nuttallides truempyi*, *Anomalinoidea capitatus*, *Bulimina jarvisi* Cushman and Parker 1936, and *Uvigerina havanensis* (Table 1).

Implications

The high percentages of planktonic foraminifera throughout the studied interval (up to 97%) and the composition of their assemblages that include acarininids, morozovelloids, turboritaliids, subbotinids and globigrinathekids with a wide range of juvenile and adult sizes and the moderately high sample diversity (up to 26 species) imply upper continental slope environments and outer shelf to bathyal depths (Murray 1991). This interpretation is consistent with the documented benthic foraminiferal assemblages that include *Lenticulina*, *Bulimina*, *Bolivina*, *Osangularia*, *Stilostomella*, *Nodosaria*, *Eponides*, *Dentalina*, *Oridorsalis*, *Uvigerina*, *Cibicidoides*, *Cylindroclavulina*, *Bathysiphon*, *Rhabdammina*, *Textularia*, *Rzehakina* and *Dorothia* (McDougal 1980; Grünig and Herb 1980; Tjalsma and Lohmann 1983; Van Morkhoven et al. 1986; Nocchi et al. 1988; Kaminski et al. 1988; Müller-Merz and Oberhänsli 1991; Gebhard 1999). Diversity of these benthic foraminiferal assemblages is represented by Fisher index α that

ranges between 3 and 33, and also indicates outer shelf to bathyal depths (Murray 1991) (text-fig. 3; Apps. A-D).

Bathyal benthic taxa such as *Stilostomella*, *Pleurostomella*, *Oridorsalis*, *Uvigerina*, *Lagena*, *Cibicidoides*, *Cylindroclavulina*, *Bathysiphon*, *Rhabdammina*, *Textularia*, *Rzehakina* and *Dorothia* are consistently present throughout the studied sections, but their relative abundances vary (Apps. A-D). Benthic foraminiferal assemblages from the lowermost parts of the *Globigerina* Marls in the Gracišće, Sveti Križ and Šterna-Butori sections contain an abundance of diverse *Lenticulina* species and common *Cibicidoides* species, oridorsalids, and buliminids, indicating outer neritic to bathyal environments (Table 1). Accordingly, paleodepth estimates of ~300-500m are proposed here for the deposits in the lowermost part of the *Globigerina* Marls. These estimates are compared with those for the underlying Foraminiferal Limestones and the "Marls with Crabs". Conformable transition from the Foraminiferal Limestones into the "Marls with Crabs" has been interpreted to represent deepening from the inner to middle neritic setting (Schubert 1904, 1905; Drobne 1977; Juracic 1979; Cosovic et al. 2004, 2006). The Foraminiferal Limestones were estimated to correspond to the lower part of the photic zone (Cosovic et al. 2004), or to about 120-150m water depth (Cosovic, personal communication, 2005). Thus, the depth of deposition for the overlying "Marls with Crabs" must have been considerably greater than 60-100m as estimated by Juracic (1979) from the percentages of planktonic foraminifera. The "Marls with Crabs" were probably deposited in about 200-300m water depth (see also Živkovic 2004). This interpretation is in agreement with the recent study of these deposits in Istria by Tarlao et al. (2005), who used macrofauna and some pseudoplanktonic forms present to estimate depositional depth of about 200m on the epibathyal slope. It is possible that the extremely small thickness of the "Marls with Crabs" was caused by low sedimentation rate during basin deepening or by erosion or sediment bypass due to the steepness of the slope (Živkovic 2004). The low sedimentation rate scenario is supported by the presence of glauconite (Odin and Fullagar 1988) in the basal part of the "Marls with Crabs" (Tarlao et al. 2005). The lowermost part of the conformably overlying *Globigerina* Marls examined here represents a significant and perhaps abrupt deepening to outer shelf and upper bathyal depths (~300-500m) as indicated by the high percentages of planktonic foraminifera (>80%) and the presence of genera common in outer shelf and bathyal environments (*Lenticulina*, *Cibicidoides*, *Nodosaria*, *Bulimina*, *Eponides*, *Dentalina* and *Hanzawaia*) (Van Morkhoven et al. 1986).

The greater abundance of bathyal genera (*Nuttallides*, *Uvigerina*, *Rectuvigerina*, *Osangularia*, *Oridorsalis*, *Stilostomella*, *Pleurostomella*, *Lagena*, etc.) (Van Morkhoven et al. 1986) in the upper parts of the *Globigerina* Marls indicates upper bathyal paleodepths. The initiation of turbiditic sedimentation, together with the appearance of some deeper water taxa (e.g., *Cibicidoides praemundulus*, *C. grimsdalei*, *C. praemundulus*, *Anomalinoidea capitatus*, *Bulimina jarvisi*, *Uvigerina havanensis*; Van Morkhoven et al. 1986) suggests the water depth increase to deeper parts of the upper bathyal and to the middle bathyal setting.

PALEOENVIRONMENTAL RECONSTRUCTION AND INSIGHTS INTO PALEO GEOGRAPHY OF THE MIDDLE EOCENE TRIESTE-PAZIN BASIN

The benthic foraminiferal assemblages indicate paleoenvironmental changes that are reflected in biofacies variation.

Biofacies 1 of the Gradišće section, dominated by the *Lenticulina-Bulimina* group in sub-facies 1b (text-figs. 3 and 4) within the *Globigerina* Marls and most of the lower Flysch (Zone E9 and lower part of Zone E10/E11), reflects mesotrophic conditions (Speijer and Schmitz 1998). Refractory organic matter was also supplied by a carbonate sediment source from a structural high, represented by the drowned carbonate platform to the southwest (text-fig. 6a). Moderate to high oxygenation, indicated by the diverse assemblages with abundant epifaunal taxa (text-fig. 3), facilitated the formation of a deep redox front and the development of rich infauna. The alternation of sub-facies 1a and 1b within the *Globigerina* Marls reflects changes in the trophic conditions. Sub-facies 1a, with higher abundances of *Bulimina* spp., *Pleurostomella* spp. and deep infaunal monothalamous taxa (e.g., *Oolina*, *Lagena* and *Fissurina*), together with occasionally common *Nuttallides truempyi* and *Dentalina* spp. (App. A), may represent short-lived episodes of high refractory organic matter flux (Gupta and Thomas 2003) within the constant supply of food represented by the sub-facies 1b (text-figs. 3 and 4).

More oligotrophic conditions, indicated by higher abundances of the *Cibicidoides* group and epifaunal morphotypes, lower diversity, and moderately high dominance (text-fig. 3), are documented in the lower part of the *Globigerina* Marls (the uppermost Zone E9 and lower Zone E10/E11 interval) of the Sveti Križ section. Such conditions might have resulted from the location of the Sveti Križ section. This area was situated along the northeastern side of the basin and the hinterland probably did not supply enough nutrients to sustain mesotrophic conditions in deeper environments. The slope environment was likely influenced mostly by low primary production at the onset of the basin deepening. Subsequently, during deposition of the uppermost part of the *Globigerina* Marls, mesotrophic conditions, as indicated by the increased abundance of the SK1 assemblage (i.e., the *Lenticulina-Bulimina* group) were also established in the Sveti Križ area (sub-facies 1b; text-figs. 3 and 4). Mesotrophic conditions might result from increased primary production or greater input of land-derived organic matter to the basin. This input of land-derived material might have activated higher primary production as a response to elevated content of nutrients in the environment. Contemporaneously, in the southwestern part of the basin (the Gradišće section), the Flysch

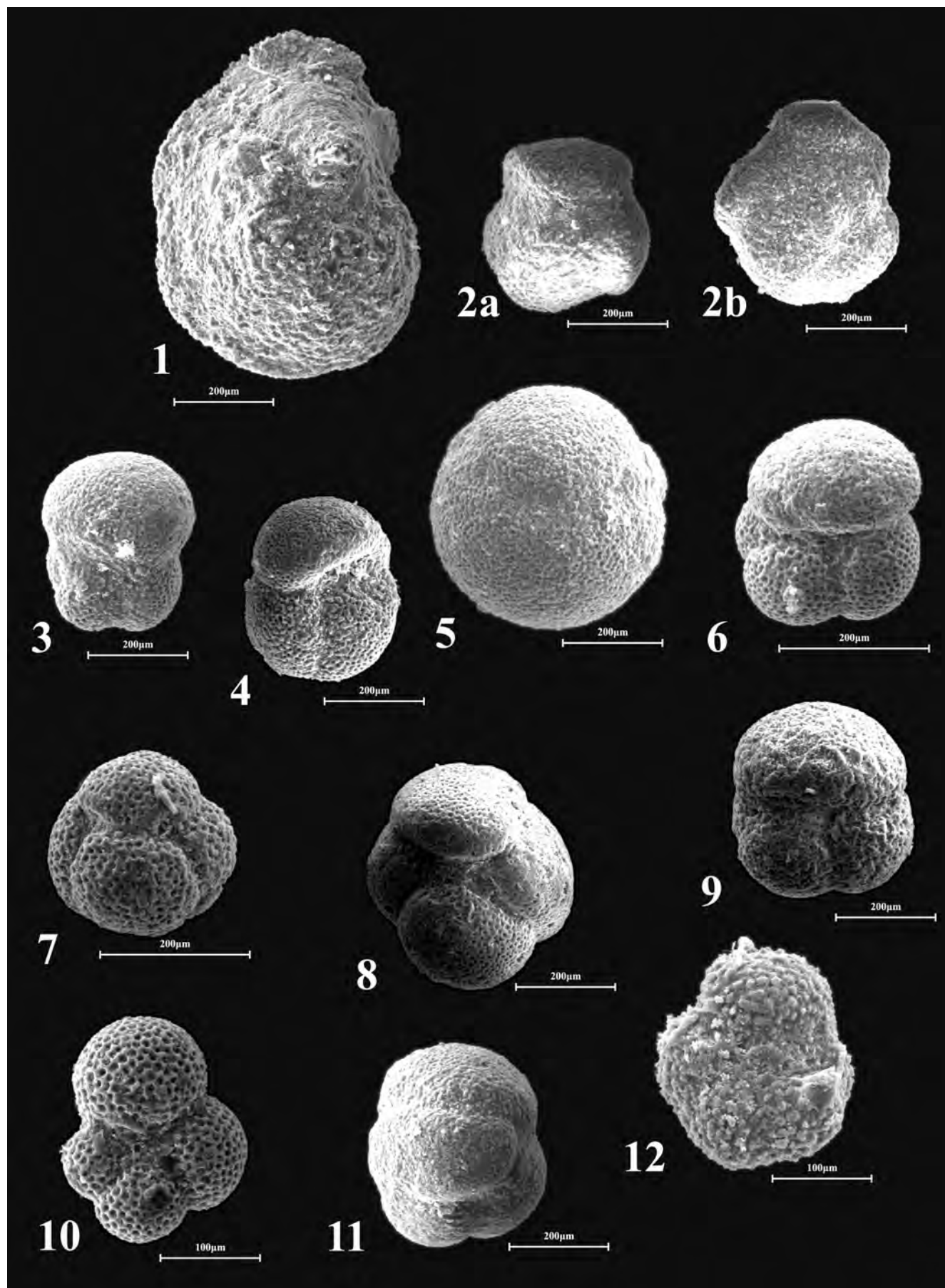
sedimentation, with thin turbidite layers alternating with thin hemipelagic sediment, had already begun along with the deepening that resulted in the change from mesotrophic to more oligotrophic conditions. The assemblages of benthic foraminifera in biofacies 2 (text-fig. 3), with decreased abundances of the typical outer neritic to upper bathyal taxa (e.g., *Lenticulina* spp., *Bulimina* spp.) and a slight increase in epifaunal morphotypes, imply deepening to a more oligotrophic environment, since the organic flux to the sea floor usually decreases with depth (e.g., Van der Zwaan et al. 1990; Herguera and Berger 1991) and distance from the shore. Frequent turbidity currents may have permitted burial of high levels of organic material within the sediment, enabling a rather abundant infaunal population to develop despite the quite oligotrophic conditions at the bottom sediment. This more distal facies may have been influenced by deeper longitudinal currents, serving as an additional supply of suspended particles, which were preferred by the tubular taxa (assemblage G2b) whose abundance increases in biofacies 2 in Zones E10/E11 in the Gradišće section (App. A; text-fig. 4). The variations in the relative abundances of the key species (*Cibicidoides* spp., *Eponides* spp., *Bathysiphon* sp., *Dentalina* spp., *Uvigerina havanensis*), mainly in the G2 assemblage in samples of biofacies 2 (text-fig. 4; App. A), however, might be a result of patchiness, a common characteristic of meiofauna in the deep-sea environment (Thiel 1983), and could be enhanced by heterogeneity of both substrate and bioturbation (Schmiedl et al. 2000).

During the basin opening and widening, new areas became drowned and subjected to deeper water conditions, as did the Šterna-Butori area in Zone E10. In the Šterna-Butori section, the lowermost part of the *Globigerina* Marls sub-facies 1a (text-fig. 3) represents sedimentation quite close to the shelf from which enough organic material may have been derived to support mesotrophic to eutrophic conditions. Such conditions are documented by high abundance of eutrophic indicators present in SB1a assemblage, with particularly abundant *Bulimina* spp. and taxa representing the SB1b assemblage (*Dentalina* spp., *Pleurostomella* spp., and *Stilostomella* spp.). This assemblage is similar to the G1 assemblage characterizing the sub-facies 1a of the Gradišće section (see comparison in Table 3), reflecting the high refractory organic flux. Moderately high diversity and low dominance, however, indicate the prevalence of

PLATE 1

SEM photographs of planktonic foraminifera from the Trieste-Pazin basin.

- | | |
|--|---|
| 1 <i>Morozovella aragonensis</i> (Nuttall) | 7 <i>Globigerinatheka kugleri</i> (Bolli, Loeblich and Tappan) |
| 2a <i>Acarinina punctocarinata</i> Fleisher | 8 <i>Dentoglobigerina venezuelana</i> Hedberg |
| 2b <i>Acarinina punctocarinata</i> Fleisher | 9 <i>Dentoglobigerina pseudovenezuelana</i> Blow and Banner |
| 3 <i>Turborotalia frontosa</i> Subbotina | 10 <i>Globorotaloides quadrocameratus</i> Olsson, Pearson and Huber |
| 4 <i>Turborotalia possagnoensis</i> (Toumarkine and Bolli) | 11 <i>Catapsydrax globiformis</i> (Blow and Banner) |
| 5 <i>Orbulinoides beckmanni</i> (Saito) | 12 <i>Acarinina medizai</i> (Toumarkine and Bolli) |
| 6 <i>Subbotina yeguaensis</i> (Weinzierl and Applin) | |



mesotrophic rather than eutrophic conditions (e.g., Van der Zwaan et al. 1999). Sub-facies 1b later developed in the deeper setting of the Šterna-Butori section in the middle part of the *Globigerina* Marls, indicating deeper and more oligotrophic conditions. This setting is supported by the increased abundance of the SB2a assemblage (the *Cibicidoides* group) (text-fig. 4) and the decreased diversity and increased dominance during the upper part of Zones E10 and E11 (text-fig. 3b). In addition, the low percentages of planktonic foraminifera in sub-facies 1b of the Šterna-Butori section (text-fig. 3b; App. B), compared to assemblages from the other parts of the section, might be a result of decreased primary productivity as a consequence of low nutrient input from the shore. This could reflect a change in land topography during the tectonically-induced evolution of the basin, as at that time the Šterna-Butori area was situated in the central part of the basin (text-fig. 1) and may have become separated from the land, hindering nutrient input.

At the beginning of Zone E12 the basin had already become larger and wider, and tectonic movements caused the emergence of the southwestern part of the basin (the Gradišće section). This is reflected in the increase of the *Lenticulina-Bulimina* group and the higher abundance of infaunal taxa in the topmost part of the Gradišće section, implying a higher organic flux in the shallower environment. Sedimentation ceased soon afterwards in this part of the Trieste-Pazin basin. At about the same time, the Sveti Križ area (text-fig. 1) became more distant from the emerging land and closer to the basin axis. The turbiditic Flysch sedimentation was already well developed, with prevailing oligotrophic conditions supported by the dominance of the *Cibicidoides* group, high abundances of epifaunal taxa, and moderate diversity and dominance (text-fig. 3c). The oligotrophic conditions were interrupted by an episode of increased organic matter flux (the base of biofacies 2), recorded by the peak abundance of *Bathysiphon* sp. and *Pleurostomella* spp. and the increased abundance of infaunal taxa (text-figs. 3c and 4c). Subsequently, the conditions again became

oligotrophic, showing a slight increase in *Lenticulina-Bulimina* group abundance before sedimentation ended in this part of the basin in the lower part of Zone E13.

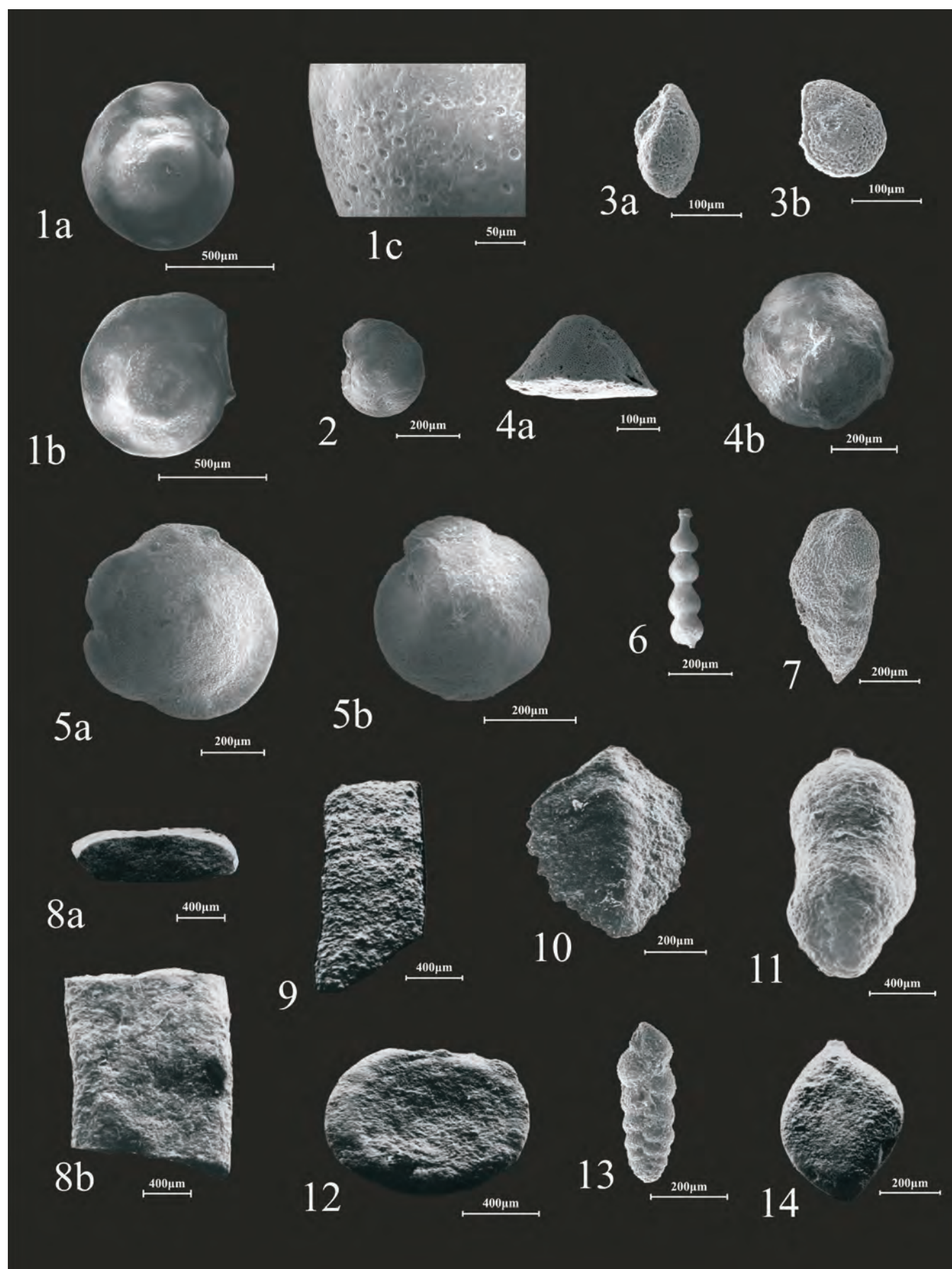
In the central part of the basin (the Šterna-Butori and the Ipšič sections), distant from the land, Flysch sedimentation was established in upper Zone E12 and sub-facies 2a was recorded in both sections (text-fig. 3). This sub-facies is defined by an abundance of foraminifera that prefer a diet of degraded organic matter, such as *Chilostomella* spp. (e.g., Schmiedl et al. 2000) and *Buliminella* sp. (Apps. C and D). These preferentially intermediate and deep infaunal species are accompanied by high abundance of epifaunal foraminifera (text-fig. 3), dependent mostly on autochthonous food supply from the primary producers (De Stigter 1996). One possible explanation for such assemblage characteristics might be the effect of interspecies competition, as presented by the TROX-2 model (Van der Zwaan et al. 1999), where such population could have existed under low food and intermediate oxygen levels. This is supported by the predominance of epifaunal forms, which supposedly implies a deep redox front (Den Dulk et al. 2000), and by the presence and environmental preferences of *Chilostomella* and *Buliminella*. These non-opportunistic taxa are documented to prefer a stable environment, maintaining their population at equilibrium with the environment (Sjoerdsma and Van der Zwaan 1992). Biofacies 2a is also characteristic of the uppermost parts of the Šterna-Butori and the Ipšič sections.

Higher oxygen levels, as indicated by higher epifaunal abundances and decreased numbers of deep infaunal taxa (biofacies 2b, text-fig. 3d), persisted during most of Zone E13 in the Ipšič section. These highly oxygenated conditions were probably the result of better ventilation in this central, deep part of the Trieste-Pazin basin at that time. The oligotrophic conditions in the Ipšič section were disrupted in the middle part of Zone E13, at the top of sub-facies 2b, by an episode recorded by the dominance of infaunal forms, very low percentages of small epifaunal specimens, and lowered *Cibicidoides* abundance, ac-

PLATE 2

SEM photographs of benthic foraminifera from the Trieste-Pazin basin.

- | | |
|---|--|
| 1a <i>Cibicidoides eocaenus</i> (Guembel) | 6 <i>Stilostomella nuttalli</i> (Cushman and Jarvis) |
| 1b <i>Cibicidoides eocaenus</i> (Guembel) | 7 <i>Bulimina tuxapamensis</i> Cole |
| 1c <i>Cibicidoides eocaenus</i> (Guembel), detail of the test | 8a <i>Bathysiphon</i> sp. |
| 2 <i>Cibicidoides alazanensis</i> (Nuttall) | 8b <i>Bathysiphon</i> sp. |
| 3a <i>Cibicidoides praemundulus</i> Berggren and Miller | 9 <i>Rhabdammina robusta</i> (Grzybowski) |
| 3b <i>Cibicidoides praemundulus</i> Berggren and Miller | 10 <i>Spiroplectammina dalmatina</i> (de Witt Puyt) |
| 4a <i>Nuttallides truempyi</i> (Nuttall) | 11 <i>Cylindroclavulina rudis</i> (Costa) |
| 4b <i>Nuttallides truempyi</i> (Nuttall) | 12 <i>Ammodiscus incertus</i> (d'Orbigny) |
| 5a <i>Oridorsalis umbonatus</i> (Reuss) | 13 <i>Karreriella subglabra</i> (Guembel) |
| 5b <i>Oridorsalis umbonatus</i> (Reuss) | 14 <i>Rzehakina epigona</i> (Rzehak) |



accompanied by moderate diversity and dominance and increased numbers of agglutinated taxa (text-figs. 3d and 4d; App. D). A similar episode was earlier recorded in sub-facies 2b of the Šterna-Butori section, at the base of Zone E13 (text-fig. 3b). This sub-facies, as in the Ipšić section, also displays decreased epifaunal populations and very low numbers of small epifaunal specimens, accompanied by abundant *Buliminella* cf. *elegantissima*, *Trochammina* sp., *Nuttallides truempyi*, and agglutinated taxa, as well as common *Oridorsalis umbonatus* (text-figs. 3b and 4b; App. B). Such assemblages indicate a higher organic flux and lowered oxygen levels. Even high percentages of the *Nt. truempyi*, an oligotrophic indicator (assemblages SB2b and IP2b; text-fig. 4b), as recorded in both sections during those intervals (Apps. B and D), may indicate higher trophic levels when accompanied by a high abundance of infaunal foraminifera (Widmark and Speijer 1997). Furthermore, *Oridorsalis umbonatus*, an important constituent of the SB2a assemblage in the Šterna-Butori section (text-fig. 4b), is indicative of an intermediate organic flux within a moderately oxygenated environment (Gupta and Thomas 2003). The faunal characteristics (i.e., the significant decrease in epifaunal abundance and the domination of benthic assemblages by infaunal taxa) recorded within the generally oligotrophic conditions are indicative of intervals with low levels of dissolved oxygen in bottom waters or high flux of organic carbon to the ocean floor (Lutze and Coulbourn 1984; Bernhard 1986; Sen Gupta and Machain-Castillo 1993; Den Dulk et al. 1998, 2000). These intervals during Zone E13 in the central part of the Trieste-Pazin basin may suggest periods of increased tectonic activity and the resulting higher input of land-derived nutrients. The position of the investigated sections in the central part of the basin, however, implies considerable distance from the shore and a low terrigenous component in the total organic flux, with occasional influence of deep-sea currents. The investigation of the Flysch deposits revealed that the sediment deposited in the southwestern part of the Trieste-Pazin basin was partially supplied by a carbonate area to the southwest, which was partly exposed and partly covered by a shallow sea (Babic and Zupanic 1996). This part of the Trieste-Pazin basin extended laterally towards the deep Venetian basin (text-figs. 6a and 6b; Premec-Fucek and Živković 2005). Another source of the sediment was of mixed carbonate-siliciclastic composition and represented a longitudinal flow from a distant, possibly at least in part, Alpine source (Babic and Zupanic 1996). The difference in the composition of the inflowing material, with diverse composition of organic and inorganic particles, indicates that deep-sea currents occasionally influenced the Trieste-Pazin basin. These currents likely varied in their properties (temperature, oxygen and organic carbon content), which may explain the observed differences in the benthic foraminiferal assemblages, reflecting the diverse paleoenvironmental characteristics in various parts of the Trieste-Pazin basin. This hypothesis, however, is difficult to prove because the geology of the southwestern Tethys, with numerous foreland basins, is very complex and the paleogeographic position of individual terrains is not well established. According to the paleogeographic map of the Late Lutetian (Meulenkamp and Sissingh 2003), Istria was an elongated, narrow, shallow basin between a deep basin to the west and land to the east (text-fig. 6a). This allowed undisturbed flow of the water throughout the Trieste-Pazin basin, enabling good ventilation of the bottom water and the development of oligotrophic conditions in the deeper settings. In their paleoceanographic reconstruction Muttoni et al. (2001) placed the Friuli-Istria platform during the Lutetian adjacent to the

Belluno basin (northern Italy) (text-fig. 6c), which during the Eocene was also characterized by turbidite sedimentation (Braga et al. 1975; Oberhänsli et al. 1984). The foraminiferal assemblages recorded from the Possagno Formation in the Belluno basin (Braga et al. 1975; Grünig and Herb 1980; Oberhänsli et al. 1984; Grünig 1985) are similar to the fauna of the Trieste-Pazin basin, suggesting a direct communication of water masses and faunal exchange between these two adjacent basins (text-fig. 6c). This implies that the communication with the Belluno basin commenced in Zones E11 or E12, because as the Trieste-Pazin basin opened it also expanded towards the northwest, as suggested by Babic and Zupanic (1996). Such a connection might have caused temporary changes in the benthic foraminiferal assemblages as a response to deep-sea currents of different properties. This connection might have occasionally persisted until the closure of the Trieste-Pazin basin and cessation of sedimentation during Zone E13 due to tectonic uplifts. The Belluno basin, on the other hand, continued to exist into the Late Eocene (e.g., Grünig and Herb 1980; Oberhänsli et al. 1984; Grünig 1985).

In conclusion, the Trieste-Pazin basin was strongly influenced by the tectonic activity and subsequent deepening processes, but the amount and type of organic material, carried from both adjacent and distant sources, had a strong influence on the paleoenvironmental conditions documented in the benthic foraminiferal record. The variability of the benthic foraminiferal assemblages from the Trieste-Pazin basin indicates strong local environmental control on different parts of the basin that influenced primary productivity. Superimposed on these local controls are more regional influences provided by the connection of the Trieste-Pazin basin and the adjacent Belluno basin. Higher resolution studies are needed to better constrain the timing and extent of occasional influence of deep-sea currents and to improve paleoceanographic interpretations of different parts of the Trieste-Pazin basin and its connection with the Belluno basin.

CONCLUSIONS

The ranges and abundances of planktonic foraminiferal species allowed the precise age determination of the deposits from the Trieste-Pazin basin of Istria, Croatia. These deposits span five Middle Eocene planktonic foraminiferal zones: *Globigerina* *natheka kugleri*/*Morozovella aragonensis* Zone (E9), *Acarinina topilensis* Zone (E10), *Morozovelloides lehneri* Zone (E11), *Orbulinoides beckmanni* Zone (E12), and *Morozovelloides crassatus* Zone (E13). Deposition took place in upper and middle bathyal settings. Benthic foraminiferal biofacies indicate that the environment evolved from an initially mesotrophic upper bathyal setting to a more oligotrophic upper to middle bathyal setting influenced by turbiditic currents. Benthic foraminiferal assemblages of the shallower settings (i.e., the *Lenticulina-Bulimina* group foraminifera) indicate mesotrophic conditions for the *Globigerina* Marls biofacies. The deeper Flysch biofacies, on the other hand, indicates periods of oligotrophic conditions documented by the foraminiferal assemblages dominated by the *Cibicidoides* group.

The characteristics of the benthic foraminiferal assemblages documented here provide insights into paleoenvironmental conditions and paleogeography of the Trieste-Pazin foreland basin during the Middle Eocene. During upper Zone E9 and lower Zone E10 the basin deepened and widened and the paleoenvironmental conditions were influenced by local control on the primary productivity and land-derived material. Due to ba-

sin widening and extending, approximately in Zone E11, the shelf in the central part of the basin became drowned and evolved into a mesotrophic slope environment. Afterwards, as a result of the intense tectonic activity with increasing distance from the shore, the environmental setting gradually changed to deeper, more oligotrophic, upper and middle bathyal conditions influenced by turbiditic currents. The short-term high flux/low oxygen intervals within generally oligotrophic Flysch biofacies were recorded during Zones E12 and E13 along the basin axis (the Sveti Križ, Šterna-Butori and Ipši sections). These intervals may have been caused by the occasional influence of deep-sea currents with different properties from a distant source and might imply connection with an adjacent basin (e.g., the Belluno basin).

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Appendix A: Counts of foraminiferal species from the Gradišće section.

Appendix B: Counts of foraminiferal species from the Šterna-Butori section.

Appendix C: Counts of foraminiferal species from the Sveti Križ section.

Appendix D: Counts of foraminiferal species from the Ipšić section.