

Benchmark data of a changing sea — Palaeogeography, Palaeobiogeography and events in the Central Paratethys during the Miocene

Mathias Harzhauser ^{a,*}, Werner E. Piller ^b

^a *Naturhistorisches Museum Wien, Geologisch-Paläontologische Abteilung, Burgring 7, A-1014 Wien, Austria*

^b *Institute for Earth Sciences (Geology and Palaeontology), Graz University, Heinrichstrasse 26, A-8010 Graz, Austria*

Received 17 January 2005; received in revised form 26 February 2007; accepted 5 March 2007

Abstract

The reconstruction and interpretation of terrestrial ecosystems and vegetational patterns in the Central European Miocene have to take into account the influence of a vast landlocked water body, namely the Paratethys Sea. As a northern appendage of the early Mediterranean Sea, it spanned a north–south gradient of at least 4° latitude and has been suggested to represent some kind of “palaeothermometer”, which reflected slight expansions or restrictions of climatic belts. Due to its vulnerable marine connections it was also highly susceptible to major (global) sea-level fluctuations which are reflected in phases of endemism. Hence, a fairly continuous record of marine nearshore assemblages throughout the Miocene reflects an extraordinary interplay of sea-level fluctuations, changes in climate, immigrations, and blooms in autochthonous elements. Whilst biostratigraphic implications of these patterns were recognised early in palaeontology, a biogeographic model is still lacking. The intermingling of palaeogeographic terms with those restricted to biogeography is still commonly used — a situation which can be overcome by integrating data from different biota into a new palaeobiogeographic scheme.

Herein, a data-set of 1809 species-level taxa (Gastropoda and Foraminifera) serves as the base for interpretations. Gastropods in particular turned out to be of greatest value for the differentiation of palaeobiogeographic units due to sensitive reactions to all environmental parameters and occupying a wide range of ecological niches. Based on the excellent gastropod record the Proto-Danubian Province, Early Danubian P., Danubian P., Balatonian P. and a Proto-Caspian Subprovince are defined. The biogeographic reorganisations are associated with five major biotic events within the gastropod faunas. These “big five” comprise four extinctions – the late Ottnangian extinction event (LOEE), the mid-Badenian-extinction-event (MBEE), the Badanian–Sarmatian-extinction event (BSEE), the Sarmatian–Pannonian-extinction event (SPEE) – and one exceptional immigration/origination event termed the early Badanian Build-up event (EBBE).

Foraminifera are less valuable for palaeobiogeographic purposes in the area and time-slice studied. Endemisms are generally lower and turn-over rates less dramatic. They are, however, very useful for stratigraphic correlations with the Mediterranean and Atlantic areas. This fairly well calibrated marine biostratigraphy of the Central Paratethys serves as stratigraphic backbone and control for continental stratigraphy.

© 2007 Elsevier B.V. All rights reserved.

Keywords: Central Paratethys; Lake Pannon; Miocene; Gastropoda; Foraminifera; Palaeobiogeography

* Corresponding author. Tel.: +43 1 52177 250; fax: +43 1 52177 459.

E-mail address: mathias.harzhauser@nhm-wien.ac.at (M. Harzhauser).

1. Introduction

The marine Oligocene and Miocene deposits of Central Europe are a heritage of the vanished Paratethys Sea. During its maximum extent this vast sea spread from the Rhône Basin in France towards Inner Asia. As a northern satellite sea of the Western Tethys (=Proto-Mediterranean) it came into existence during the latest Eocene and Early Oligocene due to the rising Alpine island chains, which acted as geographic barriers (Rögl, 1998). The rising archipelago consisted of the Alps, Dinarids, Hellenids, Pontids, and the Anatolian Massif. Subsequently, the newly formed Paratethys was partitioned into two large geotectonic units which underwent different environmental histories due to differently timed geotectonic events and global sea-level fluctuations controlling marine and non-marine phases (Popov et al., 2004). The smaller western part consists of the Western and the Central Paratethys being opposed by the larger Eastern Paratethys. The Western Paratethys comprises the Rhône Basin and the Alpine Foreland Basin of Switzerland and western Bavaria. The Central Paratethys reaches from Bavaria in the west to the Carpathian Mountains in the east where it abuts the area of the Eastern Paratethys. Herein, we focus only on the smaller, western unit. Related to this is a complex pattern of changing seaways and landbridges between the Paratethys and the Mediterranean as well as the western Indo-Pacific (e.g., Rögl, 1998, 1999). This also created a complex pattern of biogeographic relationships between these palaeobiogeographic units (Harzhauser et al., 2002). Consequently, this geodynamically controlled biogeographic differentiation necessitated the establishment of different chronostratigraphic/geochronologic scales (Fig. 1). The interplay of faunistic input from the Miocene Proto-Mediterranean–Atlantic Region and Paratethyan endemic evolution should be reflected by a discrete biogeographic terminology. The recognition of the Paratethys as a biogeographic entity which differs from the Neogene Mediterranean based on the peculiar character of the mollusc faunas goes back to Laskarev (1924). He proposed the existence of that lost sea after detailed faunistic investigations of the Vienna, Styrian, Pannonian, Dacian and Euxinian basins.

The initiating “Paratethys-event” is expressed by the formation of long-lasting anoxic bottom conditions in the early Kiscellian (Early Oligocene). Thin-bedded, black shales – the so-called “Fischschiefer” – developed in the Alpine foreland basin, bituminous laminated Tard clay was deposited in the Hungarian basin and menilites in the Carpathian Flysch trough (Baldi, 1998). A first endemic mollusc fauna evolved spreading from the Asian Eastern

Paratethys towards the west (Popov et al., 1985). The associated Eastern Paratethyan regional stage Solenovian is the name given to that peculiar fauna. Aberrant water chemistry – probably brackish water conditions – within the vast inland sea triggered a blooming and rapid evolution of a highly endemic bivalve fauna with genera such as *Janschinella*, *Korobkoviella* or *Ergenica* (Popov et al., 1985; Nevesskaja et al., 1987). Monospecific nannoplankton blooms and diatomites, too, point to reduced salinities and cool-temperate surface water reaching from Bavaria to Transcaspiya (Rögl, 1998).

2. The frame: palaeogeography, depositional regimes and major sea-level fluctuations

2.1. latest Oligocene–Early Miocene (Fig. 2A–B)

2.1.1. *Egerian* (~25–21 m.y.), *Eggenburgian* (~21–18 m.y.), *Ottangian* (~18–17 m.y.), *Karpatian* (~17–16.3 m.y.)

The *Egerian* spans part of the Late Oligocene and a large part of the Aquitanian (Baldi and Senes, 1975). Its stratotype was defined at Eger in northern Hungary (Baldi, 1975). The mainly siliciclastic depositional regime of the Kiscellian continues into the *Egerian*. Carbonate formation is subordinate throughout the *Egerian*. Typical are mixed carbonate–siliciclastic systems predominated by corallinaceans, bryozoans and larger foraminifers such as miogypsinids and lepidocyclinids (Kaiser et al., 2001) (Fig. 2).

In the Late Oligocene the Paratethys was a huge west–east oriented sea. New gateways towards the Western Tethys opened and normal marine conditions re-established. The connection towards the North Sea Basin was initiated via the Rhine Graben and a connection to the Venetian Basin opened in the southwest (Rögl, 1998; Reichenbacher, 2000). This transeuropean connection of the Rhine Graben and Mainz Basin with the Tethyan Rhône–Bresse Graben and the Paratethyan Alpine Foreland ceased during the Late *Egerian* (Reichenbacher, 2000). Paralic coal basins and freshwater environments developed in the western tip of the Paratethys (Barthelt, 1989; Berger, 1996), whilst the seaways via the still partly submerged Alpine nappes into the Western Tethys remained open (Wagner, 1996; Steininger and Wessely, 2000).

The *Eggenburgian* is a regional Lower Miocene stage with its stratotype in the NE of Austria some 60 km NW of Vienna (Steininger, 1971). The biostratigraphic framework of this stage is based largely on its characteristic mollusc fauna with large-sized pectinids (Steininger and Senes, 1971).

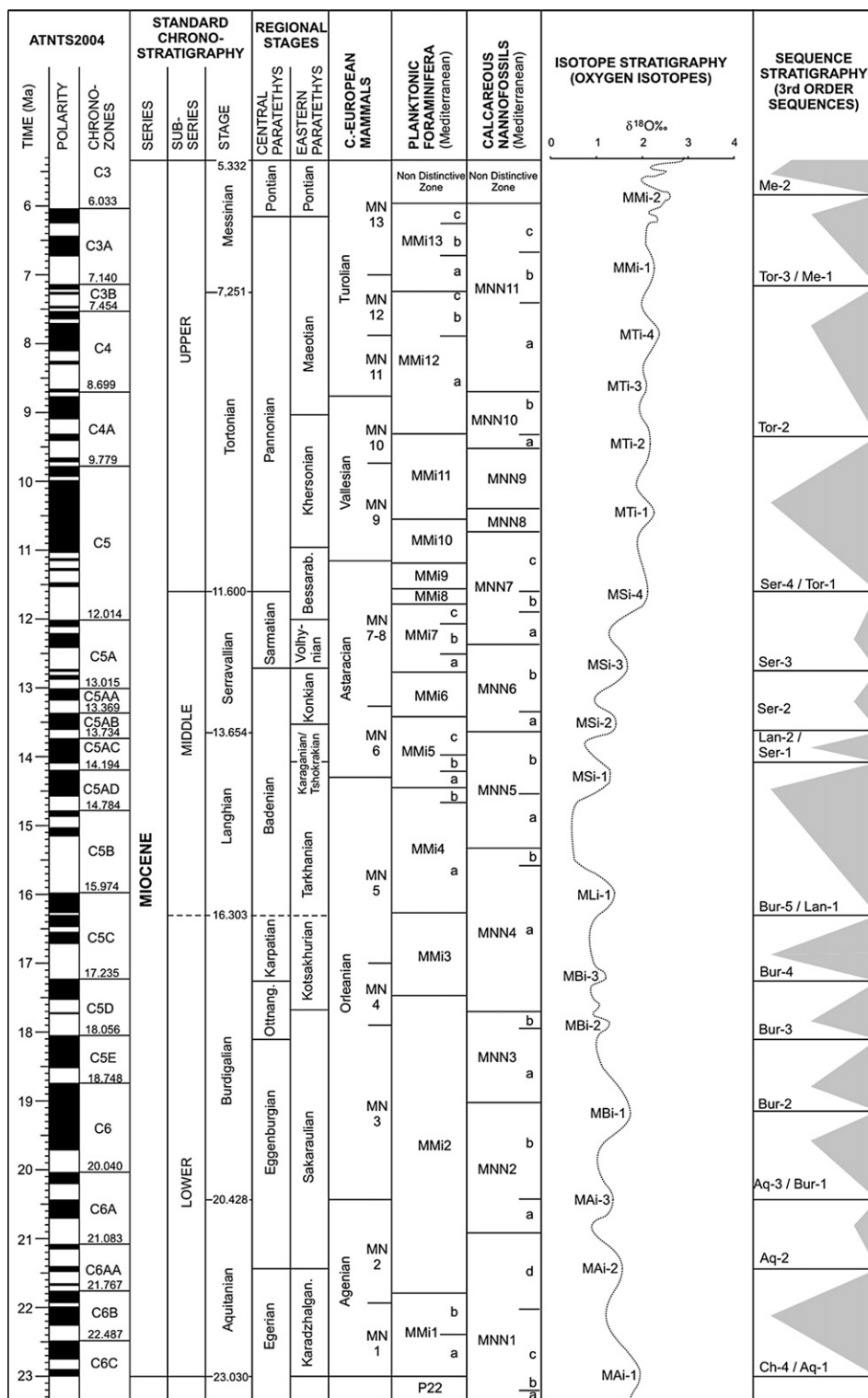


Fig. 1. Miocene chronostratigraphy and biostratigraphy. Mammal mega-zones after [Steiningger \(1999\)](#); Foraminifera and Calcareous Nannoplankton after [Sprovieri \(1992\)](#), [Sprovieri et al. \(2002\)](#), [Fornaciari and Rio \(1996\)](#), [Fornaciari et al. \(1996\)](#); oxygen isotope stratigraphy adapted from [Abreu and Haddad \(1998\)](#) and sequence stratigraphy after [Hardenbol et al. \(1998\)](#); all zones recalibrated according to [Gradstein and Ogg \(2004\)](#), [Gradstein et al. \(2004\)](#) and [Lourens et al. \(2004\)](#).

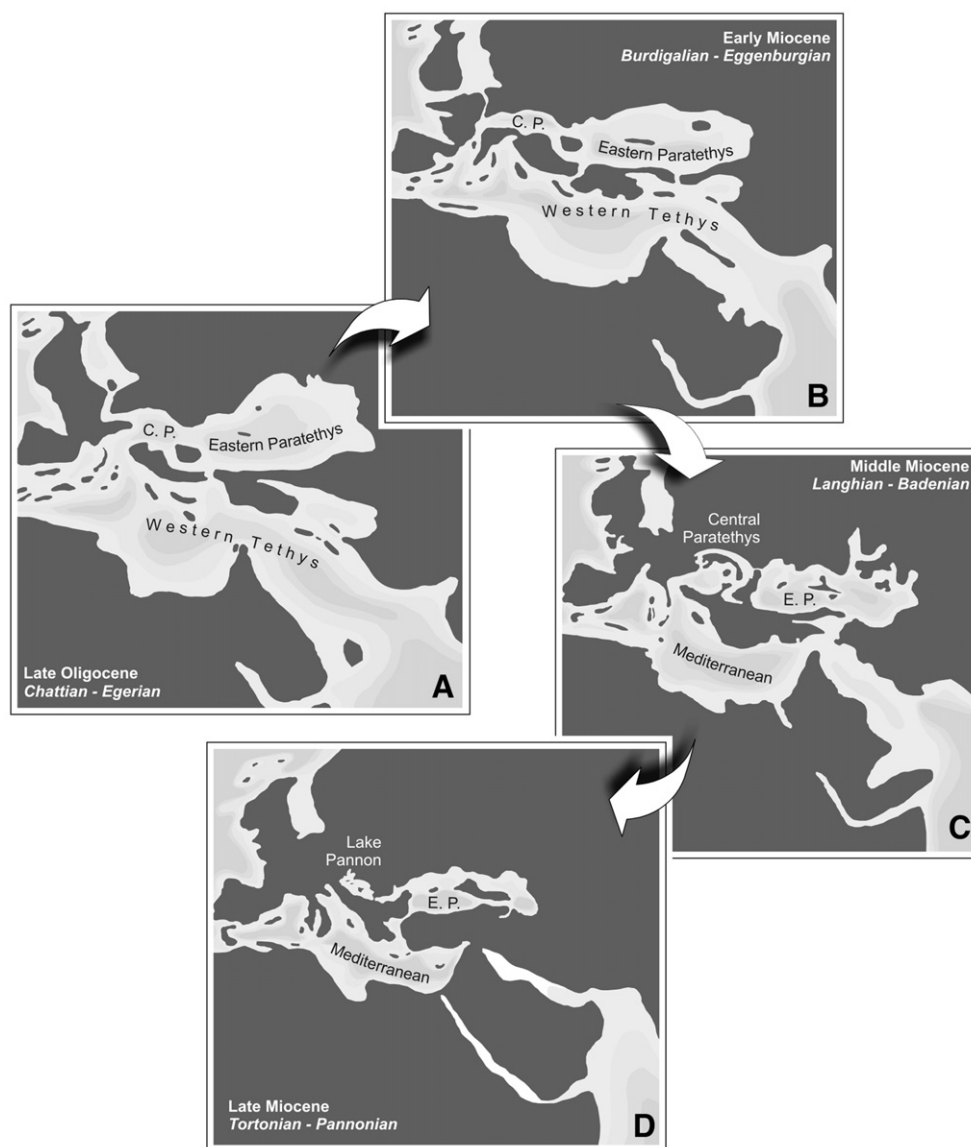


Fig. 2. Palaeogeographic sketch-maps of the circum-Mediterranean area with focus on the Paratethys Seas based on Rögl (1998), Magyar et al. (1999), Steininger and Wessely (2000), and Popov et al. (2004). Note that a serious palinspastic model incorporating large-scale rotations and displacement (e.g. Marton et al., 2003) for the entire area is still missing. [C.P. = Central Paratethys; E.P. = Eastern Paratethys] A: After the Early Oligocene birth of the Paratethys by full isolation, new connections form with the North Sea Basin in the north and the Western Tethys in the south. A geographic separation into a Western/Central Paratethys and an Eastern Paratethys becomes established. B: During the Early Miocene, the Central Paratethys is a west–east oriented deep basin with repeated connections into the Rhône Basin in the west. C: The Carpathian chain starts to structure the Central Paratethys Sea as an archipelago and the west–east trending basins become tectonised. The southern Carpathian Foreland Basin suffers from restrictions and becomes an evaporitic shoal during the middle Badenian. Connections to the Eastern Paratethys are unstable throughout the Badenian but become broad and passable during the late Badenian and especially during the Sarmatian. D: The Paratethys is strongly isolated. Whilst the Eastern Paratethys still connects with the Mediterranean Sea, the Central Paratethys has vanished giving place to brackish Lake Pannon.

The lower Eggenburgian is dominated by sandy and pelitic sedimentation. Carbonates are scarce, patchy and usually of mixed siliciclastic–carbonate type. A typical example is the shallow marine corallinean rhodolite carpets admixed with fine to medium sand, inhabited by

the scutellid echinoid *Parmulechinus hoebbarthi* (Kühn) in the Horn Basin of northern Austria (Steininger, 1971). In deep-neritic to bathyal settings typical grey calcareous clays with intercalations of sands – the so-called “Schlier” – developed. Only in the Outer Carpathians a

relic Flysch trough with turbiditic sequences prevailed (Baldi, 1998; Popov et al., 2004).

Broad connections into the Eastern Paratethys allowed the spreading of early Eggenburgian mollusc faunas as far east as the Krim peninsula and Georgia (Rögl, 1998). In addition, the western seaway via the Alpine Foreland which was sealed during the late Egerian and maybe also during the initial Eggenburgian started to open. The sea invaded the foreland successively from the west connecting to the Central Paratethys during the Eggenburgian (Berger, 1996). This newly established marine pathway of the Paratethys via the Alpine Foredeep into the Rhône Basin coincided with a second flow from the Eastern Mediterranean (Martel et al., 1994). These connections gave rise to a new hydrodynamic regime reflected in the meso- and macrotidally controlled deposits throughout the Alpine Foreland Basins lasting from the late Eggenburgian to the middle Ottnangian (Allen et al., 1985; Faupl and Roetzel, 1990). The second area of tidal deposits is described by Sztanó (1995) from the Eggenburgian of the North Hungarian Bay. Faunistically, the changes in palaeogeography are reflected by the immigration of western Mediterranean taxa such as the echinoid *Arbacia catenata* (Desor) and several bryozoans (Vavra, 1979; Kroh and Harzhauser, 1999). Among molluscs, the pectinids *Flexopecten palmatus* (Lamarck) and *Macrochlamis holgeri* (Geinitz) arrived in the Paratethys during the late Eggenburgian (Mandic and Steininger, 2003). The late Eggenburgian also differs distinctly by the initiation of a warm-temperate carbonate factory, indicated by widespread bryozoan–corallinean limestones (Nebelsick, 1989). Larger foraminifera and corals, however, are subordinate, the latter form only very small patches.

The *Ottnangian* with its stratotype at Ottnang in Upper Austria (Rögl et al., 1973) is a twofold stage with a generally normal marine development during its early phase. Sedimentation is predominately siliciclastic with widespread tidal-influenced deposits and the characteristic sandy/silty “Schlier” (Faupl and Roetzel, 1990). Carbonates, as known from the Hungarian Bántapuszta section (Kókay, 1973), are scarce and correspond in composition to the late Eggenburgian corallinean–bryozoan type. Correspondingly, corals are rare aside from few patchy colonies and did not form any carpets or reefs. Temperate conditions are discussed by Bachmann (1973) based on silicoflagellate-assemblages and the frequent occurrence of diatomites.

Thereafter, due to uplift of the Alpine Foreland Basin, the western connection ceased (Rögl, 1998) and the fluvial–lacustrine environments of the Upper Freshwater Molasse establish in the western Alpine Foreland Basin (Berger, 1996). In addition, the sea-level fall during the

Early Miocene global sea-level change of TB 2.1. cycle (Haq et al., 1988) accentuated the beginning of isolation of the Paratethys from the Mediterranean Sea during the late Ottnangian. Except for the Northern Alpine Foreland Basin, no real marine environments are known from the Carpathian–Pannonian–Dinaride domain and brackish to fresh water sedimentary environments prevailed (Kováč et al., 2004). Consequently, during the late Ottnangian and the synchronous Kotsakhurian in the Eastern Paratethys biogeographic relations between the Paratethys and the Mediterranean Sea ceased. This Ottnangian crisis is reflected in nearshore settings by brackish water conditions and a sudden evolutionary peak in bivalves, resulting in a large number of endemic genera such as *Limnopageta*, *Rzehakia*, *Lenticorbula*, or *Eoprosodacna*. This peculiar, so-called “*Rzehakia* fauna” spreads from the Eastern Paratethys into the Central and Western Paratethys Sea in the late Ottnangian (Steininger, 1973).

The *Karpatian* stage, based on the stratotype section Slup in Moravia was defined by Cicha et al. (1967) and is a time-equivalent of the late Burdigalian. The Karpatian starts with a transgression and a reorganisation of palaeogeographic patterns (Rögl et al., 2003). This transgression in the Central Paratethys area is associated with the sea-level rise at the beginning of the late Early Miocene during the global 3rd order sea-level cycle of TB 2.2. postulated by Haq et al. (1988). The lowstand sediments, represented mainly by terrestrial, alluvial, fluvial and deltaic deposits at the base of the Karpatian sequences, pass rapidly towards overlying strata of marine, neritic to shallow bathyal sediments. Sedimentation is predominated by green–blue and grey pelites and silty calcareous shales in offshore environments and clayey sand in marginal areas. Continuous sedimentation between the Ottnangian and the Karpatian is expected only in deeper parts of Central Paratethys basins whereas all shallow marine settings display a strong discordance (Rögl et al., 2003).

The early Karpatian has similarities with the Ottnangian, pointing to cool-temperate water masses with high amounts of siliceous fossils (Rögl et al., 2003). Suboxic bottom conditions in the basins, upwelling and temperate water are also suggested based on the planktonic foraminifers (Cicha et al., 2003). Carbonate production was extremely low throughout the Central Paratethys at that time. The low diversity mollusc fauna, too, is dominated by taxa persisting from the Ottnangian (Harzhauser, 2003). Warmer water indicators, such as *Globigerinoides* or *Globorotalia*, appear in the late Karpatian together with a thermophilic mollusc fauna (Harzhauser et al., 2003). This northward migration was favoured by a general warming

trend and by a new broad connection with the Mediterranean that was established via the Slovenian “Trans-Tethyan Trench Corridor” (Bistricic and Jenk, 1985). This seaway enabled a free faunal exchange between the Central Paratethys and the Mediterranean area. This change in environment was complemented by a dramatic tectonic turnover in the Central Paratethys area leading to a change from W–E trending basins towards intra-mountain basins (Rögl, 1998; Kovác et al., 2003). A typical example for the geodynamic impact is the abrupt, discordant progradation of upper Karpatian estuarine to shallow marine deposits over lower Karpatian offshore clays in the Alpine Foreland Basin and in the Carpathian Foredeep (Adámek et al., 2003). The widespread formation of evaporites in the Rumanian part of the Carpathian Foredeep and in the Transylvanian Basin points to a poor or even absent connection with the Eastern Paratethys during the late Early Miocene.

The Karpatian/Badenian (Burdigalian/Langhian) boundary is characterised by a significant sea-level drop (Haq et al., 1988; Hardenbol et al., 1998), expressed as a hiatus traceable throughout the Central Paratethys (Rögl et al., 2002). Continuous sedimentation between the Karpatian and Badenian has not been recorded up till now. Therefore, the top of the Lower Miocene in the Paratethyan basins is marked by erosional surfaces or by an angular discordance between the Lower and Middle Miocene strata, frequently called the “Styrian unconformity” (Latal and Piller, 2003).

2.2. Middle Miocene (Fig. 2C)

2.2.1. Badenian (16.3–12.7 m.y.), Sarmatian (12.7–11.6 m.y.)

The *Badenian* Stage was defined by Papp and Steininger (1978) based on the eponymous stratotype locality Baden–Sooss in the Vienna Basin. There, the characteristic grey–blue basinal clay is exposed, which contains a highly diverse benthic foraminifer assemblage and hundreds of molluscs species besides other invertebrates and vertebrates.

A threefold subdivision of the Badenian is generally accepted (Papp et al., 1978; Kovác et al., 2004) based on significant palaeogeographic and palaeoecologic changes. The early Badenian (Langhian) transgression is related to the global sea-level cycle of TB 2.3. cycle of Haq et al. (1988), based on the FAD of *Praeorbulina* in the Styrian Basin, the Vienna Basin and the Alpine Foreland Basin (Rögl et al., 2002; Kovác et al., 2004). The top of that lower Badenian cycle is indicated by an unconformity in seismic surveys in the Vienna Basin pointing to a sea-level drop of more than 120 m (Kreutzer,

1986; Weissenböck, 1996). Furthermore, in many marginal settings, e.g. the Alpine Foreland Basin or in the Eisenstadt–Sopron Basin, the end of the marine sedimentation of the first Badenian cycle can be correlated to the same event (Mandic et al., 2002; Kroh et al., 2003). Based on the co-occurrence of *Orbulina* and *Praeorbulina* in the underlying deposits (e.g. Rögl et al., 2002), the basin-wide occurrence and the remarkable magnitude of the sea-level drop, a linkage with the global sea-level drop at about 14.2 m.y. is reasonable. This event was triggered by the expansion of the East Antarctic ice sheet (Flower and Kennett, 1993; Shevenell et al., 2004) and corresponds to the Lan2/Ser1 sequence boundary of Hardenbol et al. (1998).

The second Badenian cycle is interpreted to be an expression of the global cycle TB 2.4. of Haq et al. (1988). A distinct lowstand wedge and a well-developed transgressive wedge are observed in seismic studies along the Spannberg ridge in the Matzen oil field of the central Vienna Basin (Kreutzer, 1986). In the Carpathian Foreland Basins and in the Transylvanian Basin a pronounced evaporitic phase starts, known as the Wielician crisis (Steininger et al., 1978; Kasprzyk, 1999; Chira, 2000). While evaporite formation continued in the east throughout the middle Badenian, in the western parts of the Central Paratethys this cycle is characterised by corallinean platforms with frequent caliche formation and vadose leaching (Dullo, 1983; Schmid et al., 2001).

The renewed flooding of the third Badenian cycle is biostratigraphically dated by the onset of the nannoplankton Zone NN6 (Hudácková et al., 2000; Kovác et al., 2004). The base of this biozone is defined by the last occurrence of *Sphenolithus heteromorphus* and corresponds to the Langhian/Serravallian boundary, which was calibrated by Foresi et al. (2002) at 13.59 m.y. (see also Gradstein and Ogg, 2004; Gradstein et al., 2004). Therefore, the Langhian/Serravallian boundary is located within the Badenian. Considering the dating and the magnitude of that cycle, a correlation with the global cycle TB 2.5. of Haq et al. (1988) is reasonable. This late Badenian is characterised by a stratified water body indicated by the deposition of dysoxic pelites in basinal settings in the entire Central Paratethys area (e.g. Hudácková et al., 2000). Even the platforms became affected by repeated hypoxic events as documented by Schmid et al. (2001).

Aside from the fossiliferous offshore clays, the Badenian is the acme of the Paratethyan carbonate factory. Corallinean limestones are ubiquitous but now the only noteworthy coral-reef phase of the Paratethys sets in. early Badenian reefs in southern parts of the Paratethys are fairly diverse. Especially in the Styrian Basin several

small coral reefs composed of *Montastrea*, *Tarbellastraea*, *Leptoseris* and *Porites* developed which, however, had to keep pace with high terrigenous sedimentation rates (Friebe, 1993; Riegl and Piller, 2002; Erhart and Piller, 2004). In the late Badenian, however, a distinct change in reef structures occurs. Even in the southern Paratethyan basins (e.g. Vienna Basin, Styrian Basin) no complex reefs are documented any more. Instead, coral carpets, dominated by *Porites*, *Tarbellastraea*, *Caulastrea*, *Acanthastrea* and *Stylocora* developed along detached islands (Dullo, 1983; Piller and Kleemann, 1991; Riegl and Piller, 2000, 2002). This shift in reef-structure and diversity seems to be linked to the climatic deterioration triggered by the global mid-Miocene Climate Transition (Shevenell et al., 2004). In northern parts of the Paratethys this change is even more severe, leading to a loss of algal–bryozoan–coral bioconstructions in favour of algal–serpulid–vermetid “reefs” (Pisera, 1996; Studencki, 1999).

The palaeogeographic situation changed strongly throughout the Badenian. During the early Badenian the “Trans-Tethyan Trench Corridor” via Slovenia was still open and connected the Mediterranean Sea with the Pannonian basins complex. The eastern connections, however, are still controversial. While Rögl (1998) and Steininger and Wessely (2000) postulate an open connection into the Eastern Paratethys, Studencka et al. (1998) and Popov et al. (2004) indicate a land barrier between both seas. An already subducted marine pathway between the southern margin of the Black Sea plate and the Pontids is also discussed by Rögl (1998) to connect the Eastern Mediterranean with the Central Paratethys area. A re-opening of the Tethyan gateway between the Mediterranean and the Indo-Pacific during the Langhian (early Badenian) is generally accepted (Rögl, 1998; Popov et al., 2004).

During the middle Badenian the eastern seaways were sealed. Water supply for the Central Paratethys was only available via the “Trans-Tethyan Trench Corridor”. This seaway was finally closed in the late Badenian. The entire Central Paratethys was therefore dependent upon a connection with the Eastern Paratethys via today’s western Black Sea area. Faunistic differences between the diverse Central Paratethys and the impoverished Eastern Paratethys at that time, however, exclude the Eastern Paratethys as a passage to the west (Studencka et al., 1998). Again, the enigmatic seaway between the Black Sea plate and the Pontids might have acted as a gateway (Rögl, 1998). Such a connection would also be obligatory to explain the immigration of new radiolarian assemblages into the Central Paratethys as discussed by Dumitrica et al. (1975).

The next dramatic change in marine biota sets in with the dawn of the Sarmatian. This re-orientation was triggered by a strong restriction of the open ocean connections of the Central Paratethys (Rögl, 1998), corresponding to the Ser3 sequence boundary of Hardenbol et al. (1998) and cycle TB 2.6. of Haq et al. (1988). The Badenian/Sarmatian boundary would thus be related with the glacio-eustatic isotope event MSi-3 at 12.7 m.y. (Abreu and Haddad, 1998). Correspondingly, a considerable hiatus at the Badenian/Sarmatian boundary is indicated by a strongly erosive discordance in seismic lines in Paratethyan basins (Harzhauser and Piller, 2004a,b).

The *Sarmatian*, with its stratotype in the northern Vienna Basin at the Nexing section comprising biogenic sediments of rock-forming mollusc shells (Papp and Steininger, 1974), is a strongly twofold stage. The lower Sarmatian is dominated by fine-siliciclastic sedimentation as the broad spectrum of Badenian reefal structures has vanished completely within the entire Paratethys Sea at the Badenian/Sarmatian boundary. Carbonate rocks are represented only rarely by autochthonous build-ups formed by the polychaete *Hydroides* and by bryozoans (Harzhauser and Piller, 2004a,b). These bioconstructions are best developed in the Carpathian Foredeep, extending as a patchy chain from Poland via Moldavia and Rumania to Bulgaria (Pisera, 1996).

The outcropping fine-siliciclastic sediments were mainly deposited on tidal flats or in estuaries and are rich in low-diversity molluscan faunas. In sections reflecting open water conditions, diatomites with marine diatoms may occur (Harzhauser and Piller, 2004a,b). Offshore deposits are represented by marls and silty clay with an impoverished bivalve fauna (Kojumdzieva et al., 1989).

With the onset of the late Sarmatian, sedimentation switched from siliciclastic to carbonatic throughout the Central Paratethys. Oolites and coquina-dominated sands start to spread in nearshore settings and on shallow shoals (Harzhauser and Piller, 2004a,b). Mass occurrences of the larger foraminiferal species *Spirolina austriaca* d’Orbigny characterize the latest Sarmatian. Together with this change a drastic increase in shell thickness of bivalves occurred (e.g., *Venerupis*, *Sarmatimacra*; Papp et al., 1974). The early Sarmatian polychaete–bryozoan communities collapsed and were replaced by unique foraminiferan build-ups contributed by the sessile nubeculariid genus *Sinzowella*. It is notable, that the Sarmatian oolites are the only Miocene oolites in the entire Central Paratethys area.

In the Eastern Paratethys the Sarmatian has an analogue in the regional stages Volhynian and Bessarabian. During that time the Paratethys became nearly completely

sealed off. The Central Paratethys was only connected to the Eastern Paratethys. From there, a narrow marine connection into the Mediterranean Sea formed far in the east due to tectonic movements along the Dead Sea fault system (Steininger and Wessely, 2000). The connection between both Paratethyan seas is reflected by a striking similar faunistic inventory characterised by a highly endemic and considerably impoverished fauna lacking most stenohaline taxa (Kolesnikov, 1935; Papp, 1974). This peculiar character of the marine fauna was recognised already by Suess (1866) who then introduced the term Sarmatian.

2.3. Late Miocene (Fig. 2D)

2.3.1. Pannonian (11.6–6.1 m.y.)

The Pannonian Stage is an expression of the ongoing continentalisation in central and south-eastern Europe resulting in a restriction of the aquatic realm of the Central Paratethys area to the Pannonian basins system. Now Lake Pannon formed at about 11.6 m.y. in place of the relic Paratethys Sea. The vast brackish to freshwater lake was encircled by the Alps, the Carpathians and the Dinarids. Genetically, the lower to middle Pannonian lake deposits are proposed by Harzhauser et al. (2004) to represent a single cycle starting at the Middle Miocene/Upper Miocene boundary due to the influence of the glacio-eustatic sea-level lowstand TB 3.1. of Haq et al. (1988). During phases of high water tables the deep lake areas were exposed to hostile dysoxic conditions resulting from a well developed hypolimnion (Harzhauser and Mandic, 2004). Typical deposits are grey–blue clays and marls in basinal settings; the stratotype of the Pannonian Stage, defined by Papp (1985a) at Vösendorf in the southern Vienna Basin exposes such offshore clays. Along the coasts of Lake Pannon, deltaic gravel, sand, whitish marls and lignites accumulated. While oolites and bryozoan bioconstructions are still frequent in the late Bessarabian of the Eastern Paratethys (Pisera, 1996), equivalents are completely lacking in synchronous Lake Pannon deposits. Soon, its northwestern part – e.g. Vienna Basin – turned into floodplain-environments during the late Pannonian as a consequence of the retreat of the coastline (Magyar et al., 1999; Harzhauser and Tempfer, 2004). The central and southern part remained as a several hundred metre deep sub-basin complex filled by prodelta turbidites and prograding deltaic deposits (Popov et al., 2004). Despite its shrinking size, the southern coastline along the northern Dinarids was quite stable throughout the Pannonian (Magyar et al., 1999; Popov et al., 2004).

The most conspicuous feature of Lake Pannon, however, is its mollusc fauna being characterised by a high

percentage of endemism and quick evolutionary radiations (Müller et al., 1999). The development of the fauna was controlled by the gradual freshening of the water body as well as by geodynamic processes, resulting in profound changes in lake geometry (Magyar et al., 1999). Aside from the highly evolved lymnocytherids, the manifold dreissenids display an eye-catching evolution. At that time, the Eastern Paratethys reached westward into the Dacian Basin. Its associated Bessarabian fauna is a direct descendent of the late Middle Miocene Sarmatian/Volhynian faunas (Kolesnikov, 1935) and differs fundamentally from the Lake Pannon assemblages.

3. Material, data and methods

This study presents a set of presence-data for Late Oligocene and Miocene gastropods and foraminifers in the Central Paratethys.

For foraminifers the revised and comprehensive synopsis of Cicha et al. (1998) serves as the data pool. The presence data were used in a very conservative way as questionable stratigraphic occurrences have been mainly ignored. Only in cases where questionable occurrences are sandwiched between verified older and younger data they have been treated as granted. Although data are available for the period between the Kiscellian and the Pannonian only those starting with the late Egerian have been used in this study including 425 species-level taxa. Planktic species are bracketed separately in Figs. 3 and 4.

In contrast, for the much more species-rich gastropods, no such standard exists. Therefore, the applied data represent species-level taxa based on a broad range of literature. Not all of these taxa are revised but often include species assigned to lump-genera as used in the referred literature (e.g. within turrids). Furthermore, several taxa might even represent lump-species which will turn out as species-groups after detailed investigations as demonstrated for some nassariids (Harzhauser and Kowalke, 2004) and rissooids (Kowalke and Harzhauser, 2004). In return, over-splitting of morphological variable species such as *Nassarius dolium* (Eichwald) increased the number of available literature-taxa (Harzhauser and Kowalke, 2004). Taxonomic refinement will thus change the number of species but would not change the overall pattern which is based on an exceptional number of 1384 gastropod taxa. Nevertheless, the latest revisions have been applied to older literature data. The gastropod data-set derives from following sources: Oligocene faunas from Baldi (1973, 1986), Hölzl (1962), Harzhauser and Mandic (2001); Eggenburgian faunas from Hölzl (1958), Sieber (1958), Steininger et al. (1971); Ottnangian faunas from Hölzl

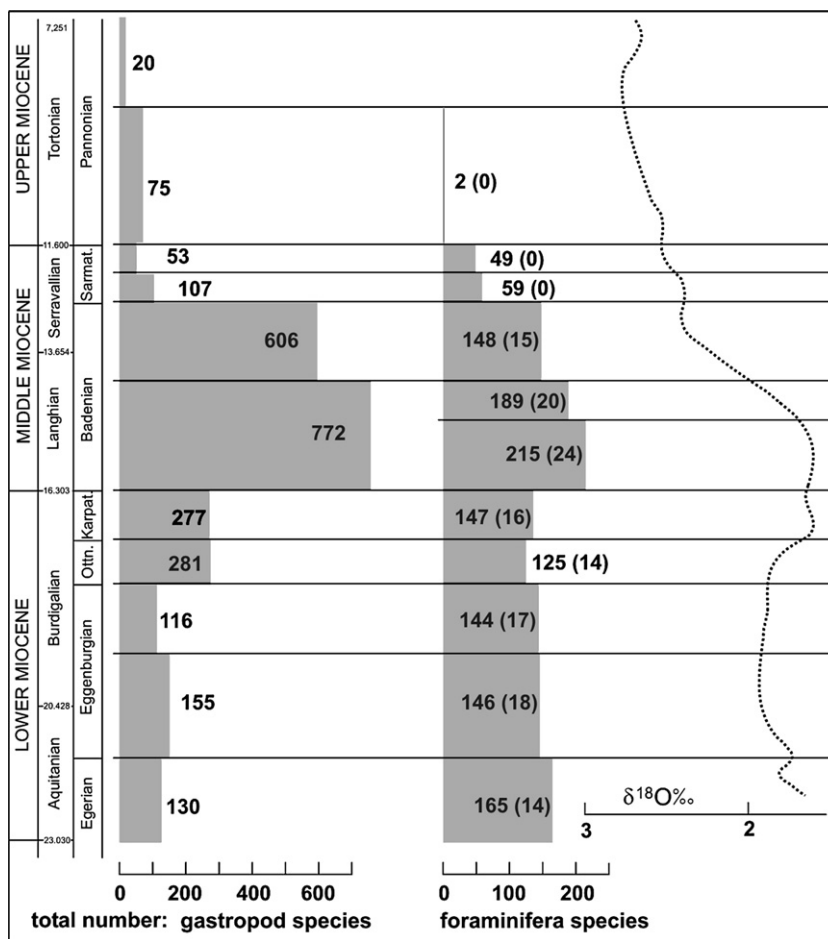


Fig. 3. Total number of gastropod (A) and foraminiferan (B) species recorded in the selected time-slices. The numbers for the Early Miocene gastropods are probably underestimations, due to some taphonomic bias concerning the poorly preserved micro-shells. Note the rough correlation of the maximum species richness in the early Badenian with the mid-Miocene climatic optimum inferred from the oxygen isotope curve (Zachos et al., 2001). The subsequent mid-Miocene climate transition with the marked excursion in the isotope curve is also well reflected in the middle–late Badenian decline of species-richness.

(1973), Steininger (1973); Karpatian faunas from Harzhauser (2003) and references therein; Badenian faunas from Atanackovic (1985), Baluk (1975, 1995, 1997, 2003), Beer-Bistricky (1958), Boettger (1896, 1902, 1906), Harzhauser and Kowalke (2004), Hilber (1879), Hörnes (1852–1856), Hörnes and Auinger (1879–1891), Kojumdzieva and Strachimirov (1960), Kókay (1966), Meznerics (1933), Sieber (1958), Strausz (1966), Svagrovský (1981, 1982a,b, 1984); Sarmatian faunas from Boda (1959), Svagrovský (1971), Harzhauser and Kowalke (2002), Jekelius (1944), Kojumdzieva (1969), Kolesnikov (1935), Papp et al. (1974); Pannonian faunas from Papp (1985b), Jekelius (1944). The stratigraphic affiliation of the various localities follows Studencka et al. (1998), Mandic and Steininger (2003), Harzhauser et al. (2003) and references therein. Tables with complete

taxonomic data-sets are provided as excel sheets at <http://www.kfunigraz.ac.at/geologie/forschung/paratethys>.

In total, about 1809 species-level taxa have been used for the analyses, representing the largest data-set ever used to decipher biogeographic patterns in the European Miocene.

To achieve a representative data-set, the Miocene of the Central Paratethys was separated into a series of well-sampled time slices corresponding to the regional stages. Concerning foraminifers only late Egerian (latest Chattian and Aquitanian) occurrences were used, for gastropods no subdivision of the Egerian was carried out. For the long stages Eggenburgian, Badenian and Pannonian a further subdivision was applied. For foraminifera a threefold division was applied for the Badenian (early, middle, late), for gastropods only a twofold

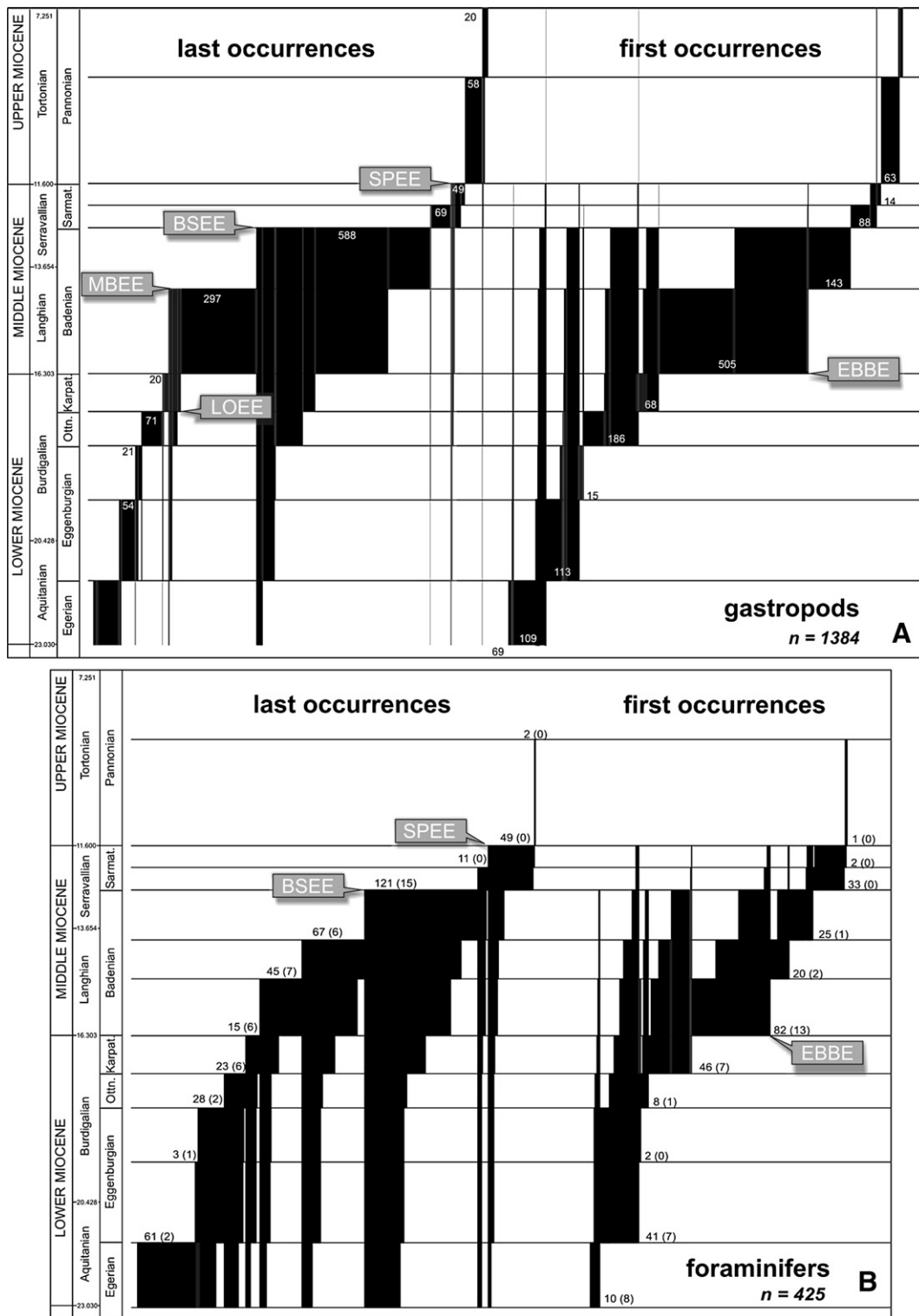


Fig. 4. Literature-based stratigraphic ranges of 1384 gastropod (A) and 425 foraminiferan (B) species in the Central Paratethys Sea (see text for references). Last occurrences on the left graphs, first occurrences on the right. The Paratethyan “big five” as based on the gastropod record are indicated: LOEE — late Otnangian-extinction-event, EBEE — early Badenian-build-up-event, MBEE — middle Badenian-extinction-event, BSEE — Badenian–Sarmatian-extinction-event, SPEE — Sarmatian–Pannonian-extinction-event. The burst of species-richness in the early Badenian is most eye-catching.

subdivision. For the latter the middle Badenian taxa are incorporated in the late Badenian, because of the sometimes speculative stratigraphic allocation. A twofold subdivision was performed for the short Sarmatian because of its strongly bipartite history (see above).

4. Results and discussion

Taking the species-level taxa as spot samples, the total number of species recorded for each time-slice can be calculated (Fig. 3). Hence, the number of taxa recorded for the 5 defined intervals from the Egerian to the Karpatian range from 125 to 165 for foraminifers and 116 to 281 for gastropods respectively. For all the considered Paratethyan faunas of the Early Miocene a constant taphonomical bias in the microgastropod record must be stated. Similarly, the Eggenburgian shallow water foraminifers are underrepresented due to poor preservation. This bias is distinctly lowered during the Badenian, but cannot account for the tremendous increase in gastropod species which blooms to 772 and 606 for the early and the late Badenian respectively, since also foraminifers reach highest numbers with 214, 189 and 148 for the early, middle and late Badenian. These high numbers drastically decline for gastropods to 107, 53, and 75 and even more drastically to 59, 49 and 2 for foraminifers in the Sarmatian and early Pannonian. Taphonomic bias in these intervals is very low and numbers are considered to reflect a large part of the ancient faunas. Foraminifers completely disappeared in the late Pannonian. The data for gastropods should be taken with caution for this time interval as they are mainly focused on the Vienna Basin and might therefore show slight underestimation.

In the next step the stratigraphic range of each species was estimated and graphically arranged in a twofold way (Fig. 4). One graph focuses on the last occurrences (LOD) in the Central Paratethys while the second one emphasises the first occurrences (FOD) both for gastropods (Fig. 4A) and foraminifers (Fig. 4B).

4.1. Small steps and big leaps

For the Early Miocene, species-richness plotted as total numbers of taxa per time-slice shows a general increase for gastropods with a minor retreat in the late Eggenburgian. Foraminifers reflect a different pattern with relative similar numbers throughout, but with a general weak decreasing trend, a low in the Otnangian and slight increase in the Karpatian. Benthic and planktic taxa behave similarly. The comparison of LOD and FOD data in Fig. 4 gives a rough impression of the fate of the Paratethyan gastropod and foraminiferan faunas.

For gastropods, the Egerian to Karpatian pattern is rather unspectacular with a slight positive balance for originations or immigrations versus extinctions. The Otnangian crisis is poorly reflected as an extinction event, because many species which vanish from the Paratethys re-appear in the Karpatian. Hence, the Egerian to Karpatian trend of decreasing extinction rates from 67% towards 7% as indicated in Fig. 5A is only slightly interrupted during the Otnangian. Instead, the crisis is better reflected as a “positive” event of increased originations due to the evolution of endemic species, especially within the genera *Staliopsis* Rzehak, *Nematurella* Sandberger and *Ctyrokya* Schlickum. For foraminifers the late Egerian represents a strong incision with the highest number of LODs (61; Fig. 4B) and the highest percentage of extinctions (37%; Fig. 5B) of all Early Miocene intervals. In contrast to gastropods, foraminifers show a high number of FODs (41) in the early Eggenburgian and only 2% of extinctions compared to 19% in the late Eggenburgian. Gastropods, on the contrary, reach extinction values of 35% in the early and 18% in the late Eggenburgian. Large differences also exist in Otnangian FODs since foraminifers show a very low number, while gastropods reach their highest number of all Early Miocene intervals. Hence, foraminifers clearly reflect the above mentioned Otnangian crisis as a phase of extinctions whilst gastropods counterbalanced the crises by endemic evolution.

This rather gradual Early Miocene development is strongly contrasted by the early Badenian build-up event (EBBE) indicated by 505 newly arriving or originating gastropod and 82 foraminiferan species, the latter comprising 13 planktic taxa. As documented by Harzhauser et al. (2003), some of the gastropod species, displaying their Paratethyan FOD in the early Badenian, are rooted in the Burdigalian of the Proto-Mediterranean–Atlantic Region. These species extend their distribution area towards the north following the increasing SST values during the Langhian climatic optimum. Typical examples are the larger foraminifers of the *Planostegina costata*-group and the gastropods *Strombus* (*Euprotomus*) *schroeckingeri* Hörnes, *Rimella decussata* (Grateloup) and *Pereiraea gervaisii* Vezian. Others develop mass-occurrences [e.g. *Tibia dentata* (Grateloup), *Tudicla rusticula* (Basterot)] or display a remarkable diversification (e.g. the nassariid genus *Cyllenina* Bellardi and the rissoiid genus *Alvania* Risso). Parallels within the bivalves are found in the carditiids, isognomids or plicatulids (Harzhauser et al., 2003). However, due to the generally poorer knowledge of the late Burdigalian and Langhian faunas in the Proto-Mediterranean–Atlantic Region, the potential Burdigalian origin

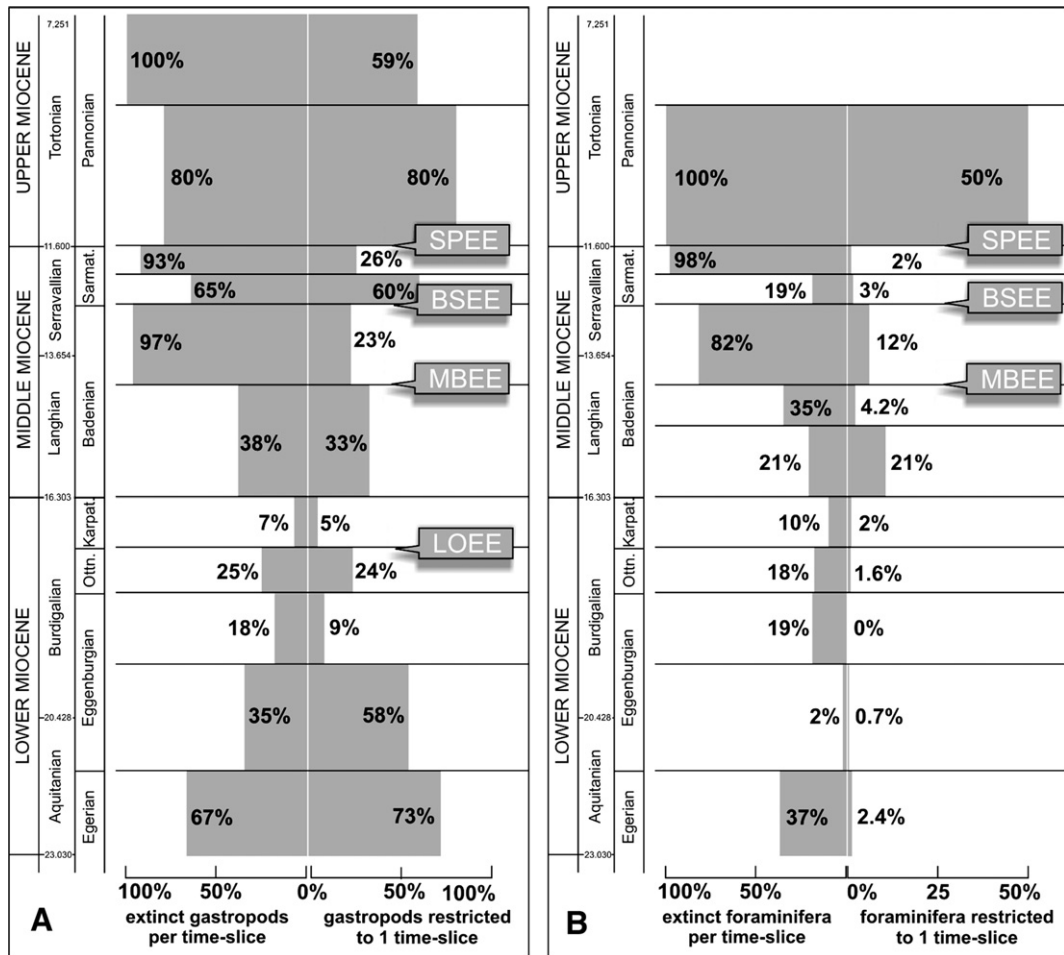


Fig. 5. Extinction-rates (left) and taxa restricted to one time-slice (right) given in percentages based on 1384 gastropod (A) and 425 foraminiferan (B) species. A generally good correlation between both values is obvious for gastropods, indicating that the index-fossils of each time-slice are prone to extinction and display a short geologic history. This coherency is interrupted only in the late Badenian and in the late Sarmatian. Both intervals are characterised by very few indigenous species but extremely high extinction rates. Foraminifers exhibit a widely different pattern with very poor correlation between the two columns and generally long living species. The extremely low values in the Eggenburgian may be due to a strong taphonomic bias.

of many early Badenian FODs remains enigmatic. This lack of information was also indicated for the bivalve faunas by Studencka et al. (1998). For the same reason Middle Miocene migrations from the Central Paratethys into the Mediterranean such as shown by Janssen (1993) for the turrid genus *Spirotropis* Sars are hard to recognise.

A plot of the total numbers of species recorded per time-slice (Fig. 3) visualizes this peak in early Badenian species-richness within gastropod and foraminiferan faunas (EBBE). Calibrating these total-number values to the global deep-sea oxygen isotope record of Zachos et al. (2001) reveals a surprising relationship. Although we refrain from interpreting this rough parallel trend in a naïve, straightforward way, the early Badenian bloom seems to be a direct expression of the mid-Miocene

climatic optimum. For foraminifers the slight increase in species number started already in the Karpatian and fits therefore the curve even better. During the Badenian, the number of new arrivals or originations is lowered: for foraminifers to 20 species in the middle and to 25 species in the late Badenian and for gastropods to 143 in the late Badenian. The number of LODs reaches a first peak of 297 species (Fig. 4A) for gastropods while for foraminifers a stepwise decline by 45 and 67 species is recorded (Fig. 4B). This negative balance for the gastropods coincides conspicuously with the onset of the Middle Miocene climate transition (Shevenell et al., 2004). Again, the plot in Fig. 3 bears striking resemblance to the oxygen isotope record of Zachos et al. (2001) both for gastropods and foraminifers. Indeed, a

slight cooling during the late Badenian is reflected by the retreat and/or decline of thermophilic mollusc taxa. This is reflected e.g. by a decrease of the strombid diversity (Harzhauser et al., 2003) and by the drop in the nassariid genus *Cyllenina* from 9 early Badenian species to 3 in the late Badenian (Harzhauser and Kowalke, 2004). According to these data, a drop of the minimum sea-surface temperature from at least 16–18 °C during the early Badenian optimum to 14–15 °C in the late Badenian is inferred. This late Badenian cooling seems to persist into the early Sarmatian, indicated by the occurrence of diatomites and the dramatic shut down of the Badenian carbonate factory (Harzhauser and Piller 2004a,b).

Whilst the Badenian development is thus probably related to a global climatic trend, the next major peak in extinctions is mainly geodynamically and climatically controlled. This Badenian–Sarmatian-extinction-event (BSEE) with 588 LODs in gastropods and 121 in foraminifers is the biggest turnover in the Paratethyan history. The BSEE concerns mainly Badenian gastropod species but is also the dead-end for most long-ranging species with Early Miocene roots. This holds true even in more pronounced fashion for foraminifers. A hint to the still unsolved trigger mechanism for the BSEE is the obvious advantage of lecitotroph larvae opposed to planktotroph larvae. Within the nassariids, Harzhauser and Kowalke (2004) documented a switch from 7% lecitotroph Badenian species towards 100% Sarmatian species with direct development. This points to a crisis that had affected the zooplankton. Correspondingly, the percentage of planktic species within the foraminifers fauna drops to zero at the BSEE and they never return again in the Central Paratethys.

With the onset of the Sarmatian a relatively high number of FODs (33) is observable in foraminifers. This fauna is characterized by large elphidiids [e.g., *E. reginum* (d'Orbigny), *E. hauerinum* (d'Orbigny), *E. koberi* Tollmann, *E. josephinum* (d'Orbigny), *Porosononium hyalinum* (Bogdanowicz)], *Anomalinoidea*-species (*A. transcarpaticus* (Pishvanova), *A. dividens* Luczkowska), and very characteristic *Schackoinella imperatoria* (d'Orbigny). Besides these a variety of miliolids occurs e.g., *Hauerina irschavensis* Vengliniskyi and Burindina, species of *Quinqueloculina*, *Varidentella* and *Affinetrina*, *Sarmatiella moldaviensis* (Bogdanowicz), *S. prima* (Bogdanowicz), and *Sinzowella novorossica* (Karrer and Sinzow). While many of these foraminiferan taxa are rooted earlier in the Miocene, a new early Sarmatian gastropod fauna is established mainly due to the radiation of the rissoid genus *Mohrensternia* Stoliczka and the archaeogastropod *Gibbula* Risso.

The mid-Sarmatian extinction of these endemisms again causes a high extinction rate of 65%, which is in contrast to only 19% in foraminifers. This event corresponds to a change in depositional environments and the subsequent loss of ecosystems to which the highly specialized early Sarmatian gastropod species have been adapted. Now the upper Sarmatian carbonate sequences reflect a highly productive carbonate factory of subtropical climate. The formation of thick oolite sequences with Persian Gulf-type ooids as well as the mass occurrences of thick-shelled shell beds require normal saline to hypersaline, subtropical conditions. The same subtropical environmental conditions are clearly necessary for the peneroplid, larger foraminifer *Spirolina austriaca* and other porcelaneous foraminifers which are much more abundant than in the early Sarmatian. This warming is also indicated by the negative peak in the oxygen isotope curve between MSi-3 and MSi-4 of Abreu and Haddad (1998) (Fig. 1).

The last big incision is represented by the Sarmatian–Pannonian-extinction-event (SPEE). Although less dramatic for gastropods in absolute numbers (49 LODs versus 63 FODs), the extinction-rate climbs up to 93%, and even to 98% for foraminifers. Like the BSEE, the SPEE is rather a geodynamically controlled event, triggered by the isolation of Lake Pannon from the Eastern Paratethys Sea. Foraminifers are represented in the early Pannonian by 2 species only (*Miliammina subvelatina* Vengliniskyi, *Trochammina? kibleri* Vengliniskyi) and disappear completely afterwards.

4.2. The impact of geodynamics

The hourglass-like outline of Fig. 5A indicates a roughly twofold structure of the extinction trends in the Central Paratethys for gastropods. From the latest Oligocene to the Karpatian a general decrease in extinction rates can be observed. A slight setback in the Ottnangian is related to the isolation of the Central Paratethys and the increasing rate of endemic evolution. The decline of Early Miocene extinctions is also reflected in the age-structure of the faunas. Only 5–24% of the species are restricted to the selected time-slices from the late Eggenburgian to Karpatian, meaning that more than 75% of the species are derived from older faunas. During that time, the Western and Central Paratethyan basins were wide west–east trending deep water basins often associated with remnants of Palaeogene Flysch troughs. This stable configuration is disrupted at the Early/Middle Miocene boundary when basin configuration switched towards shallow intra-mountain basins (Rögl, 1998) and the Pannonian back arc basin system became installed (Royden and Horváth,

1988; Kováč et al., 2003). This now highly structured archipelago sea was much more prone to geodynamic control. Consequently, the Badenian to Pannonian part of Fig. 5A reflects a trend towards increasing extinction rates usually ranging between 65–100%. At the same time the percentage of species which are restricted to a single time-slice increases and points to strong turnover. This pattern is disturbed only during the late Badenian and the late Sarmatian which both source their faunas largely from the antecedent faunas.

Again foraminifers behave differently from gastropods (Fig. 5B). A negligible percentage of species became extinct in the early Eggenburgian (2% vs. 35% in gastropods) and the foraminiferan faunas exhibit very old age structures with a minimum of 98% of the species deriving from older time-slices (Fig. 5B). This kind of stasis points

to an only weak influence of climatic changes in the Early Miocene on foraminifers compared to gastropods and reflects the still existing inherited palaeogeographic pattern (see above). Compared with gastropods, a somewhat similar reaction to geodynamically dominated environmental changes is recognized in the Middle and Late Miocene. Only the switch from the siliciclastic—to the carbonate-dominated sedimentation regime in the Sarmatian does not cause severe changes as reflected in molluscs.

4.3. New deal and taking roots

To better understand the age of the marine faunas, the percentage of “old” species was calculated for each time-slice (Fig. 6). These old groups comprise species which persist from at least one preceding time-slice,

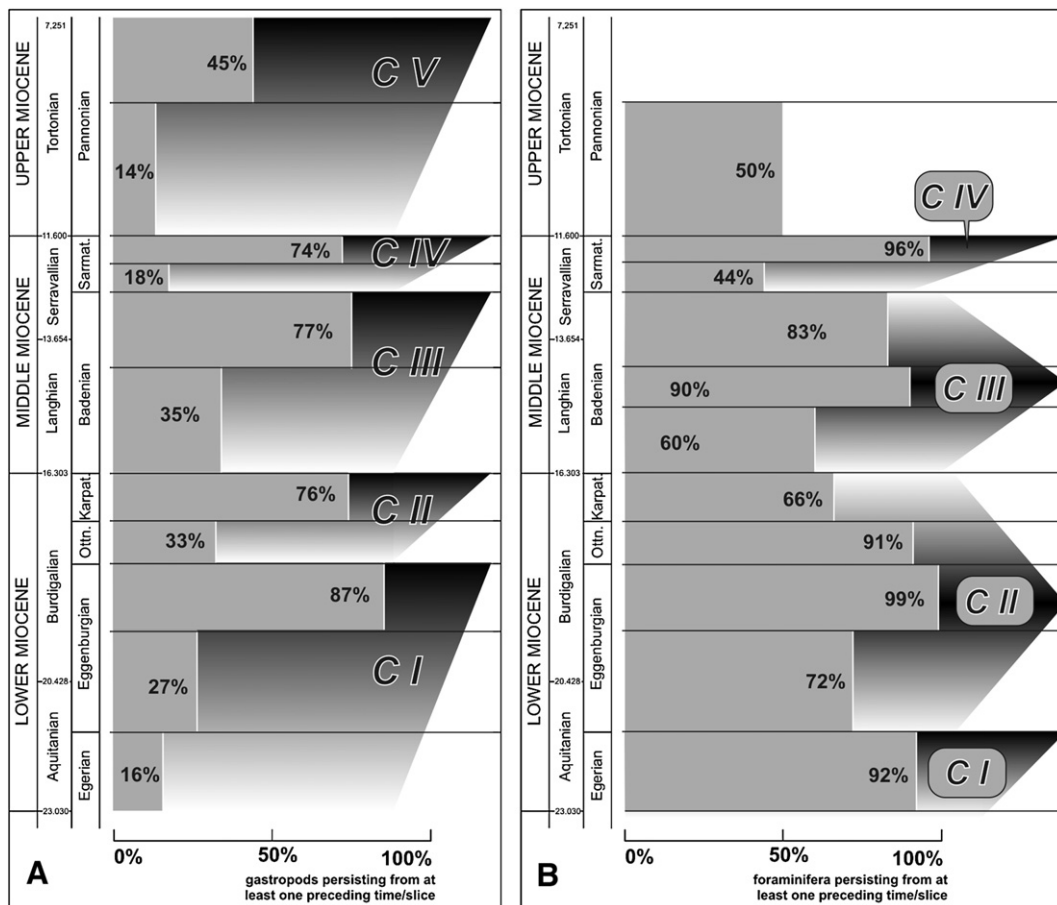


Fig. 6. Faunal cycles for Central Paratethyan gastropods and foraminifers through the Miocene. For gastropods, a cyclic pattern of “new-deal” faunas and well-established aged faunas can be depicted. Each cycle starts with the immigration (cycles I, III) or endemic evolution (cycles II, IV, V) after a – usually geodynamically triggered – collapse of the antecedent faunas. These young faunas soon grade into stable communities with high percentages of derived species. Foraminifers behave different with 2 cycles similar to gastropods’ patterns (cycle I and IV) but for the Early Miocene with deviating stratigraphic distribution; cycles II and III reflect an aging – rejuvenation pattern. Difference of foraminiferan cycle III to gastropod cycle III is probably due to different stratigraphic resolutions.

recognisable in Fig. 4 as the long “tails” in the LOD-graphs. According to that approach a young or initial fauna will display a low percentage of such veterans. Each geodynamic or oceanographic turmoil leading to high extinction rates could be expected to correlate with a low survival rate. This simple coherency would be cracked if the extinction is only of local nature allowing the re-immigration of the “old” fauna into the depredated area in the next time-slice from an adjacent biogeographic sanctuary.

The pattern in Fig. 6 indicates a sequence of 5 cycles for gastropods and only 4 for foraminifers. Due to the switch from marine to brackish and freshwater environments, the lower Pannonian sediments contain only 2 foraminiferan species and foraminifers are completely missing in the upper Pannonian; therefore this time interval cannot be taken into consideration.

For gastropods, each cycle starts with a young fauna occupying the area after a heavy incision and a large-scale loss of fauna. These “new-deal-faunas” contain only 14–35% of species persisting from the antecedent faunas. Within 1–2 m.y. these initial assemblages take root and grade into stable and old faunas with the veterans claiming a share of about 45–87%.

Cycle I starts during the Egerian and reaches up to the late Eggenburgian. Interestingly, the late Eggenburgian change of hydrologic regimes towards tide-dominated environments and the coincident slight cooling is not reflected in the gastropod fauna by immigrations or originations. The “new-deal-phase” of cycle II, comprising the Ottnangian and Karpatian, is triggered by the Ottnangian crisis and the resulting endemic evolution. In addition, several new species immigrate into the Paratethys Sea from the Western Tethys.

The big leap into cycle III is somewhat misleading as it is not triggered by any extinction event. Only 7% of the Karpatian gastropods became extinct (Fig. 5A). Instead, the exceptional species input by the EBBE results in a reorganisation of the faunas and a low percentage of persisting species. During the Badenian the total number of recorded species decreases from the early to the late Badenian from 772 to 606 and simultaneously the fauna becomes aged. Hence, the late Badenian fauna is rooted largely in the early Badenian.

The shortest cycle IV with about 1 m.y. duration is amplified by the impact of the BSEE with an extinction rate of about 97%. The low number of new originations in the late Sarmatian and the loss of all early Sarmatian *Mohrensternia*-species supports the conservative character of the late Sarmatian fauna.

Finally, cycle V is indicated by the radiation of the highly endemic Pannonian fauna which lacks nearly all

reminiscence of the Middle Miocene Paratethyan faunas. The few survivors are found in the genera *Melanopsis* Ferussac, *Tinnyea* Hantken, and *Hydrobia* Hartmann, which have been little affected by changing water chemistry due to their preference for (near-) freshwater habitats.

Considering foraminifers, not only the number of faunal cycles deviates (Fig. 6) but their basic pattern is completely different! The late Egerian contains 92% holdovers from the early Egerian or older intervals and can be interpreted to be the final interval of cycle I. The percentage for the early Egerian is 81 and for the late Kiscellian 71 reflecting an increasing aging of the fauna (not shown in Fig. 6B). Cycle II starts in the early Eggenburgian with a relatively young foraminiferan fauna with “only” 72% holdovers. This value increases to 99% in the late Eggenburgian which is in agreement with the behavior of the gastropods. The reduced number of persisting taxa in the Ottnangian, however, is not followed by an increase in the Karpatian but a remarkable drop to 66%. This reflects a rejuvenation of the fauna also expressed by the relatively high number of FODs (Fig. 4B). The beginning of the Middle Miocene and cycle III starts with a further rejuvenation (60% holdovers), aging increases in the middle Badenian to 90%, decreases, however, in the late Badenian again to 83%. For the Badenian, the differences between gastropods and foraminifers is based on the fact that a twofold subdivision of the Badenian Stage is used for the gastropods, whereas a threefold subdivision is applied to the foraminifers data-set. This discrepancy would disappear with the application of only 2 substages for the foraminifers. Cycle IV covers the Sarmatian and the pattern coincides with that of gastropods.

4.4. The toggle switch of biogeography

One of the few comparable studies in considering stratigraphic ranges of 808 Middle Miocene to Recent Caribbean mollusc genera and subgenera was performed by Jackson and Johnson (2000). In the time span in which our study overlaps with the Caribbean record, a slight difference in occurrence patterns is obvious. Jackson and Johnson (2000) present a quite regular pattern of originations and rather stepwise extinctions. This roughly constant rate of first and last occurrences is strongly opposed by the large FOD and LOD events observed in our data.

This difference is considered as an expression of the biogeographic position of each area. During the Miocene the Caribbean bioprovince was much more stable and open. In contrast, the extreme geodynamically forced position of the Central Paratethys turned it into a Janus-

faced region for biogeographers. During episodes of open marine gateways and stable marine sea-surface conditions, the immigrations from adjacent bioprovinces caused a tremendous turnover of assemblages. Hardly any evolutionary lineages can be observed during these marine phases as speciation took place “out-of-province” and the Paratethyan FODs appear as sharp events in the fossil record. Short-termed phases of isolation were frequently associated with the break down of stable marine conditions — either by collapse of circulation patterns as in the Kiscellian (Rögl, 1998) or by strong excursions of water chemistry as typical in the Sarmatian (Harzhauser and Piller, 2004a,b). In either case a sharp extinction event is the consequence. However, now the “in-province” origination can take place reflected by the radiation of a generally low-diverse endemic fauna, such as in the late Ottnangian, the early Sarmatian or the early Pannonian.

Hence, the marine life of the Paratethys Sea experienced a repeated switching from immigration-impacted faunas – demoting it just to an appendix of a larger biogeographic unit – towards core faunas of endemic centres of origin with highly significant faunistic peculiarity.

5. Palaeobiogeography

Based on these faunal patterns a biogeographic framework can be established. The Paratethys is a distinct palaeogeographic unit and, from a palaeogeographic point of view, only two terms are applicable: *Central Paratethys Sea* (from the Egerian up to the Sarmatian) and *Lake Pannon* (Pannonian). In contrast, the biogeographic content and character within these two geographic entities experienced a much stronger modulation resulting in a more rigid and detailed biogeographic framework (Fig. 7). An initial attempt at defining a clear paleobiogeographic nomenclature was presented by Harzhauser et al. (2002) with a strong focus on the Western Tethys Region. Paratethyan biogeography was discussed only cursorily, with the introduction of the terms Danubian Province and Proto-Caspian Subprovince. Herein we refine and specify the biogeographic discussion concentrating on the Central Paratethys faunas to clearly differentiate between palaeogeography and biogeography. To document the biogeographic development, different invertebrate groups can be advocated: in our study we

CHRONOSTRATIGRAPHY		GEOGRAPHY	BIOGEOGRAPHY
Tortonian	Pannonian	Lake Pannon	Balatonian Province
Serravallian	Sarmatian	Central Paratethys Sea	Proto-Caspian Subprovince
Langhian	Badenian		Danubian Province
Burdigalian	Karpatian		Proto-Caspian Subprovince
	Ottnangian		Early-Danubian Province
	Eggenburgian		
Aquitanian	Egerian		Proto-Danubian Province

Fig. 7. Synopsis of chronostratigraphic, palaeogeographic and palaeobiogeographic terms used in the area of the Central Paratethys Sea.

rely primarily on foraminifers, gastropods and selected bivalves.

Biogeographic principles and the denomination of units and their hierarchical ranking have been discussed by Westermann (2000a,b) and by Harzhauser et al. (2002). Herein we follow their suggestions.

5.1. Proto-Danubian Province and Early Danubian Province

5.1.1. Late Egerian–early Ottnangian (=late Chattian and Aquitanian–early Burdigalian)

From the Egerian to the early Ottnangian, the Paratethys area represents biogeographically a transition between the northern Proto-Eastern Atlantic–Boreal Region and the southern Western Tethys Region. In the course of the Egerian and Eggenburgian the biota develop a distinct character which allows the differentiation of a Proto-Danubian Province (Egerian) and an Early Danubian Province (Eggenburgian–early Ottnangian).

The Proto-Danubian Province consists of at least three faunal types from the biogeographers' point of view. The most interesting component, demonstrating the Paratethyan identity of the fauna, consists of endemic taxa unknown from other biogeographic units. Among the gastropods *Calliostoma hegeduesi* (Baldi), *Aporrhais callosa* (Telegdi-Roth), *Ocenebra bistrata* (Gümbel), *Nassarius hungaricus* (Gábor), *Egereia collectiva* Gábor, and *Fasciolaria plexa* (Wolff) are typical representatives of this endemic species group. In addition, bivalves such as *Acanthocardia bojorum* (Mayer), *Astarte hoelzli* (Harzhauser and Mandic), and *Lucinoma barrandei* (Mayer) are characteristic for the Central Paratethys. In total, the amount of endemic mollusc species was calculated by Baldi (1973) to range around 30%.

The second large group represents species which display strong affinities to the Proto-Eastern Atlantic–Boreal Region in northern Europe. Among them *Drepanocheilus speciosus* (Schlotheim), *Galeodea megacephala* (Philippi), *Ficus concinnus* (Beyrich), *Orthosurcula regularis* (Koninck), and the *Boreotrophon deshayesi*-group are characteristic. *Peronidia nysti* (Deshayes), *Cyclocardia orbicularis* (Sowerby), *Pycnodonte gigantea callifera* (Lamarck), and *Saxolucina heberti* (Deshayes) are immigrating bivalves with roots in the North Sea Basin, Paris Basin and Maince Basin faunas where they are documented even in the Early Oligocene (Harzhauser and Mandic, 2001). This strong “northern” aspect stands in contrast to the rather poor influence of the “southern”, adjacent bioprovince — the Western Tethys Region. If the cosmopolitan species are omitted, only few species such as *Angaria scobina* (Brongniart), *Tibia dentata* (Grateloup),

Strombus bonellii (Brongniart), *Ficus conditus* (Brongniart), and *Euthriofusus burdigalensis* (Defrance) seem to indicate a southern origin. Among the bivalves *Eucrassatella carcarenensis* (Michelotti) and *Costellamussiopecten northamptoni* (Michelotti) serve as examples for the Western Tethyan character within the Egerian Paratethyan faunas. In total, the Proto-Danubian Province is highly characteristic with an amount of 73% of species which are restricted in time to the Egerian.

A warm temperate to tropical character can be postulated for the Egerian faunas contributing to the Proto-Danubian Province. Among these are miogypsinids [*Miogypsina septentrionalis* Drooger, *M. gunteri* Cole, *Miogypsinoides complanatus* (Schlumberger), *M. formosensis* Yabe and Hanzawa] and lepidocyclinids (*Lepidocyclina* (*Eulepidina*) *dilatata* (Michelotti), *L. (Nephrolepidina) morgani* Lemoine and Douville, *L. (N.) tournoueri* Lemoine and Douville]. Mangrove habitats are also postulated for the coastal fringes of the Egerian Paratethys based on the mollusc fauna (Baldi, 1973; Barthelt, 1989; Harzhauser and Mandic, 2001). Characteristics are *Tympanotonos*–*Granulolobium* assemblages and the rarely preserved large-sized mangrove snail *Ellobium subjudae* (d'Orbigny) as described by Janssen (1984) from Hungary.

The Early Danubian Province gradually develops from its Egerian forerunner. The earliest Eggenburgian mollusc fauna still bears witness to northern migrations. These northern (North Sea Basin) and western (Eastern Atlantic) remnants are represented among others by the aporrhaid gastropod *Drepanocheilus speciosus* (Schlotheim), the scaphopod *Antalis kickxi transiens* (Steininger) and bivalves such as *Arctica girondica* (Cossmann and Peyrot). This temperate flavour is lost completely during the early Eggenburgian, when a tropical fauna suddenly appears in the entire Paratethys area. This immigration and turn-over event is marked by the larger foraminifers *Amphistegina bohdanowiczi* Bieda and *Miogypsina intermedia* Droger as well as by the giant cardiid *Laevicardium kuebecki* (Hauer) and the total loss of elements derived from the Proto-Eastern Atlantic–Boreal Region. Only the mud-flats with a diversified potamidid fauna and vast *Crassostrea*-bioherms are still highly reminiscent of their Egerian counterpart.

Faunistic comparisons with Early Miocene nearshore faunas of the Eastern Mediterranean (Mut Basin, Turkey in Mandic et al., 2004; Central Iran in Harzhauser et al., 2002) document a tight relation of the early Danubian Province with the Proto-Mediterranean–Atlantic Region and a low endemism. A second wave of immigrations during the Eggenburgian brings additional elements of the Proto-Mediterranean–Atlantic Region, such as the

pectinid *Flexopecten palmatus* (Lamarck) and the echinoid *Arbacia*.

Due to the gradual faunistic development no large extinction event can be recognized. This successive shift is also well reflected in the cycle 1 in Fig. 6A for gastropods.

5.2. Proto-Caspian Subprovince

5.2.1. Late Ottnangian (~middle Burdigalian)

The gradual evolution of the latest Oligocene to Early Miocene Paratethyan faunal provinces is heavily interrupted during the late Ottnangian (=early Kotsakhurian in the Eastern Paratethys; Fig. 1) when isolation caused a complete breakdown of biogeographic relations between the Paratethys and the Mediterranean seas. A second phase of a rather uniform endemic Paratethys mollusc fauna, coinciding with the westward extension of the *Proto-Caspian Subprovince*, developed. This biogeographic unit is characterised by its conspicuously large number of endemic bivalve genera such as *Limnopageta*, *Rzehakia*, *Lenticorbula*, or *Eoprosodacna* (Kvaliashvili, 1962). This peculiar, so-called “Rzehakia fauna” reaches even the Central and Western Paratethys Sea in the Late Ottnangian and is the reason to propose a westward extension of the Eastern Paratethyan Proto-Caspian Subprovince. Within the gastropods the endemisms are rather at the species level comprising many taxa with generic roots in freshwater and brackish water faunas of the Early Miocene (e.g. *Nematurella* Sandberger).

5.3. Danubian Province

5.3.1. Karpatian–Badenian (=late Burdigalian–Langhian–early Serravallian)

The closure of the Tethys seaway in the late Early Miocene resulted in the breakdown of the Western Tethys Region into two separated biogeographic regions. In the west the Proto-Mediterranean–Atlantic Region became established, being characterised by very homogenous marine faunas from the Bay of Biscay in the west to the Central Iran in the east (Harzhauser et al., 2002). In the Paratethys Sea good marine connections formed after the Ottnangian crisis allowing immigration of “Mediterranean–Atlantic” faunal elements from the south. At times of high immigration rates such as the late Early Miocene Karpatian or the early Middle Miocene Badenian, the “Mediterranean” character became predominant. The Karpatian gastropods display about 70–75% typical inhabitants of the Proto-Mediterranean–Atlantic Region. A second wave of immigration with about 500 new occurrences within the gastropods followed in the early Badesian (=Langhian).

In total, about 270 gastropod species of the Karpatian are opposed by more than 770 species of the early Badenian. A weaker but similar trend is recorded in foraminifers with 147 Karpatian and 215 early Badenian species. This “Badenian bloom” is traceable within most gastropod families but is most conspicuous within the cypraeids, turrids, cancellariids, nassariids, or muricids. The Nassariidae, for example, are present with 8–13 species during the Eggenburgian to Karpatian but in the early Badenian they increase to 53 species within the Central Paratethys (Harzhauser and Kowalke, 2004). Similarly, among the Rissoidae only 3 species of *Rissoa* and *Alvania* in the Karpatian of the Korneuburg Basin compare with 28 species of *Alvania* in the Badenian of the Central Paratethys (Kowalke and Harzhauser, 2004). In addition, planktic foraminifers exhibit their highest species richness in the Miocene of the Central Paratethys with a rise from 16 in the Karpatian to 24 in the early Badenian. These immigrations are interpreted to have followed the expansion of the tropical zone during the Burdigalian/Langhian climatic optimum and are also well traceable by the increase in larger foraminiferan taxa [*Planostegina giganteiformis* (Papp), *P. costata*-group, *Amphistegina mammilla* (Fichtel and Moll), *Borelis melo* ssp., *Dendritina haueri* d’Orbigny]. The related Langhian rise in relative sea-level, causing a considerable transgression also in the Paratethyan basins, provides further support for the takeover by Mediterranean taxa.

The distribution-patterns of some species such as *Strombus* (*Euprotomus*) *schroeckingeri* and *Rimella decussata* within the nearshore gastropod faunas strongly suggest a western connection into the Central Paratethys via the Trans-Tethyan Trench Corridor in Slovenia. In contrast, these taxa are completely missing in the Carpathian Foredeep. New preliminary isotope data which indicate a different composition of the early Badenian seawater in the Styrian Basin compared to that of the Alpine Foreland Basin also suggest a geographic separation of sea-surface currents in these water bodies (cf. Bojar et al., 2004 versus Latal et al., 2006).

Hence, this Central Paratethyan fauna was part of the Proto-Mediterranean–Atlantic Region, being termed the Danubian Province. This biogeographic affiliation lasted from the Karpatian up to the late Badenian (late Burdigalian to early Serravallian) and is thus independent from local geodynamic developments. The major sea-level drop at the Burdigalian/Langhian boundary and the changing tectonic regime in the Alpine–Carpathian area are not reflected in a strong biogeographic separation from the Proto-Mediterranean–Atlantic Region. Similarly, the two major changes in relative sea-level at about 14.2 m.y. and 13.6 m.y. did not trigger a

shift of biogeographic entities, which would require a separation as a distinct region. Only in the Carpathian Foredeep some local evolution is observed. There, species such as *Nassarius podolicus* (Hoernes and Aunger) and *Nassarius zborzewskii* (Andrzejowski) arose from the widespread Paratethyan *Nassarius dujardini-schoenni* stock (Harzhauser and Kowalke, 2004). This evolution was triggered by the geographic position of this basin which suffered various disconnections from the other basins of the Central Paratethys, leading to the formation of evaporites during the Wielician phase of the Badenian. These endemics could be the foundation for the definition of a Wielician Subprovince within the Danubian Province.

5.4. Proto-Caspian Province versus Balatonian Province

5.4.1. Sarmatian–Pannonian (=late Serravallian–Tortonian)

The Danubian Province was terminated abruptly by the Sarmatian crisis in the late Middle Miocene. A dramatic change of the water chemistry caused severe impoverishment of the marine fauna called herein the Badenian–Sarmatian-extinction event (BSEE). The geodynamic reconnection with the Eastern Paratethys allowed the establishment of a rather uniform highly endemic Sarmatian mollusc and polychaete fauna. This requires a change in biogeographic classification and the Paratethys represents now the Proto-Caspian Province, still part of the Proto-Mediterranean–Atlantic Region.

The BSEE was not complete because many of the early Sarmatian foraminifers are hangovers from earlier intervals and the gastropod fauna is obviously a descendent of the marine Badenian assemblages, containing many marine Badenian survivors (Boda, 1959; Svagrovský, 1971; Papp et al., 1974). The Paratethyan origin of the Sarmatian fauna is evident from “Sarmatian” type faunas occurring already in the latest Badenian (Svagrovský, 1959; Senes, 1974). A candidate as some kind of centre of origin for a part of the Sarmatian fauna is the Polish–Ukrainian–Bulgarian foredeep basins. Only there, taxa such as *Nassarius coloratus sarmaticus* (Laskarew) and *Nassarius kulensis* (Kojumdzieva) managed to pass the BSEE but are unknown from any other Central Paratethys basin (Harzhauser and Kowalke, 2004).

Thus, the seemingly abrupt faunistic turn-over was probably a step-like event. In the fossil record, however, it is overemphasised and accentuated by the erosion and depositional gaps due to the major 3rd order sea-level drop at the Badenian/Sarmatian boundary (Harzhauser and Piller, 2004a,b). The few marine relics are conspecific with their Badenian ancestors but usually develop smaller

and more delicate shells. Amongst these marine relics a comparison of the diversity with that of the ancestor Badenian fauna may give an idea of the heavy incision. For example the muricids, representing at least 60 species during the Badenian in the Central Paratethys, decline to the single species *Ocenebra striata* (Eichwald). Correspondingly, the less diverse turritellids, counting approximately 20 Badenian species, and the ubiquitous naticids with about 6 Badenian species, both were reduced to one species each in the early Sarmatian.

The endemic evolution of the Proto-Caspian Province remains homogenous during the entire Sarmatian in the Central Paratethys and up to the early Bessarabian in the Eastern Paratethys. At roughly 11.6 m.y., due to the glacio–eustatic sea-level lowstand TB 3.1., the Paratethys splits geographically into the Pannonian Lake in the west and the Eastern Paratethys in the East. The brackish to freshwater lake system of Lake Pannon experienced a quick radiation of endemic molluscan taxa which allow a differentiation of a Balatonian Province. In the Eastern Paratethys the Proto-Caspian Province continued during the Bessarabian and Chersonnian. The fauna of the Balatonian Province, however, with endemics such as *Conger* and *Orygoceras* seems to be rooted in the Early Miocene lakes of the dinarides (cf. Middle Miocene ancestors in Kochansky-Devide and Sliskovic, 1978 and Brusina, 1902). This indicates a somewhat “cryptic” endemic fauna, contributing to a widely neglected long-lived bioprovince in the “backyard of Europe”.

6. Conclusions

The development of the Central Paratethyan marine faunas allows the recognition of several important patterns. In contrast to ecologically and palaeogeographically stable regions, the geodynamic impact on the faunistic trends is exceptionally strong. The general trend of continentalisation throughout the Miocene is reflected in repeated isolations of the gradually vanishing Central Paratethys Sea. The interplay of immigrations from the Proto-Mediterranean–Atlantic Region and endemic evolution usually fed by elements of the Proto-Caspian Subprovince is reflected by a high turn-over rate during the geodynamical instable Middle and Late Miocene. In contrast, low extinction rates coincide with the relatively stable development of the Early Miocene.

Five distinct Miocene faunal cycles are delineated based on 1348 gastropod species. Each cycle starts with immigration or endemic evolution, giving the faunas a “young” character. These young faunas with about 14–35% “old” species soon grade into stable communities with percentages of derived species ranging around 70–

80% (Fig. 6). This pattern is amplified by four extinction events and by one exceptional build-up event. The latter, termed early-Badenian-build-up-event (EBBE) and the successive mid-Badenian-extinction-event (MBEE) coincide with highest species-richness in the history of the Central Paratethys. A link with the Middle Miocene climatic optimum, allowing thermophiles to invade the north, and the onset of the Middle Miocene climate transition causing the mid-Badenian decline is reliable. Foraminifers turned out to be more conservative and stable. Whilst gastropods tend to recover extinctions partly by endemic evolution, foraminifers display generally less dramatic turn-over rates and are less prone to endemisms (except for the Sarmatian stage). This stability and wide geographic distribution, however, render Paratethyan foraminifers as a reliable biostratigraphic tool for correlation with the Mediterranean and Atlantic Miocene record.

In terms of biogeography, the geographic units Central Paratethys Sea and Lake Pannon have been settled by 4 distinct biogeographic entities. During the Late Oligocene and Early Miocene the Central Paratethys experienced the shift from the Proto-Danubian Province towards the Early Danubian Province. The latter was strongly connected to the Western Tethys Region whilst the Proto-Danubian Province was also influenced by contacts with the Proto-Eastern Atlantic–Boreal Region. Community collapse due to geographic isolation allowed the spreading of the faunas of the Proto-Caspian Subprovince from the east into the Central Paratethys. The first take-over by elements of that faunal-type occurred during the Late Otnangian, the second one during the Sarmatian. During the intervening phase the Danubian Province was rapidly established. The faunistic nexus with the Proto-Mediterranean–Atlantic Region is explained by a heavy wave of northward immigrations during the early Badenian (Langhian). In the Late Miocene, the fully endemic Balatonian Province came into existence, coinciding with the formation of Lake Pannon. Early and Middle Miocene records of freshwater systems in the Dinarids, contributed by typical taxa of the Balatonian Province, indicate that this biogeographic unit may have a long but somewhat enigmatic history.

Acknowledgments

This paper is part of the NECLIME and the EEDEN projects. The studies were supported by FWF-grants P-14366-Bio and P-13745-Bio. Many thanks to Fred Rögl (NHM-Vienna), Oleg Mandic (NHM-Vienna) and Andreas Kroh (NHM-Vienna) for discussions and valuable information. Our sincere thanks go to William

A. Berggren (Rutgers University, New Jersey) and Mikael Fortelius (Helsinki University) who greatly improved the paper by their comments and suggestions.

References

- Abreu, V.S., Haddad, G.A., 1998. Glacioeustatic fluctuations: the mechanism linking stable isotope events and sequence stratigraphy from the Early Oligocene to Middle Miocene. In: Graciansky, C.-P., Hardenbol, J., Jacquin, T., Vail, P.R. (Eds.), *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins*. SEPM, Special Publications, vol. 60, pp. 245–260.
- Adámek, J., Brzobohatý, R., Pálenský, P., Sikula, J., 2003. The Karpatian in the Carpathian Foredeep (Moravia). In: Brzobohatý, R., Cicha, I., Kovář, M., Rögl, F. (Eds.), *The Karpatian—an Early Miocene Stage of the Central Paratethys*. Masaryk University Brno, pp. 75–87.
- Allen, Ph.A., Mange-Rajetzy, M., Matter, A., Homewood, P., 1985. Dynamic palaeogeography of the open Burdigalian seaway, Swiss Molasse basin. *Eclogae Geologicae Helveticae* 78, 351–381.
- Atanackovic, M.A., 1985. Mekusci Morskog Miocena Bosne. *Geologija Bosne i Hercegovine, Fossilna Fauna i Flora* 1, 1–308.
- Bachmann, A., 1973. Die Silicoflagellaten aus dem Stratotypus des Otnangien. In: Papp, A., Rögl, F., Senes, J. (Eds.), *M2 Otnangien. Die Innviertler, Salgótarján, Bántapuszta Schichtengruppe und die Rzehakia Formation. Chronostratigraphie und Neostatotypen, Miozän der Zentralen Paratethys*, vol. 3, pp. 275–295.
- Baldi, T., 1973. Mollusc Fauna of Hungarian Upper Oligocene (Egerian). *Akad. Kiado, Budapest*, pp. 1–511.
- Baldi, T., 1975. Holostatotypus: Eger, Wind's brick yard. Hungary (Boundary Stratotype: Kiscellian/Egerian; O/OMA-c). In: Baldi, T., Senes, J. (Eds.), *OM, Egerien. Die Egerer, Pouzdraner, Puchkirchener Schichtgruppe und die Bretkaer Formation. Chronostratigraphie und Neostatotypen*, vol. 5, pp. 97–112.
- Baldi, T., 1986. Mid-Tertiary Stratigraphy and Palaeogeographic Evolution of Hungary. *Akad. Kiado, Budapest*, pp. 1–201.
- Baldi, T., 1998. Paleogene and early Miocene in Hungary. In: Cicha, I., Rögl, F., Rupp, C., Ctyroka, J. (Eds.), *Oligocene–Miocene Foraminifera of the Central Paratethys. Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft*, vol. 549, pp. 50–53.
- Baldi, T., Senes, J., 1975. OM, Egerien. Die Egerer, Pouzdraner, Puchkirchener Schichtgruppe und die Bretkaer Formation. *Chronostratigraphie und Neostatotypen* 5, 1–577.
- Baluk, W., 1975. Lower Tortonian gastropods from Korytnica, Poland. *Palaeontologia Polonica* 32, 1–186.
- Baluk, W., 1995. Middle Miocene (Badenian) gastropods from Korytnica, Poland; Part II. *Acta Geologica Polonica* 45, 153–255.
- Baluk, W., 1997. Middle Miocene (Badenian) gastropods from Korytnica, Poland; Part III. *Acta Geologica Polonica* 47, 1–75.
- Baluk, W., 2003. Middle Miocene (Badenian) gastropods from Korytnica, Poland; Part IV Turridae. *Acta Geologica Polonica* 53, 29–78.
- Barthelt, D., 1989. Faziesanalyse und Untersuchungen der Sedimentationsmechanismen in der Unteren Brackwasser-Molasse Oberbayerns. *Münchner Geowissenschaftliche Abhandlungen* 17, 1–118.
- Beer-Bistricky, E., 1958. Die miozänen Buccinidae und Nassariidae des Wiener Beckens und Niederösterreichs. *Mitteilungen der Geologischen Gesellschaft in Wien* 49, 41–84.
- Berger, J.-P., 1996. Cartes paléogéographiques-palinspastiques du bassin molassique suisse (Oligocène inférieur – Miocène moyen). *Neues Jahrbuch für Geologie und Paläontologie* 202, 1–44.
- Bistrice, A., Jenk, K., 1985. Area No. 224 b1: Transtethyan Trench “Corridor”. In: Steininger, F.F., Senes, J., Kleemann, K., Rögl, F.

- (Eds.), Neogene of the Mediterranean Tethys and Paratethys. Stratigraphic Correlation Tables and Sediment Distribution Maps, vol. 1. University Vienna, Vienna, pp. 72–73.
- Boda, J., 1959. Das Sarmat in Ungarn und seine Invertebraten-Fauna. *Jahrbuch der Ungarischen Geologischen Anstalt* 47, 569–862.
- Boettger, O., 1896. Zur Kenntnis der Fauna der mittelmiozänen Schichten von Kostež im Banat. *Verhandlungen und Mitteilungen des Siebenbürgischen Vereins der Naturwissenschaften zu Hermannstadt* 46, 49–66.
- Boettger, O., 1902. Zur Kenntnis der Fauna der mittelmiozänen Schichten von Kostež im Krassó-Szörényer Komitat. (Mit einem Situationsplan der Fundpunkte). II. *Verhandlungen und Mitteilungen des Siebenbürgischen Vereins für Naturwissenschaften zu Hermannstadt* 51, 1–200 (Jahrgang 1901).
- Boettger, O., 1906. Zur Kenntnis der Fauna der mittelmiozänen Schichten von Kostež im Krassó-Szörényer Komitat. (Gasteropoden und Anneliden.) III. *Verhandlungen und Mitteilungen des Siebenbürgischen Vereins für Naturwissenschaften zu Hermannstadt* 54 (I–VIII+1–99).
- Bojar, A.-V., Hiden, H., Fenninger, A., Neubauer, F., 2004. Middle Miocene seasonal temperature changes in the Styrian basin, Austria, as recorded by the isotopic composition of pectinid and brachiopod shells. *Palaeogeography, Palaeoclimatology, Palaeoecology* 203, 95–105.
- Brusina, S., 1902. *Iconographia Molluscorum Fossilium in tellure tertiaria Hungariae, Croatiae, Slavoniae, Dalmatiae, Bosniae, Herzegovinae, Serbiae et Bulgariae inventorum*. 30 plates, Agram (Officina Soc. Typographicae).
- Chira, C., 2000. Nannoplancton calcaros si molluste Miocene din Transylvania, Romanian. *Editura Carpatica* 1–183.
- Cicha, I., Senes, J., Tejkal, J., 1967. M3 (Karpation) Die Karpatische Serie und ihr Stratotypus. *Chronostratigraphie und Neostatotypen, Miozän der Zentralen Paratethys* 1, 1–312.
- Cicha, I., Rögl, F., Rupp, C., Ctyroká, J., 1998. Oligocene–Miocene foraminifera of the Central Paratethys. *Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft* 549, 1–325.
- Cicha, I., Rögl, F., Ctyroká, J., 2003. Central Paratethys Karpatian Foraminifera. In: Brzobohatý, R., Cicha, I., Kováč, M., Rögl, F. (Eds.), *The Karpatian — an Early Miocene Stage of the Central Paratethys*. Masaryk University Brno, pp. 169–188.
- Dullo, W.-C., 1983. Diagenesis of fossils of the Miocene Leitha Limestone of the Paratethys, Austria: an example for faunal modifications due to changing diagenetic environments. *Facies* 8, 1–112.
- Dumitrica, P., Gheta, N., Popescu, G., 1975. New data on the biostratigraphy and correlation of the Middle Miocene in the Carpathian area. *Dari Seama ale Sedintelor* 61/4, 65–84.
- Erhart, C., Piller, W.E., 2004. Fazies und Geometrie des Leithakalk-Steinbruches Retznei/Rosenberg bei Ehrenhausen (Stmk.). *Berichte des Institutes für Erdwissenschaften*, vol. 9. Karl-Franzens Universität Graz, p. 116.
- Faupl, P., Roetzel, R., 1990. Die Phosphoritsande und Fossilreichen Grottsande: Gezeitenbeeinflusste Ablagerungen der Innviertler Gruppe (Ottományen) in der oberösterreichischen Molassezone. *Jahrbuch der Geologischen Bundesanstalt* 133/2, 157–180.
- Flower, B.P., Kennett, J.P., 1993. Middle Miocene ocean-climate transition: high-resolution oxygen and carbon isotopic records from Deep Sea Drilling Project Site 588A, southwest Pacific. *Paleoceanography* 8/4, 811–843.
- Foresi, L.M., Bonomo, S., Caruso, A., Di Stefano, A., Di Stefano, E., Salvalorini, G., Sprovieri, R., 2002. Calcareous Plankton High Resolution Biostratigraphy (Foraminifera and Nannofossils) of the Uppermost Langhian-Lower Serravallian Ras Il-Pellegrin Section (Malta). *Rivista Italiana di Paleontologia e Stratigrafia* 108, 195–210.
- Fornaciari, E., Rio, D., 1996. Latest Oligocene to early Middle Miocene quantitative calcareous nannofossil biostratigraphy in the Mediterranean region. *Micropaleontology* 42, 1–36.
- Fornaciari, E., Di Stefano, A., Rio, D., Negri, A., 1996. Middle Miocene quantitative calcareous nannofossil biostratigraphy in the Mediterranean region. *Micropaleontology* 42, 37–63.
- Friebe, J.G., 1993. Sequence stratigraphy in a mixed carbonate-siliciclastic depositional system (Middle Miocene; Styrian Basin, Austria). *Geologische Rundschau* 82, 281–294.
- Gradstein, F.M., Ogg, J.G., 2004. Geologic time scale 2004 — why, how, and where next! *Lethaia* 37, 175–181.
- Gradstein, F.M., Ogg, J.G., Smith, A.G., Bleeker, W., Lourens, L.J., 2004. A new geologic time scale with special reference to Precambrian and Neogene. *Episodes* 27, 83–100.
- Haq, B.U., Hardenbol, J., Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea level changes. In: Wilgus, C.K. (Ed.), *Sea-level changes — an integrated approach*. Society of Economic Paleontologists and Mineralogists, Special Publications, vol. 42, pp. 71–108.
- Hardenbol, J., Thierry, J., Farley, M.B., Jacquin, T., Graciansky, P.-C., Vail, P.R., 1998. Mesozoic and Cenozoic Sequence Chronostratigraphic Framework of European Basins. In: Graciansky, P.-C., Hardenbol, J., Jacquin, T., Vail, P.R. (Eds.), *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins*. SEPM, Special Publications, vol. 60, pp. 3–13.
- Harzhauser, M., 2003. The marine Gastropods, Scaphopods and Cephalopods of the Karpatian in the Central Paratethys. In: Brzobohatý, R., Cicha, I., Kováč, M., Rögl, F. (Eds.), *The Karpatian — an Early Miocene Stage of the Central Paratethys*. Masaryk University, Brno, pp. 193–202.
- Harzhauser, M., Kowalke, T., 2002. Sarmatian (Late Middle Miocene) gastropod assemblages of the Central Paratethys. *Facies* 46, 57–82.
- Harzhauser, M., Kowalke, T., 2004. Survey of the Nassariid Gastropods in the Neogene Paratethys. *Archiv für Molluskenkunde* 133, 1–61.
- Harzhauser, M., Mandic, O., 2001. Late Oligocene Gastropods and Bivalves from the Lower and Upper Austrian Molasse Basin. In: Piller, W.E., Rasser, M. (Eds.), *The Paleogene of Austria*. Österreichische Akademie der Wissenschaften, Schriftenreihe der Erdwissenschaftlichen Kommissionen, vol. 14, pp. 671–795.
- Harzhauser, M., Mandic, O., 2004. The muddy bottom of Lake Pannon — a challenge for dreissenid settlement (Late Miocene; Bivalvia). *Palaeogeography, Palaeoclimatology, Palaeoecology* 204, 331–352.
- Harzhauser, M., Piller, W.E., 2004a. The Early Sarmatian — hidden seesaw changes. *Courier Forschungsinstitut Senckenberg* 246, 89–112.
- Harzhauser, M., Piller, W.E., 2004b. Integrated Stratigraphy of the Sarmatian (Upper Middle Miocene) in the western Central Paratethys. *Stratigraphy* 1, 65–86.
- Harzhauser, M., Tempfer, P., 2004. Late Pannonian Wetland Ecology of the Vienna Basin based on Molluscs and Lower Vertebrate Assemblages (Late Miocene, MN 9, Austria). *Courier der Senckenbergischen Naturforschenden Gesellschaft, Frankfurt/Main* 246, 55–68.
- Harzhauser, M., Piller, W.E., Steininger, F.F., 2002. Circum-Mediterranean Oligo-Miocene biogeographic evolution — the gastropods' point of view. *Palaeogeography, Palaeoclimatology, Palaeoecology* 183, 103–133.
- Harzhauser, M., Mandic, O., Zuschin, M., 2003. Changes in Paratethyan marine molluscs at the Early/Middle Miocene

- transition — diversity, paleogeography and paleoclimate. *Acta Geologica Polonica* 53, 323–339.
- Harzhauser, M., Daxner-Höck, G., Piller, W.E., 2004. An integrated stratigraphy of the Pannonian (Late Miocene) in the Vienna Basin. *Austrian Journal of Earth Sciences* 95/96, 6–19.
- Hilber, V., 1879. Neue Conchylien aus den mittelsteirischen Mediterraanschichten. *Sitzungsberichte der Akademie der Wissenschaften, mathematisch-naturwissenschaftliche Classe* 79, 416–464.
- Hözl, O., 1958. Die Mollusken-Fauna des oberbayrischen Burdigals. *Geologica Bavarica* 38, 1–348.
- Hözl, O., 1962. Die Molluskenfauna der oberbayrischen marinen Oligocänmolasse zwischen Isar und Inn und ihre stratigraphische Auswertung. *Geologica Bavarica* 50, 1–143.
- Hözl, O., 1973. Faziostratotypus: Kaltenbachgraben. In: Papp, A., Rögl, F., Senes, J. (Eds.), *M2 Ottnangien; Die Innviertler, Salgótarján, Bántapusztaer Schichtengruppe und die Rzehakia Formation. Chronostratigraphie und Neostatotypen, Miozän der zentralen Paratethys*, vol. 3, pp. 155–196.
- Hörnes, M., 1852–1856. Die fossilen Mollusken des Tertiär-Beckens von Wien. I. Band. Univalven. *Abhandlungen der Geologischen Reichsanstalt*, vol. 1–10, pp. 1–736.
- Hörnes, R., Auinger, M., 1879–1891. Die Gastropoden der Meeresablagerungen der ersten und zweiten Miozänen Mediterranstufe in der österreichischen-ungarischen Monarchie. *Abhandlungen der k. k. geologischen Reichsanstalt*, 1–12, pp. 1–382.
- Hudácková, N., Holocová, Zlinská, A., Kováč, M., Nagymaros, A., 2000. Paleogeology and eustasy: Miocene 3rd order cycles of relative sea-level changes in the Western Carpathian — North Pannonian basins. *Slovak Geological Magazine* 6, 95–100.
- Jackson, J.B.C., Johnson, K.G., 2000. Life in the last few million years. *Paleobiology* 26/4, 221–235 (supplement).
- Janssen, A.W., 1984. Late Oligocene Molluscs from a sand-pit near Máriahalom (Hungary): a preliminary study. *Annales Universitatis Scientiarum Budapestinensis de Rolando Eötvös nominatae. Sectio Geologica* 24, 109–150.
- Janssen, R., 1993. Taxonomy, evolution and spreading of the turrid genus *Spirotropis* (Gastropoda: Turridae). *Scripta Geologica, Special Issue* 2, 237–261.
- Jekeli, E., 1944. Sarmat und Pont von Soceni. *Memorille Institutului geologici al Romaniei* 5, 1–167.
- Kaiser, D., Rasser, M., Nebelsick, J.H., Piller, W.E., 2001. Late Oligocene algal limestones on a mixed carbonate–siliciclastic ramp at the southern margin of the Bohemian Massif (Upper Austria). In: Piller, W.E., Rasser, M. (Eds.), *The Paleogene of Austria. Österreichische Akademie der Wissenschaften, Schriftenreihe der Erdwissenschaftlichen Kommissionen*, vol. 14, pp. 197–224.
- Kasprzyk, G., 1999. Sedimentary evolution of the Badenian (Middle Miocene) gypsum deposits in the northern Carpathian Foredeep. *Geological Quarterly* 43, 449–654.
- Kochansky-Devide, V., Sliskovic, T., 1978. Miocenske Kongerije Hrvatske, Bosne i Hercegovine. *Palaeontologia Jugoslavica* 19, 1–98.
- Kojumdzieva, E., 1969. Sarmatien. *Lés fossiles de Bulgarie* 8, 1–223.
- Kojumdzieva, E., Strachimirov, B., 1960. Tortonien; Le Tortonien du type viennois. *Lés fossiles de Bulgarie* 7, 13–246.
- Kojumdzieva, E.I., Paramonova, N.P., Belokry, L.S., Muskhelishvili, L.V., 1989. Ecostratigraphic subdivision of the Sarmatian after molluscs. *Geologica Carpathica* 40, 81–84.
- Kókay, J., 1966. Geologische und paläontologische Untersuchungen des Braunkohlengbietes von Herend-Márkó (Bakony-Gebirge, Ungarn). *Geologica Hungarica, Series Palaeontologica* 36, 1–147.
- Kókay, J., 1973. Faziostratotypen der Bántapusztaer Schichtengruppe. In: Papp, A., Rögl, F., Senes, J. (Eds.), *M2 Ottnangien. Die Innviertler, Salgótarján, Bántapusztaer Schichtengruppe und die Rzehakia Formation. Chronostratigraphie und Neostatotypen, Miozän der zentralen Paratethys*, vol. 3, pp. 227–243.
- Kolesnikov, V., 1935. Sarmatische Mollusken. *Paläontologie der USSR*, vol. 10/2. Leningrad, pp. 1–416 (in Russian with German descriptions).
- Kováč, M., Andreyeva-Grigorovich, A.S., Brzobohatý, R., Fodor, L., Harzhauser, M., Oszczypko, N., Pavelic, D., Rögl, F., Saftic, B., Sliva, B., Stráňík, Z., 2003. Karpatian paleogeography, tectonics and eustatic changes. In: Brzobohatý, R., Cicha, I., Kováč, M., Rögl, F. (Eds.), *The Karpatian — an Early Miocene Stage of the Central Paratethys*. Masaryk University Brno, pp. 49–72.
- Kováč, M., Barath, I., Harzhauser, M., Hlavaty, I., Hudackova, N., 2004. Miocene depositional systems and sequence stratigraphy of the Vienna Basin. *Courier Forschungsinstitut Senckenberg* 246, 187–212.
- Kowalko, T., Harzhauser, M., 2004. Early ontogeny and paleoecology of the Miocene rissoid gastropods of the Central Paratethys. *Acta Palaeontologica Polonica* 49, 111–134.
- Kreutzer, N., 1986. Die Ablagerungssequenzen der miozänen Badener Serie im Feld Matzen und im zentralen Wiener Becken. *Erdöl-Erdgas-Kohle* 102, 492–503.
- Kroh, A., Harzhauser, M., 1999. An echinoderm fauna from the Lower Miocene of Austria: paleoecology and implications for central Paratethys paleobiogeography. *Annalen des Naturhistorischen Museums in Wien* 101, 145–191.
- Kroh, A., Harzhauser, M., Piller, W.E., Rögl, F., 2003. The Lower Badenian (Middle Miocene) Hartl Formation (Eisenstadt-Sopron Basin, Austria). In: Piller, W.E. (Ed.), *Stratigraphia Austriaca. Österreichische Akademie der Wissenschaften, Schriftenreihe Erdwissenschaftliche Kommissionen*, vol. 16, pp. 87–109.
- Kvaliashvili, G.A., 1962. The *Oncophora* (Rzehakia) formation of Eurasia. *Academia Nauk Gruzinskoy SSR, Tbilisi* 1–231 (in Russian with English abstract).
- Laskarev, V.N., 1924. Sur les equivalentes du Sarmatien supérieur en Serbie. *Zbornik Cvijic*, pp. 73–85.
- Latal, C., Piller, W.E., 2003. Stable Isotope Signatures at the Karpatian/Badenian Boundary in the Styrian Basin. In: Brzobohatý, R., Cicha, I., Kováč, M., Rögl, F. (Eds.), *The Karpatian — an Early Miocene stage of the central Paratethys*. Masaryk University Brno, pp. 37–48.
- Latal, C., Piller, W.E., Harzhauser, M., 2006. Shifts in oxygen and carbon isotope signals in marine molluscs from the Central Paratethys around the Lower/Middle Miocene transition. *Palaeogeography, Palaeoclimatology, Palaeoecology* 231, 347–360.
- Lourens, L., Hilgen, F., Shackleton, N.J., Laskar, J., Wilson, D., 2004. The Neogene Period. In: Gradstein, F., Ogg, J., Smith, A. (Eds.), *Geologic Time Scale 2004*. Cambridge University Press.
- Magyar, I., Geary, D.H., Müller, P., 1999. Paleogeographic evolution of the Late Miocene Lake Pannon in Central Europe. *Palaeogeography, Palaeoclimatology, Palaeoecology* 147, 151–167.
- Mandic, O., Steininger, F.F., 2003. Computer-based mollusc stratigraphy — a case study from the Eggenburgian (Early Miocene) type region (NE Austria). *Palaeogeography, Palaeoclimatology, Palaeoecology* 197, 263–291.
- Mandic, O., Harzhauser, M., Spezzaferri, S., Zuschin, M., 2002. The paleoenvironment of an early Middle Miocene Paratethys sequence in NE Austria with special emphasis on paleoecology of mollusks and foraminifera. *Geobios Mémoire spécial* 35, 193–206.
- Mandic, O., Harzhauser, M., Piller, W.E., Schlaf, J., Rögl, F., Schuster, F., Wielandt-Schuster, U., Nebelsick, J.H., Kroh, A., Bassant, Ph., 2004. Paleogeology of an epicontinental flooding — Burdigalian (Early

- Miocene) of the Mut Basin (Southern Turkey). *Courier Forschungsinstitut Senckenberg* 248, 57–92.
- Martel, A.T., Allen, Ph.A., Slingerland, R., 1994. Use of tidal-circulation modelling in paleogeographical studies: an example from the Tertiary of the Alpine perimeter. *Geology* 22, 925–928.
- Marton, E., Drobne, K., Cosovic, V., Moro, A., 2003. Palaeomagnetic evidence for Tertiary counterclockwise rotation of Adria. *Tectonophysics* 377, 143–156.
- Meznerics, I., 1933. Die Minuten der tortonischen Ablagerungen von Steinabrunn in Niederösterreich. *Annalen des Naturhistorischen Museums in Wien* 46, 319–359.
- 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.
- Nebelsick, J.H., 1989. Temperate water carbonate facies of the Early Miocene Paratethys (Zogelsdorf Formation, Lower Austria). *Facies* 21, 11–40.
- Nevesskaja, L.A., Goncharova, I.A., Iljina, L.B., Paramonova, N.P., Popov, S.V., Voronina, A.A., Chepalyga, A.L., Babak, E.V., 1987. History of Paratethys. *Annales de l'Institut Géologique de Hongrie* 70, 337–342.
- Papp, A., 1974. Die Molluskenfauna der Sarmatischen Schichten-gruppe. In: Papp, A., Marinescu, F., Senes, J. (Eds.), *M₅ Sarmatien. Chronostratigraphie und Neostatotypen*, vol. 4, pp. 318–427.
- Papp, A., 1985a. Holostratotypus: Vösendorf, Wiener Becken (Österreich). In: Papp, A., Jámor, Á., Steininger, F.F. (Eds.), *M₆ Pannonian (Slavonien und Serbien). Chronostratigraphie und Neostatotypen. Miozän der Zentralen Paratethys*, vol. 7, pp. 187–198.
- Papp, A., 1985b. Gastropoda (Neritidae, Viviparidae, Valvatidae, Hydrobiidae, Stenothyridae, Truncatellidae, Bulimidae, Micromelaniidae, Thiaridae) und Bivalvia (Dreissenidae, Limnardiidae, Unionidae) des Pannonien. In: Papp, A., Jámor, Á., Steininger, F. (Eds.), *M₆ Pannonien (Slavonien und Serbien). Chronostratigraphie und Neostatotypen. Miozän der Zentralen Paratethys*, vol. 7, pp. 276–339.
- Papp, A., Steininger, F., 1974. Holostratotypus Nexing N.Ö. In: Papp, A., Marinescu, F., Senes, J. (Eds.), *M₅ Sarmatien. Chronostratigraphie und Neostatotypen. Miozän der Zentralen Paratethys*, vol. 4, pp. 162–166.
- Papp, A., Steininger, F., 1978. Holostratotypus: Baden-Soos. In: Papp, A., Cicha, I., Senes, J., Steininger, F. (Eds.), *M₄ Badenian (Moravien, Wielicien, Kosovien). Chronostratigraphie und Neostatotypen. Miozän der Zentralen Paratethys*, vol. 6, pp. 138–145.
- Papp, A., Marinescu, F., Senes, J., 1974. *M₅ Sarmatien. Chronostratigraphie und Neostatotypen. Miozän der Zentralen Paratethys* 4, 1–707.
- Papp, A., Cicha, I., Senes, J., Steininger, F., 1978. *M₄ Badenien (Moravien, Wielicien, Kosovien). Chronostratigraphie und Neostatotypen. Miozän der Zentralen Paratethys* 6, 1–594.
- Piller, W.E., Kleemann, K., 1991. Middle Miocene reefs and related facies in eastern Austria. Vienna Basin. VI. International Symposium on Fossil Cnidaria including Archaeocyatha and Porifera. *Excursion-Guidebook, Excursion B*, vol. 4, pp. 1–28.
- Pisera, A., 1996. Miocene reefs of the Paratethys: a review. *SEPM* 5, 97–104.
- Popov, S.V., Ilyina, L.B., Nikolaeva, I.A., 1985. Molluscs and ostracods from the Solenian horizon of the eastern Paratethys. *Paleontological Journal* 1985/1, 28–41.
- Popov, S.V., Rögl, F., Rozanov, A.Y., Steininger, F.F., Shcherba, I.G., Kovács, M., 2004. Lithological–Paleogeographic maps of Paratethys. 10 Maps Late Eocene to Pliocene. *Courier Forschungsinstitut Senckenberg* 250, 1–46.
- Reichenbacher, B., 2000. Das brackisch-lakustrische Oligozän und Unter-Miozän im Mainzer Becken und Hanauser Becken: Fischfaunen, Paläoökologie, Biostratigraphie, Paläogeographie. *Courier Forschungsinstitut Senckenberg* 222, 1–143.
- Riegl, B., Piller, W.E., 2000. Biostromal coral facies — a Miocene example from the Leitha Limestone (Austria) and its actualistic interpretation. *Palaaios* 15, 399–413.
- Riegl, B., Piller, W.E., 2002. Reefs and coral carpets in the Miocene Paratethys (Badenian, Leitha Limestone, Austria). *Proceedings 9th International Coral Reef Symposium, Bali*, vol. 1, pp. 211–216.
- Rögl, F., 1998. Palaeogeographic considerations for Mediterranean and Paratethys seaways (Oligocene to Miocene). *Annalen des Naturhistorischen Museums in Wien* 99, 279–310.
- Rögl, F., 1999. Mediterranean and Paratethys. Facts and hypotheses of an Oligocene to Miocene paleogeography (short overview). *Geologica Carpathica* 50, 339–349.
- Rögl, F., Schultz, O., Hölzl, O., 1973. Holostratotypus und Fazios-tratotypen der Innviertler Schichtengruppe. In: Papp, A., Rögl, F., Senes, J. (Eds.), *M₂ Ottnangien. Die Innviertler, Salgótarján, Bántapusztaer Schichtengruppe und die Rzehakia Formation. Chronostratigraphie und Neostatotypen. Miozän der Zentralen Paratethys*, vol. 3, pp. 140–196.
- Rögl, F., Spezzaferri, S., Coric, S., 2002. Micropaleontology and biostratigraphy of the Karpatian–Badenian transition (Early–Middle Miocene boundary) in Austria (Central Paratethys). *Courier Forschungsinstitut Senckenberg* 237, 47–67.
- Rögl, F., Brzobohatý, R., Cicha, I., Coric, S., Daxner-Höck, G., Dolakova, N., Harzhauser, M., 2003. Paleobiological characterization and definition of the Karpatian stage. In: Brzobohatý, R., Cicha, I., Kovács, M., Rögl, F. (Eds.), *The Karpatian — a Lower Miocene Stage of the Central Paratethys*. Masaryk University, Brno, pp. 357–360.
- Royden, L., Horváth, F., 1988. The Pannonian Basin. A study in basin evolution. *American Association of Petroleum Geologists, Memoir* 45, 1–394.
- Schmid, H.-P., Harzhauser, M., Kroh, A., 2001. Hypoxic Events in a Middle Miocene Carbonate Platform of the Central Paratethys (Austria, Badenian, 14 Ma). *Annalen des Naturhistorischen Museums in Wien* 102, 1–50.
- Senes, J., 1974. Die Herkunft der endemischen Fauna des Sarmats. In: Papp, A., Marinescu, F., Senes, J. (Eds.), *M₅ Sarmatien. Chronostratigraphie und Neostatotypen. Miozän der Zentralen Paratethys*, vol. 4, pp. 139–140.
- Shevenell, A.E., Kennett, J.P., Lea, D.W., 2004. Middle Miocene Southern Ocean cooling and Antarctic cryosphere expansion. *Science* 305, 1766–1770.
- Sieber, R., 1958. Systematische Übersicht der jungtertiären Gastropoden des Wiener Beckens. *Annalen des Naturhistorischen Museums in Wien* 62, 123–192.
- Sprovieri, R., 1992. Mediterranean Pliocene biochronology: a high resolution record based on quantitative planktonic foraminifera distribution. *Rivista Italiana di Paleontologia e Stratigrafia* 98, 61–100.
- Sprovieri, R., Bonomo, S., Caruso, A., Di Stefano, A., Di Stefano, E., Foresi, L.M., Iaccarino, S., Lirer, F., Mazzei, R., Salvatorini, G., 2002. An Integrated calcareous plankton biostratigraphic scheme and biochronology of the Mediterranean Middle Miocene. *Rivista Italiana di Paleontologia e Stratigrafia* 108, 337–353.
- Steininger, F., 1971. Holostratotypus und Fazios-tratotypen der Eggenburger Schichtengruppe im Raum von Eggenburg in Niederösterreich (Österreich). In: Steininger, F., Senes, J. (Eds.), *M₁ Eggenburgien. Die Eggenburger Schichtengruppe und ihr Stratotypus. Chronostratigraphie und Neostatotypen*, vol. 2, pp. 104–167.

- Steininger, F., 1973. Die Molluskenfaunen des Otnangien. In: Papp, A., Rögl, F., Senes, J. (Eds.), M2 Otnangien. Die Innviertler, Salgótarján, Bántapuszta Schichtgruppe und die Rzehakia Formation. Chronostratigraphie und Neostatotypen, Miozän der zentralen Paratethys, vol. 3, pp. 380–615.
- Steininger, F.F., 1999. Chronostratigraphy, Geochronology and Biochronology of the “European Land Mammal Mega-Zones” (ELMMZ) and the Miocene “Mammal-Zones” (MN-Zones). In: Rössner, G.E., Heissig, K. (Eds.), The Miocene Land Mammals of Europe. Dr. Friedrich Pfeil, München, pp. 9–24.
- Steininger, F., Senes, J., 1971. M1 Eggenburgien. Die Eggenburger Schichtengruppe und ihr Statotypus. Chronostratigraphie und Neostatotypen 2, 1–827.
- Steininger, F.F., Wessely, G., 2000. From the Tethyan Ocean to the Paratethys Sea: Oligocene to Neogene Stratigraphy, Paleogeography and Paleobiogeography of the circum-Mediterranean region and the Oligocene to Neogene Basin evolution in Austria. Mitteilungen der Österreichischen Geologischen Gesellschaft 92, 95–116.
- Steininger, F., Ctyroky, P., Ondrejickova, A., Senes, J., 1971. Die Mollusken der Eggenburger Schichtengruppe. In: Steininger, F., Senes, J. (Eds.), M1 Eggenburgien. Die Eggenburger Schichtengruppe und ihr Statotypus. Chronostratigraphie und Neostatotypen, vol. 2, pp. 356–591.
- Steininger, F., Rögl, F., Müller, C., 1978. Geodynamik und paläogeographische Entwicklung des Badenien. In: Papp, A., Cicha, I., Senes, J., Steininger, F. (Eds.), M4 Badenian (Moravien, Wielicien, Kosovien). Chronostratigraphy und Neostatotypen, Miozän der Zentralen Paratethys, vol. 6, pp. 110–127.
- Strausz, L., 1966. Die Miozän-Mediterranen Gastropoden Ungarns. Akadémiai Kiadó, Budapest. 693 pp.
- Studencka, B., Gontsharova, I.A., Popov, S.V., 1998. The bivalve faunas as a basis for reconstruction of the Middle Miocene history of the Paratethys. *Acta Geologica Polonica* 48, 285–342.
- Studencki, W., 1999. Red-algal limestone in the Middle Miocene of the Carpathian Foredeep in Poland: facies variability and palaeoclimatic implications. *Geological Quarterly* 43, 395–404.
- Suess, E., 1866. Untersuchungen über den Charakter der österreichischen Tertiärlagerungen, II. Über die Bedeutung der sogenannten “brackischen Stufe” oder der “Cerithienschichten”. Sitzungsberichte der k. Akademie der Wissenschaften 1, 1–40 (Abth. 54).
- Svagróvský, J., 1959. Asociácie mäkkýšov brakických uloženín vrehného tortónu a spodného sarmatu východného Slovenska. *Geologické Práce* 55, 215–254.
- Svagróvský, J., 1971. Das Sarmat der Tschechoslowakei und seine Molluskenfauna. *Acta Geologica et Geographica Universitatis Comenianae, Geologica* 20, 1–473.
- Svagróvský, J., 1981. Lithofazielle Entwicklung und Molluskenfauna des oberen Badenien (Miozän M4d) in dem Gebiet Bratislava-Devínska Nová Ves. *Západné Karpaty, Seria Paleontológia* 7, 1–203.
- Svagróvský, J., 1982a. Gastropoda, Prosobranchia. Teil I. Archaeogastropoda and Mesogastropoda des oberen Badenien von Borský Mikuláš (NO-Teil des Wiener Beckens) und ihre stratigraphische Bedeutung. *Geologický Zborník; Geologica Carpathica* 33, 3–50.
- Svagróvský, J., 1982b. Gastropoda, Prosobranchia. Teil II. Neogastropoda des oberen Badenien von Borský Mikuláš (NO-Teil des Wiener Beckens) und ihre stratigraphische Bedeutung. *Geologický Zborník; Geologica Carpathica* 33, 437–462.
- Svagróvský, J., 1984. Gastropoda, Euthyneura, Opisthobranchia des oberen Badenien von Borský Mikuláš (NO-Teil des Wiener Beckens) und ihre stratigraphische Bedeutung. *Geologický Zborník; Geologica Carpathica* 35, 165–194.
- Sztanó, O., 1995. Palaeogeographic significance of tidal deposits: an example from an early Miocene Paratethys embayment, Northern Hungary. *Palaeogeography, Palaeoclimatology, Palaeoecology* 113, 173–187.
- Vavra, N., 1979. Die Bryozoenfauna des österreichischen Tertiärs. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* 157, 366–392.
- Wagner, L.R., 1996. Stratigraphy and hydrocarbons in Upper Austrian Molasse Foredeep (Active margin). In: Wessely, G., Liebl, W. (Eds.), Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe. European Association of Geoscientists and Engineers. Special Publications, vol. 5, pp. 217–235.
- Weissenböck, M., 1996. Lower to Middle Miocene sedimentation model of the central Vienna Basin. In: Wessely, G., Liebl, W. (Eds.), Oil and Gas in Alpidic Thrustbelts and Basins of the Central and Eastern Europe. European Association of Geoscientists and Engineers. Special Publications, vol. 5, pp. 355–363.
- Westermann, G.E.G., 2000a. Biochore classification and nomenclature in paleobiogeography: an attempt at order. *Palaeogeography, Palaeoclimatology, Palaeobiogeography* 158, 1–13.
- Westermann, G.E.G., 2000b. Marine faunal realms of the Mesozoic: review and revision under the new guidelines for biogeographic classification and nomenclature. *Palaeogeography, Palaeoclimatology, Palaeobiogeography* 163, 49–68.
- Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science* 292, 686–693.