Miocene syn-rift lacustrine sediments in the Mecsek Mts. (SW Hungary)

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Abstract

The Pannonian Basin, a major back-arc basin in the Alpine–Carpathian orogenic belt, experienced its syn-rift phase during the Early–Middle Miocene. Studying coeval sediments can provide important information on the initiation of the extension. This paper investigates syn-rift deposits in the Mecsek Mts. in SW Hungary from a tectono-sedimentary aspect, using stratigraphy, palaeontology and structural observations to constrain palaeoenvironments and their tectonic background. Our study shows that in the Mecsek area the widespread Early Miocene fluvial sedimentation was not directly followed by inundation by the Central Paratethys sea, instead, a phase of lacustrine deposition in the Karpatian–Early Badenian (late Burdigalian–early Langhian) preceded the marine flooding. The lake sediments have a low-diversity but abundant, endemic mollusc and ostracod fauna, dominated by the bivalve *Congeria boeckhi* and the gastropod *Ferebithynia vadászi*. Identical faunas at various sites indicate that "Lake Mecsek" was a single water body, covering the present-day Mecsek Mts. and their surroundings. Wedge-shaped clastic bodies along faults, fault scarp breccias and semi-soft sediment deformations suggest that extensional tectonic activity related to the rifting of the Pannonian Basin played a role in lake basin formation. The accumulation of lakes was probably also enhanced by increased precipitation during the Miocene Climatic Optimum. The Central Paratethys flooded the area in the Badenian (Langhian) and deposited normal marine sediments over the lacustrine ones. Considering the fauna, the sedimentary succession, the structural background and evolution history, the Mecsek area seems to be part of the Illyrian bioprovince and related to the Dinaride Lake System.

Keywords Pannonian basin · Syn-rift · Lake · Palaeoenvironment · Mecsek · Paratethys

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1 Introduction

The Pannonian Basin is a major back-arc basin among the mountain ranges built by the Alpine orogeny in Europe, namely the Carpathians, the Eastern Alps and the Dinarides (Fig. 1). From a geodynamic aspect, its evolution has been subdivided into the Early to Middle Miocene syn-rift, the Late Miocene post-rift and the latest Miocene to recent neotectonic phases (Horváth and Tari 1999; Horváth et al. 2006). The basic features of the basin formed during the syn-rift phase; by the end of the Middle Miocene, the lithospheric units composing the basement reached a geographical configuration that more or less corresponds to the present-day situation (Horváth et al. 2006). The syn-rift phase was characterised by considerable (50–120%) eastward lithospheric extension and rifting attributed mostly to subduction rollback in the Carpathians and subduction-related mantle upwelling under the back-arc basin (Tari et al. 1992; Horváth et al. 2006; Balázs et al. 2016).
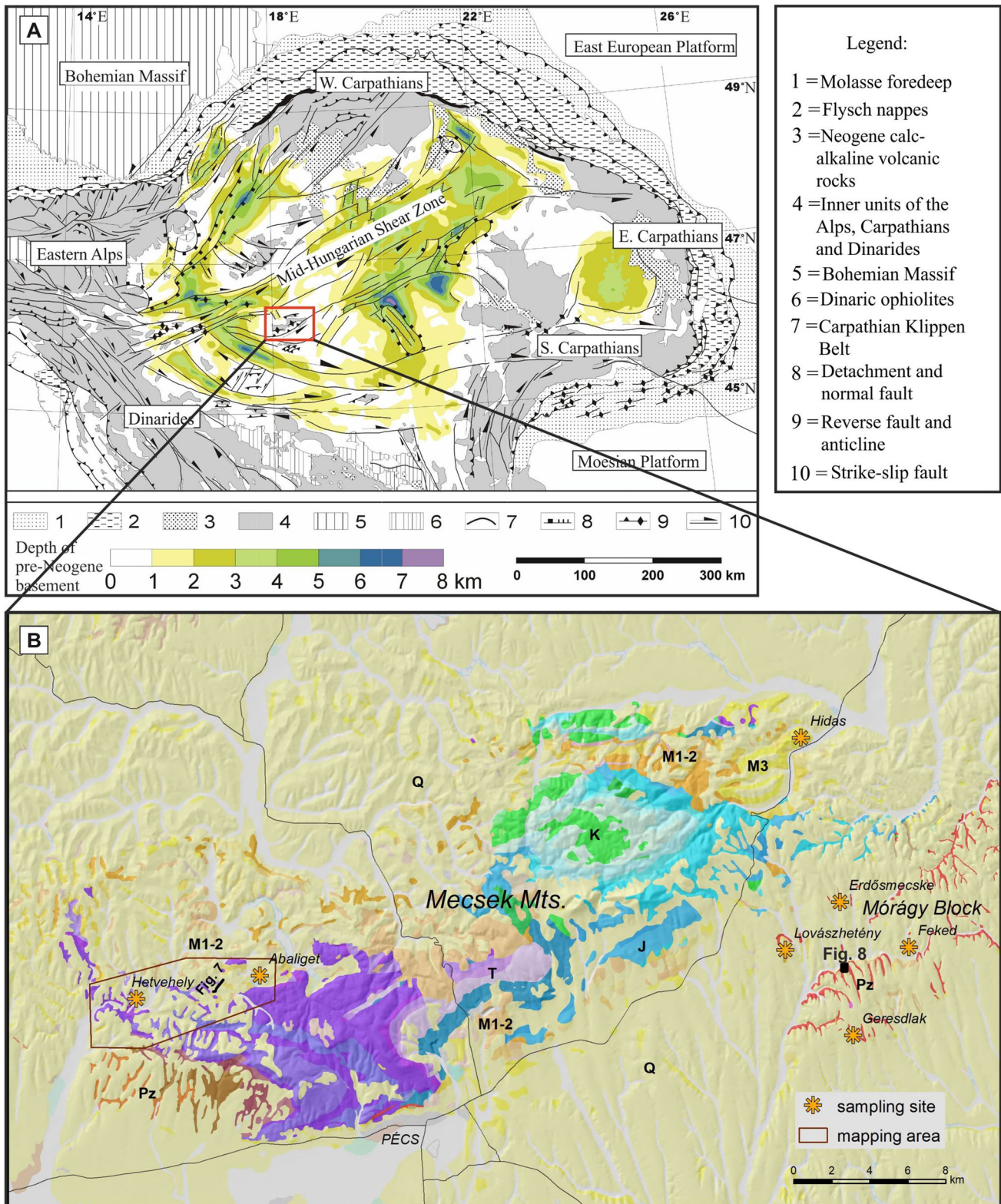
Fig. 1 Study area within the Neogene tectonic framework of the Pannonian Basin. **a** Major Neogene structures of the Pannonian Basin and depth of pre-Neogene basement (Horváth et al. 2015); **b** study area with sampling sites. Legend: *Pz* Palaeozoic rocks, *T* Triassic, *J* Jurassic, *K* Cretaceous, *M1-2* Lower–Middle Miocene, *M3* Upper Miocene, *Q* Quaternary

Extensional tectonics related to the late-stage evolution of the Dinarides and the opening of the Pannonian Basin allowed the formation of freshwater sedimentary basins in the Dinarides and along the southern margin of the Pannonian Basin. Lake basins in present-day Croatia, Serbia, Bosnia and Herzegovina and Montenegro, grouped into the Dinaride and Serbian Lake Systems (Harzhauser and Mandic 2008; Krstic et al. 2003, 2012; Neubauer et al. 2015), have been intensely studied recently, also including the aspect of deciphering the geodynamic background behind basin formation (e.g. Matenco and Radivojević 2012; Radivojević and Rundić 2016; Andric et al. 2017; Sant et al. 2017; Pavelić and Kovačić 2018). In south-west Hungary syn-rift age (Lower–Middle Miocene) rocks crop out in the Mecsek Mts., from Lower Miocene fluvial clastics developing to Middle Miocene marine sediments. These deposits are thought to be coeval with the initiation of the extension but have not yet been studied in a tectono-sedimentary aspect.

To understand the beginning of basin evolution, it is important to study continental deposits that accumulated in fault-bounded, isolated grabens because these sediments reflect rift initiation. Among them, lake deposits may indicate rapid subsidence and thus deserve attention. Their transition to marine accumulations gives further information on basin evolution. Biostratigraphic and radiometric age data are also crucial to get an image about the timing of local and regional tectonic events and, thereby, to better understand the spatiotemporal development of rifting. In the Mecsek Mts., the stratigraphic interval representing the transition from fluvial to marine deposits is classified into the Budafa Formation, the subject of this study. The exact age, depositional environment and relationship of its sub-units are debated. Here we present new biotic, stratigraphic and tectonic data on this formation collected during recent geological mapping and focused investigation of the early syn-rift sediments. These data and their preliminary interpretation in a tectonic framework are presented here to provide a base for further, in-depth structural geological and sedimentological studies and for evaluating geodynamic evolution.

2 Geological setting

The Mecsek area lies in the SW Pannonian Basin, on the tectonic block south of the Mid-Hungarian Shear Zone, on the Tisza-Dacia Megaunit (Fig. 1). Syn-rift age freshwater sediments of the Pannonian Basin crop out mostly on the southern part of this unit and along its boundary zone with Dinaric units. In the NW part of the Pannonian Basin marine sedimentation was dominant at the time, only minor freshwater accumulations are known in the N and NW of

Hungary (Nagymarosy and Hámor 2012; Kókay 2006). In the inner part of the Tisza-Dacia Megaunit, within Hungary, the only outcrops of freshwater deposits are located in the Mecsek Mts. Subsurface occurrences are known below the Great Hungarian Plain (Balázs et al. 2016; Lemberkovics et al. 2018).

In the Mecsek Mts. and wider surroundings, the basement is composed of various Palaeo-Mesozoic crystalline and sedimentary rocks (Fig. 1). Palaeogene (uppermost Eocene) clastics have a very restricted distribution south of the Mecsek Mts. and have been reported from only five boreholes (Wéber 1985). In most of the area the first deposits overlying the basement are of Miocene age, similarly to other parts of the SW Pannonian Basin (Haas 2012), indicating long-lasting pre-Miocene subaerial denudation.

The Neogene stratigraphy of the Mecsek area has been summarised by Hámor (1970) for the eastern and by Chikán (1991) and Barabás (2010) for the western part of the mountains. Sedimentation starts with widespread Lower Miocene fluvial clastics, from conglomerates to variegated clays (Szászvár Fm.) (Figure 2). They are overlain by the Budafa Formation, traditionally considered to be of Karpatian (late Burdigalian) age (Gyalog 1996; Gyalog and Budai 2004; Budai et al. 2015). The succession continues in the Badenian (Langhian) with normal marine Leitha limestones (Lajta Limestone Fm. Pécsszabolcs and Rákos Members) in the littoral zone and offshore sands and silts (Tekeres and Szilágy Fms.) in the basins, locally with coal-bearing swamp deposits (Hidas Fm.) along the shores.

Within the Budafa Fm., sediments of varied lithologies are classified into three members. The Pécsvárad Limestone Member, traditionally called "*Congeria* beds", is built up of coarse conglomerates, sandstones and bioclastic limestones consisting of mollusc coquinas dominated by *Congeria* shells. The Komló Claymarl Member ("fish scale-bearing clay marl") is composed of dark grey, greenish-grey, massive or laminated silty clay marl, calcareous silt and fine sands, with numerous fish scales and bones, and sometimes with tuff interbeds. The uppermost Budafa Sandstone Member ("Budafa sandstone") is dominated by coarse-grained sediments, i.e., yellowish-grey sand, sandstone, gravel and conglomerate, with marine fauna. Although in his pioneering paper Wenz (1931) describes the two typical molluscs of the Pécsvárad Limestone as freshwater species, in recent comprehensive works on the Miocene of the region the complete Budafa Formation has been interpreted to represent marine flooding with brackish to euhaline water in a delta to lagoonal to normal marine environment (Hámor 1970; Barabás 2010).

Significantly different stratigraphic models exist for the Budafa Formation. Hámor (1970) and Chikán (1991) consider the three members to primarily overlie each other, with
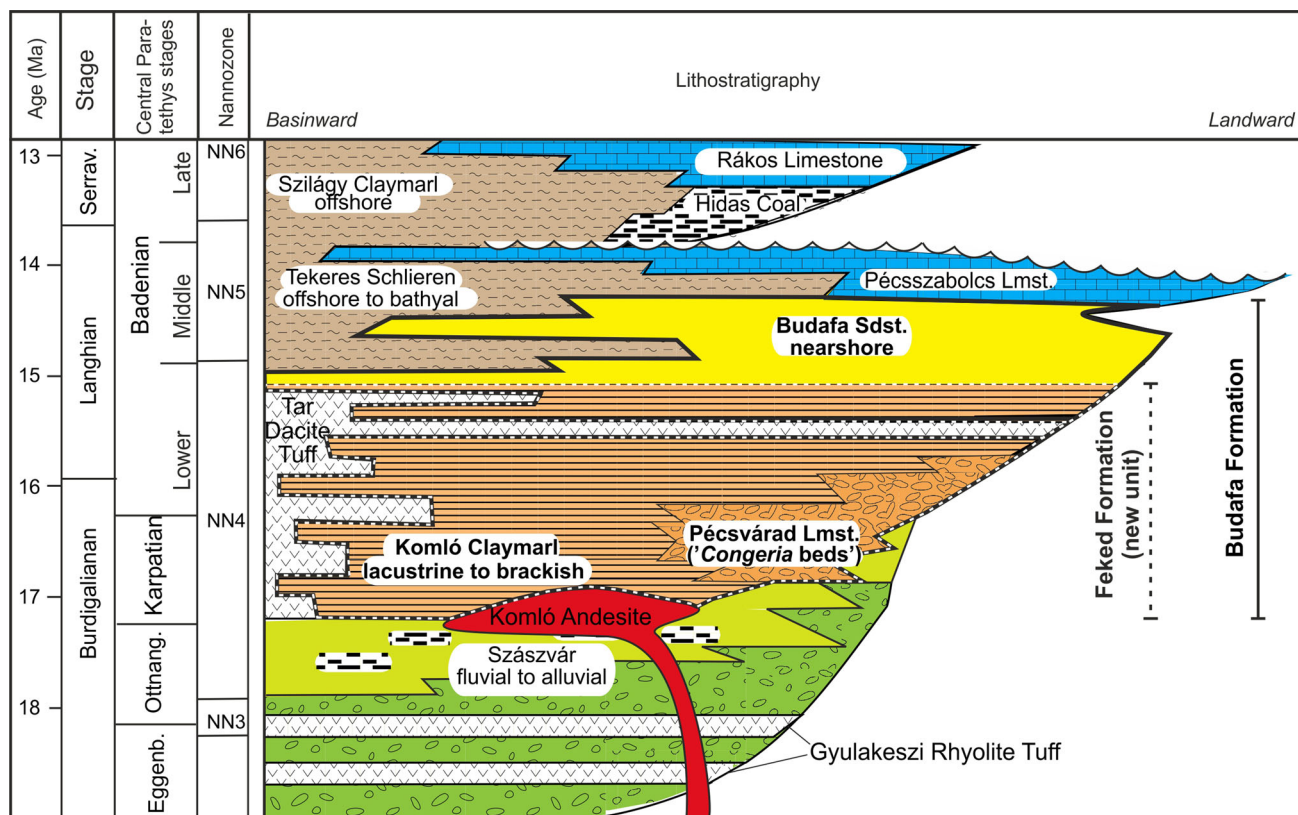
Fig. 2 Lower–Middle Miocene stratigraphic chart of the Mecsek area (after Sztanó in Sebe et al. 2015, modified). The figure was compiled using data by Hámor (1970), Chikán (1991), Báldi et al. (2002) and Barabás (2010) and modified based on own observations. The chart reflects the revised stratigraphic scheme of the area developed using data presented in this study. Feked Fm. is a new stratigraphic unit proposed in this paper. Chronostratigraphic frame of stages and zones after Piller et al. (2007) and Hohenegger et al. (2014)

interfingering transitions. In contrast, Barabás (2010) argues that practically all units from the base of the Miocene fluvial succession through the Budafa Fm. to the offshore Tekeres Fm. interfinger laterally and—with the exception of the Tekeres Fm. appearing only in the Karpatian—span the entire time interval from the Eggenburgian–Ottnangian to the Early Badenian. The fact that some papers (Hámor 1970 and especially Chikán 1991) include sediments of different lithologies and depositional environments into the same member (e.g. fluvial + lagoonal, fluvial + marine), mostly based on their contemporaneous deposition, further complicates the picture. The stratigraphic chart of Fig. 2 reflects the view of the authors of this paper and has been created by modifying these previous models based on own work. The arguments behind the relationships displayed in the chart are described in Sect. 4.

3 Methods

Representative sites distributed across the mountains and along the stratigraphic column were chosen for examination. Typical lithologies were described and the stratigraphic relationship of the outcrops observed. If tectonic deformations—faults, folds, fissures—were present in an outcrop, they were measured with compass and documented. In addition, as part of an applied research project related to radioactive waste disposal, detailed surface geological mapping at a 1:10,000 scale was carried out in a part of the western Mecsek Mts. (Fig. 1b), where Cenozoic sediments are mostly represented by the Szászvár and Budafa Formations. To investigate vertical and lateral changes and relationships of the stratigraphic units, in addition to field work descriptions of boreholes drilled previously in the area were studied at The State Geological, Geophysical and Mining Data Store of the Mining and Geological Survey of Hungary in Budapest and Pécs.

Samples for palaeontological analyses were taken to better constrain the depositional environment, with emphasis on salinity and water depth. Macroflora was collected and analysed together with previously collected material already stored in public collections and also with published data (e.g., Staub 1882; Pálfalvy 1953, 1961; Andreánszky 1955; Hably 2001; Hably and Thiébaut 2002) to gain information on climate and topography. Habitat and vegetation types were inferred based on the

palaeoecological requirements of the found plant taxa. The recently collected macroflora has been deposited in the palaeobotanical collection of the Hungarian Natural History Museum.

Within the mapping project two samples from tuff interbeds within the Komló Claymarl were taken and measured for K/Ar dating. After mild crushing and sieving of the samples, the 0.125–0.25 mm size fraction was selected for further treatment. Biotite was separated from the feldspars and the volcanic glass by a heavy liquid (Na–polytungstate) with a specific gravity of 2.80 g/cm^3. The separated size fractions were analyzed by the K/Ar method following the procedure of Balogh (1985) in the K–Ar laboratory of the Institute for Nuclear Physics, Hungarian Academy of Sciences, Debrecen. The potassium content was measured on 50 mg sample aliquots after dissolution by HF and HNO$_3$, by a Sherwood-400 type flame spectrophotometer with an accuracy better than $\pm$ 1.5%. Sample splits were subjected to heating at 100 °C for 24 h under vacuum in order to remove atmospheric Ar contamination that adsorbed on the surface of the mineral particles. Argon was extracted from the minerals by fusing the samples by high frequency induction heating at 1300 °C. The released Ar was cleaned from the active gases (H$_2$O, CO$_2$ etc.) in two steps in a low-blank vacuum system by St-700 and Ti sponge getters. The isotopic composition of the spiked Ar was measured by a Nier-type mass spectrometer. The atmospheric Ar ratio was analyzed each day during the measurement period and averaged 295.9 $\pm$ 1.85 (1σ) for 60 independent determinations. This value is not significantly different from the theoretical one (295.5; Nier 1950). All isotope measurements were corrected by the atmospheric ^{40}Ar/^{36}Ar ratios determined on the day of the analysis. The accuracy and reproducibility of the isotope ratio measurements were periodically controlled by the Rodina 2/65 internal standard for which the radiogenic ^{40}Ar content averaged 13.79 $\pm$ 0.12 (2σ) $\times$ 10^{-6} cm^3 g^{-1} STP after five independent determinations. The recommended value is 13.71 $\times$ 10^{-6} cm^3 g^{-1}. The decay constants recommended by Steiger and Jäger (1977) were used for age calculation with an overall error of $\pm$ 2%.

4 Results

Observations of the spatial relationship of the rock bodies belonging to the three members of the Budafa Formation both in the field and in borehole documentations showed that the first two members—Pécsvárad Limestone and Komló Claymarl—are closely related. This is further supported by the results of palaeontological analyses. The first two members will therefore be presented and evaluated together. They will be described in detail to help to infer the palaeoenvironment and the processes related to the initiation of the major extensional deformation. The third member, Budafa Sandstone is distinct from the previous two considering both its distribution and its depositional environment. As this member is unambiguously normal marine, it will only be briefly presented and its age discussed. In agreement with Barabás (2010), we only classify sediments into the same stratigraphic unit if their lithofacies are similar and they indicate the same depositional environment. Therefore e.g., fluvial sediments are not included in any of the members presented here even if this was the case in some previous papers, but are classified into the Szászvár Formation. Contemporaneous fluvial and lacustrine sediments are handled as two interfingering stratigraphic units.
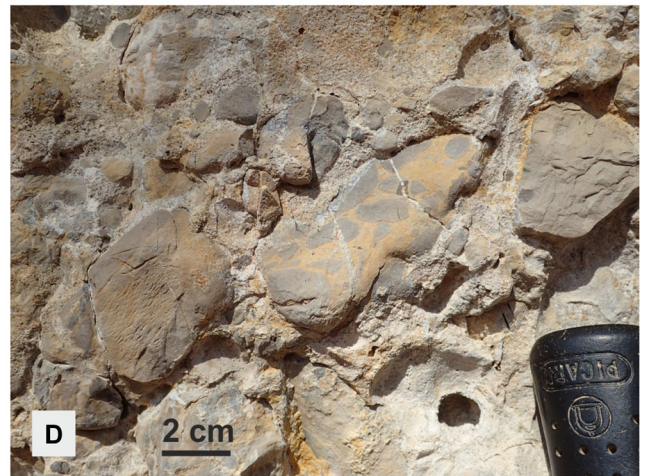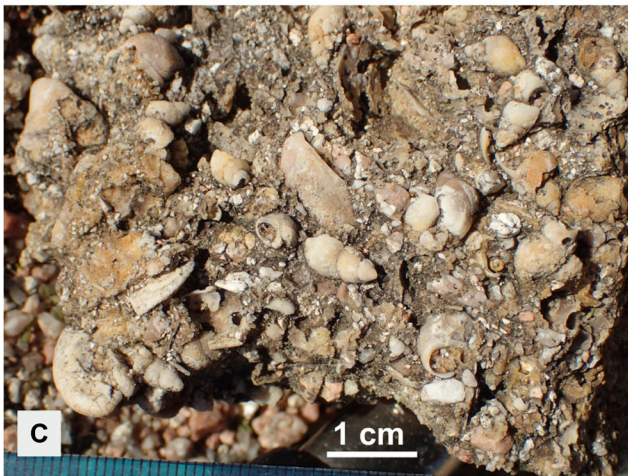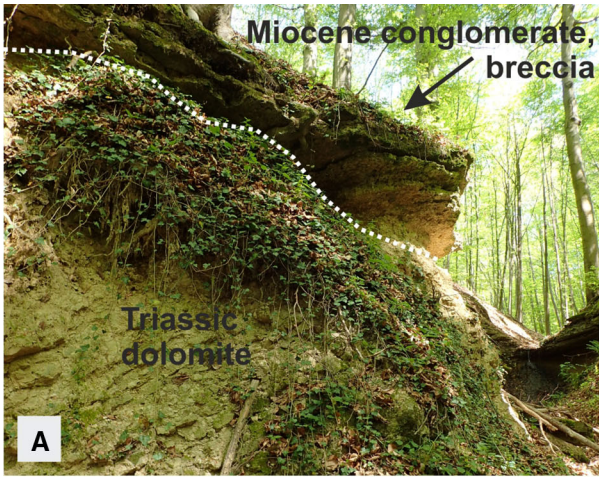
4.1 Pécsvárad and Komló members

4.1.1 Lithology and stratigraphy

Usually these two stratigraphic units can be relatively well separated based on lithology. In marginal positions they often interfinger.

The Pécsvárad Limestone is typically a few to 15–20 m thick and contains coarse sediments: conglomerate, gravel, coarse sand(stone) and *Congeria* and *Ferebithynia* (*Bulimus*) mollusc coquinas (Fig. 3). It overlies either basement rocks or—especially in the NW and NE part of the area—Lower Miocene fluvial gravels and sands. Its lithology depends on the underlying rocks: in the main body of the Mecsek Mts. with widespread Mesozoic limestones it is mostly (bioclastic) limestones and carbonate conglomerates, while above the strongly weathered and easily disintegrating granitoid rocks of the Mórágy Block in the east it is made up of coarse, immature, only briefly transported sands with coquinas. At some sites in the NW the unit may interfinger with the older Miocene fluvial gravels and sands in the form of *Congeria* beds appearing repeatedly in the fluvial succession. The good sorting of conglomerate and sand beds, their frequent alternation with each other and with similarly well-sorted coquinas, the dominantly good rounding of the coarse clastics with only subordinate breccia beds within the conglomerates, the parallel or subparallel bedding planes and occasional cross-bedding indicate a high-energy, littoral environment.

The Komló Claymarl is dominated by grey clayey silt and clay marl, with subordinate amounts of sand (Fig. 3). It may follow Lower Miocene fluvial sediments, or rests on older—pre-Cenozoic—formations. In the latter case it either has a few metres of coarse basal sediments in the form of the Pécsvárad Limestone and the fine deposits develop from the coarse ones after an alternating transition, or the clay marls directly overlay the basement rocks.

Panel A: Miocene conglomerate, breccia; Triassic dolomite

Panel B: mollusc coquina; granite sand

Panel C: 1 cm

Panel D: 2 cm

Panel E: siltstone; fine sandstone

Panel F: claymarl; dacite tuff; claymarl

◄ **Fig. 3** Typical appearance and lithofacies of the Pécsvárad Limestone and Komló Claymarl Members. Pécsvárad Mb.: **a** Conglomerate and breccia resting unconformably on basement carbonate rocks (Abaliget); **b** coarse sand and mollusc coquina, typical over granitic basement (Lovászhetény); **c** coquina of *Congeria* and *Ferebithynia* (*Bulimus*) shells with granite pebbles (Feked); **d** limestone conglomerate derived from the directly underlying basement rocks (Abaliget). Komló Mb: **e** massive carbonate-cemented siltstone and fine sandstone (Abaliget); **f** dacite tuff interbedd in massive claymarl, sampled for K/Ar dating (Abaliget)

Upwards this unit is covered by sands and silts of shallow- or deepwater marine formations (Budafa Sandstone along the margins or Tekeres Fm. in the basins). The thickness of the Komló Claymarl is a few tens of metres next to the mountains, while it can reach 400–600 m in boreholes in the basins. The unit contains the same molluscs as the Pécsvárad Limestone, either scattered or as separate beds. Near the shores several dm thick massive coquinas also occur. The fine grain size, the thick, structureless and homogeneous clay marl and silt beds and the typically scattered occurrence of fossils refers to low-energy, sublittoral environment. Intercalated sand beds and layers made up of molluscs indicate occasional transport from shallow waters.

The two members together overlie both the Lower Miocene fluvial deposits and basement rocks, indicating that they are younger than the fluvial sediments. In the NW part of the Mecsek Mts. the interfingering of the Pécsvárad Mb. with the fluvial clastics and the stratigraphic relationships of interbedded tuff horizons suggests that here fluvial sedimentation continued longer than elsewhere, contemporaneously with the deposition of the Pécsvárad Mb. To better support this idea, more radiometric datings of the pyroclastics will be necessary.

4.1.2 Fossils

Micropalaeontological samples from both units contained almost exclusively ostracods. The ostracod assemblage is of low diversity and comprises *Heterocypris* (?) sp., *Heterocypris* cf. *salina* (Brady), *Cyclocypris* (?) sp., *Candona* sp., *Candona* (*Pseudocandona*) sp., *Candonopsis* sp., ostracoda indet. (probably gen. nov., sp. nov.). Some specimens are very similar to those determined as the recent taxon *Heterocypris* cf. *salina* (Brady). The *Candona* (*Pseudocandona*) sp. specimens resemble those found in the ostracod assemblage in the Lower Badenian freshwater sediments in the Eastern Alps (Aflenz Basin; Zorn and Coric 2011, Figs. 15–18). Another taxon identified as *Candonopsis* sp. shows great similarity to the *Candonopsis* sp. specimens reported from an Ottnangian–Karpatian rich fresh- or brackish water ostracod assemblage in the North

Croatian Basin (Mt. Požeška Gora, Sadovi section; Hajek-Tadesse et al. 2009, Fig. 5/7). A peculiar, decorated taxon (Ostracoda indet.) occurred in several of our outcrops (Fig. 4b). It is different from published taxa, probably endemic to the Mecsek area and it is considered to represent a new genus. Its description is in progress. Based on these taxa, a freshwater or slightly brackish (oligo-/meso-haline), littoral environment can be assumed for the sediments (Meisch 1998).

The mollusc fauna has a very low diversity and is dominated by two taxa: *Congeria boeckhi* and *Ferebithynia* (originally *Bulimus*) *vadászi* (Fig. 4c, d). Their original descriptions were given by Wenz (1931) from the Feked and Geresd localities and they are considered to be endemic to the Mecsek region. Holotypes of the two species are deposited in the Collection of the Mining and Geological Survey of Hungary. These two molluscs often occur in rock-forming quantities making up coquina beds. The shells are generally poorly preserved in limestones. In many layers they occur as moulds, or locally both moulds and shells are found. The shells are sometimes recrystallized. In silts and clay marls the shells can be well-preserved. Hámor (1970) mentioned unidentified *Congeria* species accompanying *Congeria boeckhi*. We also found a few, more elongated, drop-shaped specimens belonging to the *Congeria* genus, but their poor preservation did not allow their classification. Small specimens of poorly preserved *Gyraulus*? sp. and *Stagnicola*? sp. have also been encountered. Further taxa mentioned in the literature are *Theodoxus* sp. and thin-shelled and worn fossils of *Brotia* sp. (Hámor 1970; Nagymarosy and Hámor 2012). The large number of specimens with respect to the low diversity of the fauna indicates fresh or maximum slightly brackish water.

Among the vertebrate fossils, fish remains are most common, including dominantly scales and single bones or bone fragments (Fig. 4e, f). Otoliths or articulated skeletons occur sporadically. Further vertebrate remains were reported from the sandstone and *Congeria* beds of the Mórágy Hills (Erdősmecske-Feked) (Vadász 1935; Kordos 1985): *Testudo* and *Tryonix* sp., Crocodilus indet., *Aceratherium* sp., *Brachypotherium brachypus*, *Rhinoceros* sp., *Dorcatherium* sp., *Eocerus* (*Eotragus*) *cristatus*. Although the finding site is not exactly known, a *Zygolophodon turicensis* tooth found near Erdősmecske (Gasparik 2001) most probably also comes from these beds. The fish remains have not been investigated yet. The reptilian and mammal assemblage only includes terrestrial and freshwater taxa.

A rich macroflora is preserved in the Komló Claymarl (Fig. 5). It comprises mainly remains of gymnosperms and angiosperms and is dominated by the latter; tiny fossils of
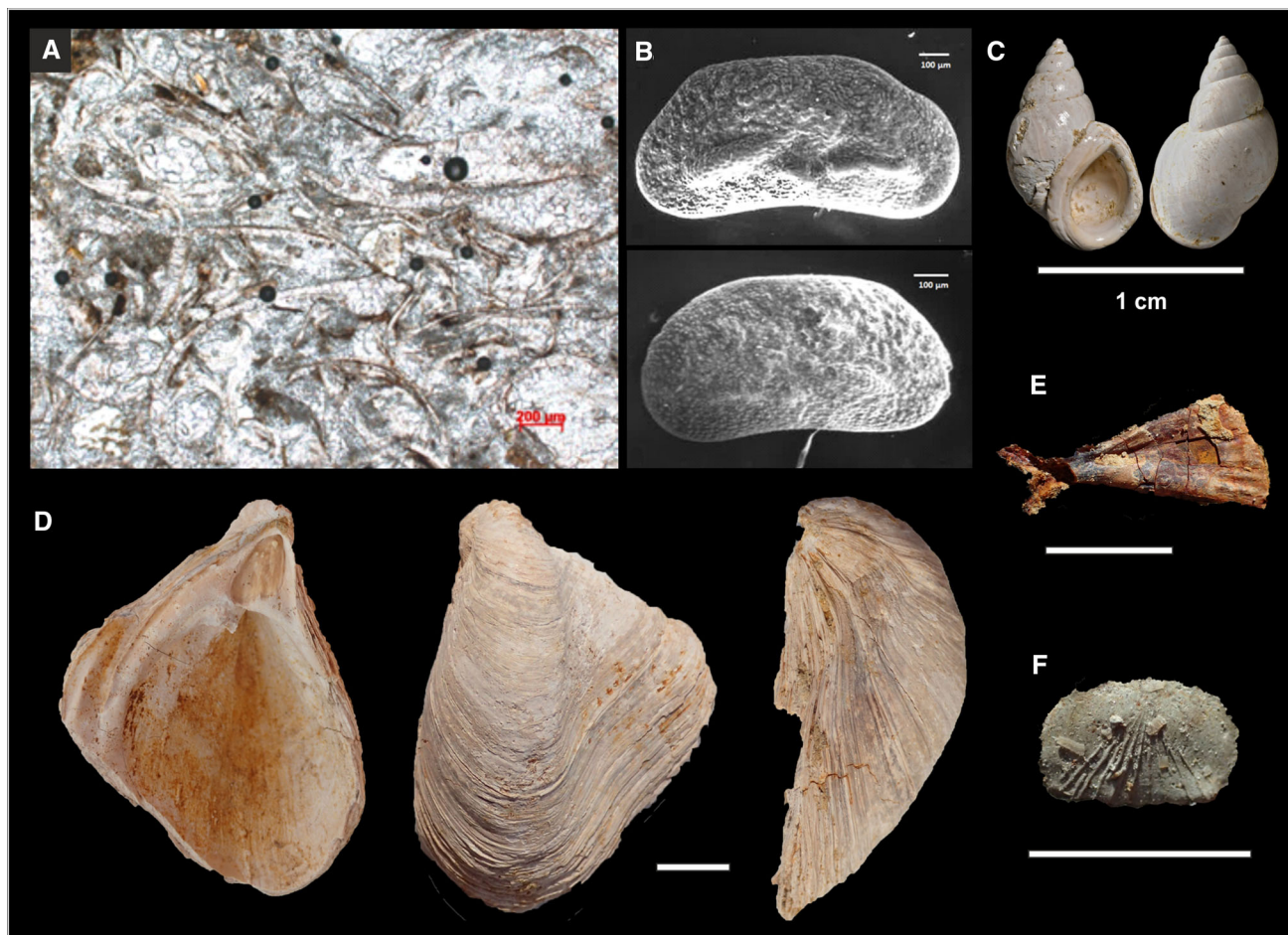
Fig. 4 Faunal representatives of the lacustrine sediments. **a** Ostracod shells (Lovászhetény); **b** left and right valve of ostracoda indet. (n. g., n. sp.) (Lovászhetény); **c** *Ferebithynia* (*Bulimus*) *vadászi* (Geresdlak); **d** *Congeria boeckhi* (Feked); **e, f** fish bone and scale (Abaliget). Scale bar is 200 μm in **a**, 100 μm in **b** and 1 cm in all other figures

ferns or horsetails occur very rarely. Four main vegetation types could be distinguished in the area.

1. The zonal vegetation indicates mesophytic habitats and was formed of subxerophytic plants tolerating slightly dry conditions. The most important elements in this vegetation were *Zizyphus paradisiaca*, the Fabaceae family (*Podocarpium podocarpum*, *Leguminocarpum mecsekense,* Leguminosae gen. et sp.), *Cedrelospermum* and *Ailanthus*. Presumably instead of a closed canopy forest a more open, savanna-like vegetation was formed, suggested by the dominant arboreal species having winged (probably anemochorous) seeds.

2. At higher elevations and probably closer to the shore, mesophytic vegetation requiring more humid conditions occurred. These were thermophilous pine forests, analogous to the vegetation model of the modern Canary Islands, below which laurel forests could be reconstructed. The latter comprised members of the Lauraceae family, i.e., *Daphnogene*, *Laurophyllum*, and a member of the Juglandaceae family, the thermophilous *Engelhardia*. Presumably, *Smilax* as a liana and palms also lived in this vegetation.

3. Swamp vegetation included arboreal as well as herbaceous plants. The main woody elements were *Glyptostrobus europaeus, Myrica lignitum* dominating the shrub layer and *Nyssa*. Close to open water herbaceous monocots must have prevailed.

4. Another edaphic vegetation type was the riparian. Vegetation on the lower floodplains was formed of *Populus* and *Carya* whereas on higher levels by *Acer* and *Ulmus* forests.

The high ratio of the definitely thermophilous, palaeotropical elements is noteworthy in the zonal vegetation, for instance *Daphnogene*, *Laurophyllum*, *Engelhardia*, *Cedrelospermum*, *Ailanthus,* and species belonging to the Fabaceae family, which occur in the flora as dominant or frequent accessory elements. They indicate that the climate must have been warm subtropical. The subtropical laurel forest and the deciduous forest with moderate
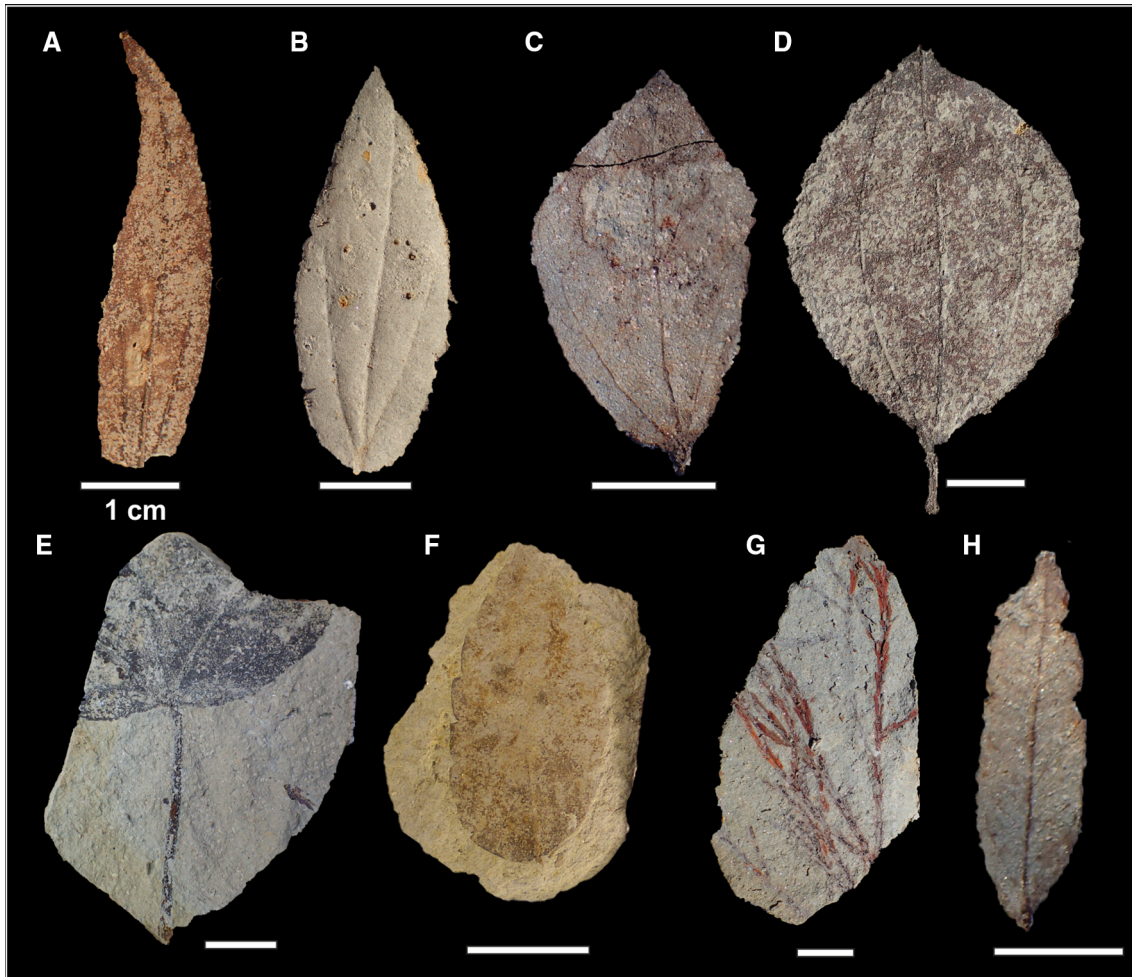
Fig. 5 Selected macroflora from the lacustrine deposits. **a** *Daphnogene cinnamomifolia* forma *lanceolata*, **b**, **c** *D. cinnamomifolia*, **d** *Zizyphus paradisiaca*, **e** *Liquidambar europaea*, **f** *Zelkova zelkovifolia*, **g** *Glyptostrobus europaeus*, **h** *Podocarpium podocarpum*

rainfall demand indicate that humid and dry periods alternated within the year. At the same time it was not a completely dry climate, the dry periods must have been followed by rainy seasons with abundant rainfall which provided enough humidity for both the swamp-riparian and the zonal vegetation.

In the recently collected material swamp plants like *Glyptostrobus europaeus* and *Myrica lignitum* occurred only sporadically. This points to the restricted areal distribution of low-relief coastal plains at least in the western Mecsek area. The two zonal vegetation types preferring different, partly higher elevations also indicate that the relief must have been dissected, even close to the shores.

4.1.3 Age data

The Pécsvárad and Komló Members contain no biostratigraphically relevant fossils. Nagymarosy and Hámor (2012) classify the Komló Claymarl as earliest Badenian based on a single sample yielding NN4 zone nannoflora;

they cite a personal communication and there is no information about the location or the exact taxonomic composition of the sample.

K/Ar ages measured previously on dacite tuff interbeds in the Komló Claymarl have relatively high uncertainties. Data from the Mecsek area range from 17.1 to 15.0 Ma, with errors of > 2 Ma (Hámor et al. 1979; Table 1). In the borehole Tengelic-2 $\sim$ 30 km NE of our study area, K/Ar ages from the > 300 m thick rhyolite and dacite tuff accumulations below the Komló Claymarl range from 16.0 ± 0.7 to 13.8 ± 0.7 Ma (Halmai et al. 1982). The isochron diagram constructed from the archive data (Fig. 6.) suggests an age of 15.5 ± 0.5 Ma. However, the measured ages are not in stratigraphic order, and—after another, not dated tuff interval—the clay marl is overlain by biostratigraphically dated Badenian sediments, thus caution must be taken when using these age data. From the two samples we took from tuff interbeds in the Komló Claymarl during this study, one was inappropriate for measurement due to post-sedimentary alteration. The other

Table 1 Published and newly acquired radiometric ages from tuff horizons in the Komló Claymarl

Locality/Borehole	Depth (m)	Mineral	K (%)	40Ar$_{rad}$ (ccSTP/g)	r (%)	Age (Ma ± 1σ)	References
Tengelic (T-2)	872.5	Biotite	6.57	4.21E−06	0.5	16.0 (0.7)	Halmai et al. (1982)
Tengelic (T-2)	899.2	Biotite	7.00	4.12E−06	0.22	14.7 (1.0)	
Tengelic (T-2)	926	Biotite	7.09	3.91E−06	0.41	13.8 (0.7)	
Tengelic (T-2)	949.6	Biotite	6.54	3.77E−06	0.46	14.9 (0.7)	
Tengelic (T-2)	979	Biotite	7.23	4.38E−06	0.57	15.1 (0.7)	
Tengelic (T-2)	995.7	Biotite	7.16	4.27E−06	0.35	14.9 (0.8)	
Tengelic (T-2)	1019	Biotite	6.72	4.02E−06	0.45	15.0 (0.7)	
Tengelic (T-2)	1061	Biotite	6.58	4.09E−06	0.51	15.6 (0.7)	
Tengelic (T-2)	1090.6	Biotite	6.88	4.15E−06	0.66	15.1 (0.6)	
Tengelic (T-2)	1133	Biotite	6.47	4.09E−06	0.13	15.8 (1.7)	
Tengelic (T-2)	1165.5	Biotite	6.06	3.88E−06	0.57	16.0 (0.7)	
Pécs-Vasas railroad cut		Biotite	4.59	2.84E−06	0.11	16.2 (2.2)	Hámor et al. (1979)
Zengővárkony-33	108.5–110	Biotite	5.46	3.65E−06	0.12	17.1 (2.4)	
Zengővárkony-33	108.5–111	Plagioclase	0.61	3.77E−07	0.18	16.0 (1.9)	
Abaliget, SK-062-2		Biotite	6.52	4.28E−06	0.37	16.8 (0.6)	New radiometric age

Fig. 6 Isochron diagram constructed from archive and new radiometric age data of tuff horizons in the Komló Claymarl
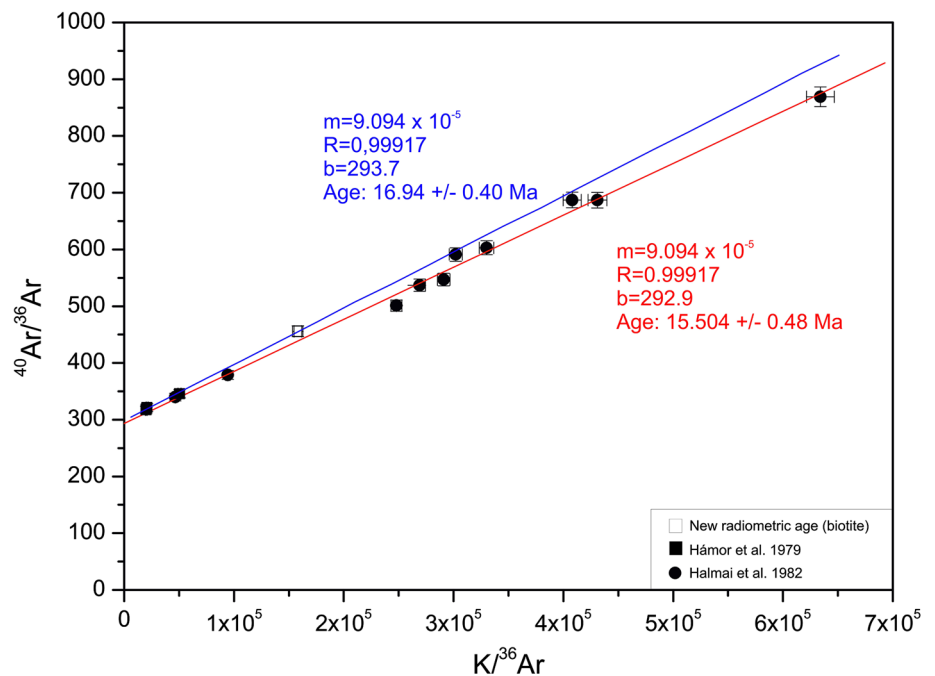
one (taken from the tuff horizon on Fig. 3f) gave an age of 16.82 ± 0.65 Ma, i.e., a Karpatian (late Burdigalian) age (Table 1). Plotting the new radiometric age on an isochron diagram with the archive ages of Hámor et al. (1979), the data provide and isochron age of 16.9 ± 0.4 Ma. The intercept of the isochron at 293.7 indicates that no secondary processes (weathering, hydrothermal alteration) affected the dated mineral samples and the calculated age can be accepted as a true geological age.

4.1.4 Structural observations

It was possible to observe structural features both in the Pécsvárad and Komló Members from which syn-sedimentary faulting can be inferred.

The spatial arrangement and thickness distribution of sediments may be influenced by the existence of syn-sedimentary faults. The coarse clastics of the Pécsvárad Mb. are usually only a few metres thick, but at some locations

next to basement outcrops they attain a thickness—sometimes together with some clay marl interbeds—as much as 80–100 m. In a cross-section constructed across these exposures it is visible that the thickening is local: laterally conglomerates attenuate and change into the fine sediments of the Komló Claymarl (Fig. 7). In such situations the wedge-shaped conglomerate body can be interpreted either as a "scarp breccia" that formed in front of a fault plane, or simply as a clastic wedge that accumulated along the steep, fault-controlled side of the basin.

Faulting-influenced sedimentation can also be inferred in the east, in the Mórágy Block, where the Pécsvárad Mb. is composed mostly of coarse granite sand and gravel. Here a quarry exposed the very base of the Miocene sequence. Careful mapping of the otherwise strongly weathered rocks revealed that the basal contact of the Miocene with the basement is sedimentary, while laterally the rocks are separated by steep faults (Fig. 8). Next to the fault planes, within a distance of a few metres, the Miocene sand contains angular granite blocks. Angular shape indicates little or no transport, thus the blocks should originate from the disintegration of the fault scarps. After the long denudation period indicated by the gap below the Miocene sands, it can be excluded that older fault scarps survived on the easily weathering granite, therefore the presence of fault

scarp breccias must refer to the syn-depositional activity of the faults.

Small-scale pre-diagenetic deformations can be observed in the western part of the Mecsek Mts., in the Nyáras Valley south of the village Abaliget, where several outcrops expose deformed sediment packages of the Pécsvárad Limestone (Fig. 9). Within a strongly tilted to vertical succession made up of alternating conglomerate and sandstone beds, regularly spaced open fractures are present. These cracks only cut the conglomerate beds and do not continue into the sandstones (Fig. 9b). Within the conglomerates the cracks are irregular: they run among the clasts, the pebbles themselves are not fractured (Fig. 9c). These features show that formation of the cracks happened when the sediment was not yet fully cemented but was in a semi-consolidated state. Considering the typically fast cementation of littoral conglomerates, this can be interpreted as syn-sedimentary (pre-diagenetic) deformation. Open cracks refer to local extension. This may be caused either directly by faulting, or indirectly, by seismically triggered slope instability. Strong tilting of the beds is attributable to later, post-sedimentary events related to basin inversion.

Tensional fractures related to the Komló Claymarl also occur. In a nearby outcrop 2–15 cm wide irregular cracks
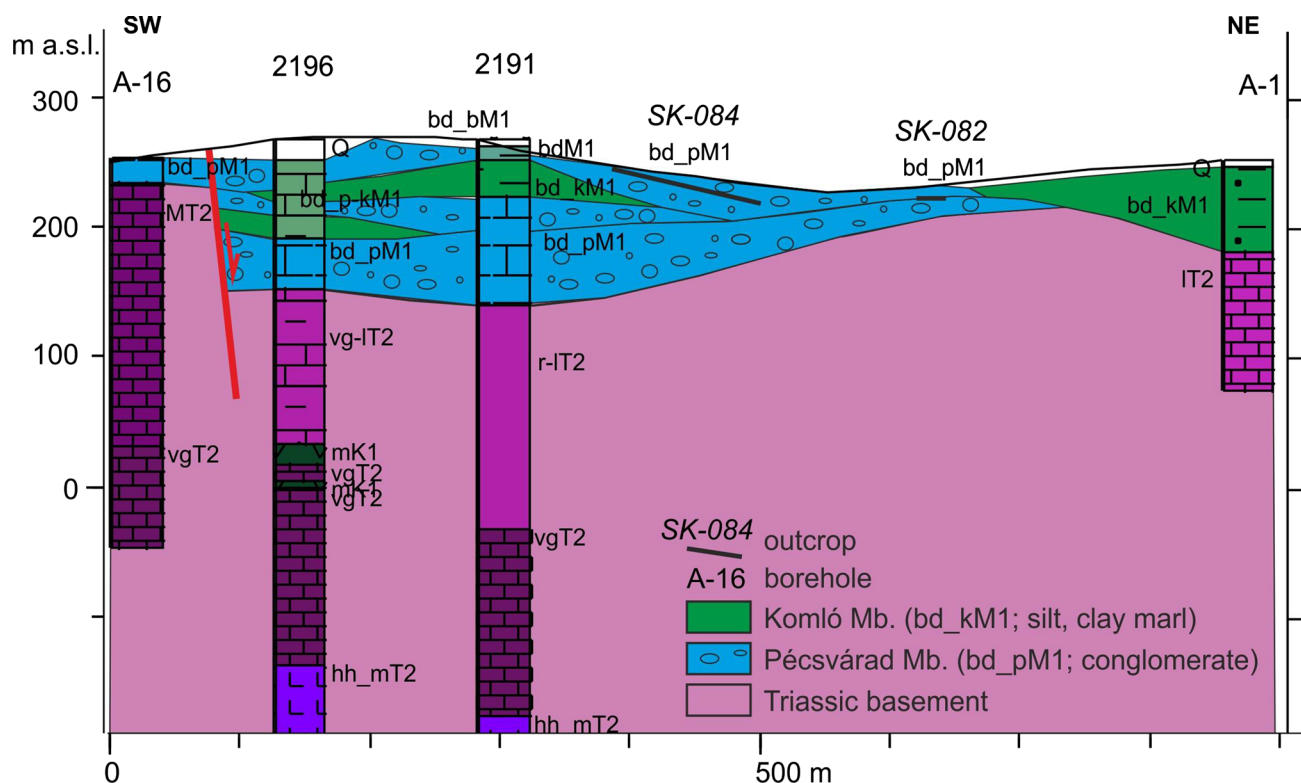

Fig. 7 Geological cross-section in the western Mecsek (SW of the village Abaliget) showing fault-related local thickening of the littoral lacustrine deposits. For the location of the cross-section please see

Fig. 1b. Legend: *hh_mT2, vgT2, vg-lT2, lT2, r-lT2, MT2* Triassic formations, *mK1* Lower Cretaceous basalt dyke
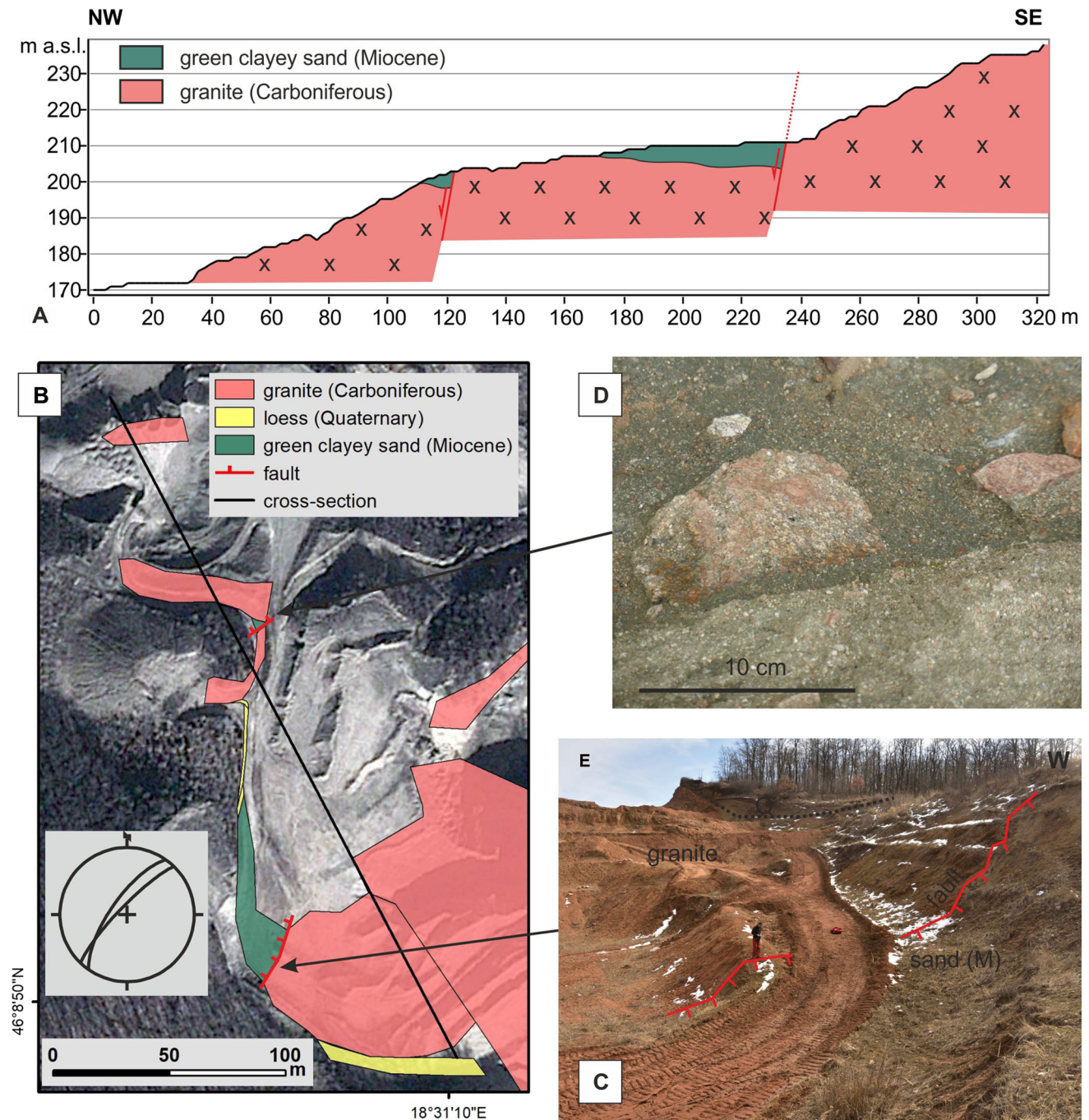
Fig. 8 Tectonic contact of the Miocene basal lacustrine sediments with the crystalline basement (Geresdlak, granite quarry). **a** Cross-section of the quarry and **b** its location in a map with observed outcrops over GoogleEarth satellite image; stereoplot shows orientation of the boundary faults between Carboniferous and Miocene rocks; **c** tectonic boundary in outcrop (see person in centre for scale); **d** granite blocks in the Miocene sand next to a fault plane. For the location of the map area please see Fig. 1b

occur in Middle Triassic dolomites, filled by dolomite fragments and by the clay marl directly overlying the dolomites (Fig. 9f, g). Although there is no direct and unequivocal evidence that these tensional fractures formed during the deposition of the clay marl and not later, their occurrence near the previously described syn-sedimentary deformations makes this probable.

4.2 Budafa sandstone member

4.2.1 Lithology and stratigraphy

The Budafa Sandstone consists of coarse-grained sediments, i.e., yellowish-grey, massive or cross-bedded sand, sandstone, and—often polymictic—gravel and
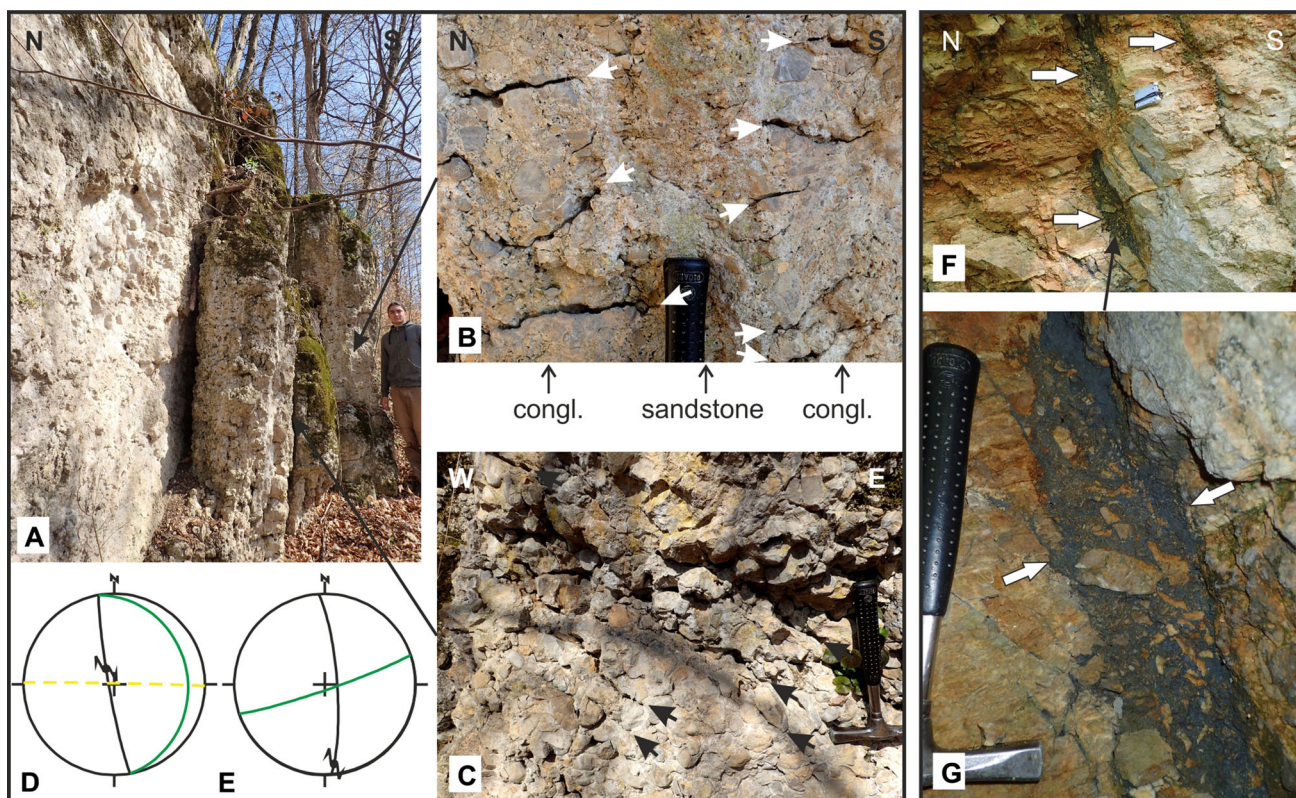
Fig. 9 Structural features in the lacustrine deposits in the western Mecsek. **a** Vertically tilted conglomerate-sandstone succession of the Pécsvárad Limestone Mb. with syn-sedimentary tensional cracks (Abaliget). **b** Cracks (shown by arrows) only cut the conglomerate beds and do not continue into the sandstones. **c** Cracks (shown by arrows) in the bedding plane of a conglomerate bed running between the clasts. **d** Present orientation of cracks (green solid line) and bedding (yellow dashed line). **e** Original orientation of cracks acquired by backtilting with bedding. **f, g** Tensional fractures in Middle Triassic dolomite filled with the directly overlying Komló Claymarl (Abaliget)

conglomerate, with a maximum thickness of 400–700 m. It is recognised by the presence of normal marine micro- and macrofauna. It is the uppermost member of the Budafa Formation and has a large areal distribution: it can overlie both previous members, Lower Miocene fluvial sediments or the basement. Laterally it interfingers with the offshore Tekeres Fm. towards the basins, while upwards it grades into Leitha limestones. Its boundary with the Miocene units is typically interfingering.

4.2.2 Fossils and age

In agreement with previous literature, we found a well-preserved and diverse microfauna in our micropalaeontological samples: besides foraminifers and ostracods, red algae and colonial coral fragments were present, as well as mollusc shell fragments (Fig. 10). Based on the common occurrence of *Amphistegina hauerina* d'Orb., *Heterostegina costata* d'Orb. (larger foraminifer) and *Flexus reussianus* Ruggieri (ostracod) assemblages, deposition of the sediment took place in the Badenian (Brestenska and Jiricek 1978; Cicha et al. 1986; Gross 2002). The microfossil assemblage indicates a nearshore, littoral/infralittoral (< 70–100 m depth) sedimentary environment characterised by wave-agitated, normal salinity water and a tropical/subtropical climate (Gross 2002). This is further supported by the macrofauna, which typically includes pectinids, ostreids, boring clams and colonies of coralline algae and bryozoans. The Budafa Formation as a whole is traditionally considered to be of Karpatian age, even in most recent literature (Gyalog 1996; Gyalog and Budai 2004; Budai et al. 2015). However, neither the new micropalaeontological analyses nor the revision of archive fossil lists (Hámor 1970; Chikán 1991) demonstrated forms proving a Karpatian age. Therefore it is concluded that the deposition of the Budafa Sandstone and the marine flooding of the area happened in the Badenian. As taxon lists of the microfauna are dominated by benthic foraminifers having broad temporal ranges, most of them spanning the Badenian, and age-indicating planktonic species are missing, it is not possible to confine the age more precisely. *Orbulina* species appearing in some of the taxon lists of Hámor (1970) indicate that the accumulation of the Budafa Sandstone lasted at least until the Middle Badenian.
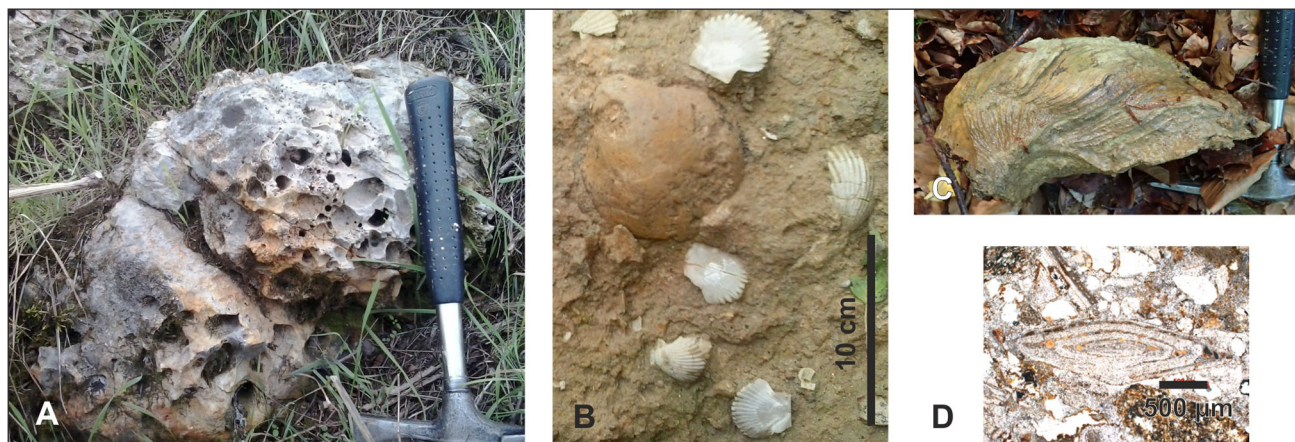
Fig. 10 Fossils from the marine sediments. **a** Traces of boring clams; **b** glycymeris and pectinids, **c** *Crassostrea gryphoides* (**a–c** Hetvehely), **d** *Amphistegina hauerina* (Abaliget)

5 Discussion

5.1 Stratigraphy and palaeoenvironment of the lacustrine phase

Palaeontological data and the spatial relationship of the first two members of the Budafa Formation—Pécsvárad Limestone and Komló Claymarl—indicate that their deposition happened under similar palaeoenvironmental conditions.

The coarse sediments—wave-abraded conglomerates, coarse sands, mollusc coquinas—of the Pécsvárad Limestone represent the basal, transgressive littoral sediments of the same water body which deposited the silts and clay marls of the Komló Mb. in deeper and/or more open water. The absence of marine forms in the Pécsvárad Limestone and in the overwhelming portion of the Komló Claymarl indicates that these waters were not connected to normal salinity seas. Rocks of these two stratigraphic units are therefore no lagoonal sediments and do not indicate the onset of marine transgression (as previously stated by Hámor (1970), Barabás (2010) and Nagymarosy and Hámor (2012)), but are lacustrine deposits. The few layers with poorly preserved foraminifers reported from thick offshore successions of the Komló Claymarl (Hámor 1970) may indicate short-lived, temporary marine incursions. This is in accord with the observed interfingering transition between the clay marl and the overlying marine deposits; still, the Komló Mb. as a whole is interpreted principally as lake sediment.

The identity of faunas in the presently patchy occurrences of the lake sediments suggest that a contiguous water body and not a system of smaller lakes existed in the area. From here on, we will call this water body "Lake Mecsek". The expression appeared in the paper of Neubauer et al. (2015) with reference to Wenz (1931), and

although Wenz himself did not talk about a certain lake, we find this name useful and descriptive. The age of lacustrine sedimentation is hard to constrain exactly due to the endemicity of the fauna. The new K/Ar age of 16.82 ± 0.65 Ma and biostratigraphic dating of the overlying marine deposits described above indicate a Karpatian to Early Badenian age for the lake.

The Pécsvárad and Komló Members are both interpreted as lake deposits. To be able to handle these two closely related units together and to differentiate them from the marine deposits of the overlying Budafa Sandstone Mb., it would be better not to include all three units in the same formation, but split the first two as a separate formation. For the name of the new stratigraphic unit, we propose Feked Formation (Fig. 2), from the settlement around which both the *Congeria* beds and the clay marls have good outcrops and from which area Wenz (1931) described the two endemic molluscs dominating the macrofauna of the unit. With this split, the Budafa Sandstone would rise to the formation level. This proposal is currently under discussion in the Stratigraphic Committee of Hungary.

5.2 Tectonic and climatic controls on sedimentation

The thickening of deposits next to a fault and wedge-shaped clastic bodies are classic examples of syn-sedimentary faulting, as also described in other studies (e.g. Andrić et al. 2017). Pre-diagenetic (soft-sediment) deformations and fault scarp breccias in the lake deposits also refer to syn-sedimentary extensional movements. These features indicate that the creation of accommodation space was fault-controlled. Lacustrine deposits overstepping onto previously uncovered basement in addition to overlying the Lower Miocene fluvial succession speak for extensive flooding of the area. The direct contact between the

basement and the Komló Claymarl observable at numerous locations, without the coarse littoral sediments of the Pécsvárad Limestone in between, indicates sudden lake level rises. Faults probably not only created the lake basin(s) but also produced a generally rugged relief: a dissected topography is further supported by the vegetation types. Although more examinations are needed, the local thickening of coarse conglomerates in front of faults and the increasing ratio of fine sediments away from them suggest that the lake basins might have been asymmetric. This is typical of the syn-rift phase and has been documented at many sites in the region (e.g. Tomljenović and Csontos 2001; Matenco and Radivojević 2012; Andrić et al. 2017; Balázs et al. 2016, 2017).

From field and seismic section studies of the under- and overlying rock units Csontos et al. (2002) inferred moderate N–S convergence and strike-slip faulting in the otherwise subsiding Mecsek area. Strike-slip motion is characteristic of the entire evolution of the Pannonian Basin (Horváth 2007; Horváth et al. 2006), and transtension has also been proposed for the Early to Middle Miocene tectonic evolution of the Mecsek area (Tari 1992; Benkovics 1997). Our observations do not exclude a lateral kinematic component. The lake basins do not point to convergence, but seem to have been formed under a regime having a clearly extensional component, with or without strike-slip movement. More investigations are needed to clarify the style of deformation.

Beside tectonic processes, climate can also control lake formation through increased humidity and a positive shift in the water balance. A climatic trigger has been demonstrated for the creation of some Dinaride lakes (e.g. Lake Gacko; Mandic et al. 2011), and supposed to have played a role in the initiation of the whole Dinaride Lake System (Sant et al. 2017). The existence of Lake Mecsek temporally overlaps with the period of the warm and humid Miocene Climatic Optimum (17–15 Ma, Zachos et al. 2001), shown both by the above discussed age data and the presence of thermophilous biota like the subtropical vegetation or the crocodylian remains. The role of climate should therefore also be considered in lake formation. Precipitations higher than today are inferred in Central Europe from herpetological data both for the Karpatian and the Early Badenian (Böhme et al. 2011), with uniformly warm and humid conditions in the Karpatian and increased seasonality in the Early Badenian (Böhme 2003). While our macroflora data do reflect a seasonally dry climate, they do not refer to considerably increased humidity, as the zonal vegetation contains subxerophytic plants as well. The comprehensive analysis of Neogene macroflora data for the Pannonian Basin did not indicate a significantly increased precipitation for the Karpatian either (Erdei et al. 2007). Consequently, the climate can have played a role in the

initiation of lacustrine environment, but probably geodynamic processes exerted the principal control on lake formation.

5.3 Relationship with the Dinaride Lake System

As Lake Mecsek was located in the SW Pannonian Basin, it is inevitable to discuss its relationship with the southern lake systems. This relationship is not obvious based on existing literature. Krstić et al. (2012) and Harzhauser and Mandic (2008) included SW Hungary—the former even NW Hungary and E Austria—in the Dinaride Lake System. According to Mandic et al. (2012), the Mecsek area was not part of the Dinaride Lake System, but they belonged to the same (Illyrian) bioprovince. In their work on Neogene freshwater gastropod bioprovinces, Neubauer et al. (2015) classified Lake Mecsek together with the Dinaride Lake System to the Illyrian Region based on its geographic position.

From the palaeobiogeographic aspect, the mollusc fauna of the lacustrine sediments of the Mecsek is evidently highly endemic. Outside the Mecsek area, the two dominant species have only been reported from NW Hungary (Bakony Mts.), from Upper Badenian shallow lacustrine limestones overlying a coal deposit (Wenz 1931; Kókay et al. 1991; Kókay 2006). There they are accompanied by at least five other gastropod genera. *Congeria boeckhi* occurs in the Medvednica Mts. in NW Croatia—the northernmost member of the Dinaride Lake System—as well, similarly dominating the fossil assemblage as in the Mecsek (Kochansky-Devidé and Slišković 1978; Kovačić et al. 2016). Our investigations show that endemism also appears in the ostracod assemblage of the Mecsek. Thus the Mecsek area has several characteristics that have been stated as typical of the Dinaride Lake System, including the lacustrine depositional environments, the high endemicity of the faunas (molluscs as well as ostracods) and the dominance of dreissenids (Harzhauser and Mandic 2008; Harzhauser and Mandic 2010; Neubauer et al. 2015; Mandic et al. 2017). Furthermore, based on available age data, Lake Mecsek existed coevally with the lakes located directly south of Hungary: the peak period of the Dinaride Lake System covered the Karpatian–Early Badenian (Sant et al. 2017). These points suggest that Lake Mecsek was part of the Illyrian bioprovince, as suggested by Neubauer et al. (2015), and its evolution history is parallel with that of the Dinaride Lakes and of lakes of the Southern Pannonian Basin, treated separately from the Dinaride Lakes by Mandic et al. (2012). What is obviously different is the low diversity of the fauna compared to that of the southern lakes (Harzhauser and Mandic 2008; Neubauer et al. 2015).

As for the geodynamic background, Csontos et al. (2002) suggested that the Tertiary tectonic evolution of the

mountains in SW Hungary (Mecsek and Villány) resembles that of N Croatia, and invoke the northerly progression of the Adriatic plate as a driving force. Matenco and Radivojević (2012) showed that in the SW part of the Pannonian Basin the process of basin formation may have been controlled, or at least influenced, by the Dinaric orogeny, namely by subduction rollback of a Dinaric slab causing migration of extension. At present we do not possess enough data to decide if this has been true for SW Hungary as well; in this respect, future studies in the Mecsek area will be able to provide important data to better understand the evolution of the Pannonian Basin.

5.4 The end of lacustrine sedimentation

The Budafa Sandstone above the lacustrine sediments has a micro- and macrofauna indicating euhaline marine conditions, thus indicates the flooding of the area by the Paratethys. Its areal distribution is wider than that of the underlying units, referring to general subsidence of the region. Marine inundation was a result of further extension and lithospheric thinning of the Pannonian Basin (Horváth et al. 2006). Based on biostratigraphic dating of the Budafa Sandstone, this happened in the Badenian, similarly to neighbouring areas in the southern Pannonian Basin (e.g. Ćorić et al. 2009; Mandic et al. 2012).

6 Conclusions

Our study shows that in the Mecsek area the widespread Early Miocene fluvial sedimentation was not directly followed by inundation by the Central Paratethys. Instead, the two phases were separated by a period of lacustrine deposition in the Karpatian–Early Badenian (late Burdigalian–early Langhian). Lake sediments are represented by the Pécsvárad Limestone and Komló Claymarl Members of the presently used Budafa Formation. The low-diversity but abundant, endemic mollusc and ostracod fauna indicates that Lake Mecsek was a single water body covering the area of the present-day Mecsek Mts. and their surroundings. Lake basin formation can be attributed to synsedimentary tectonic movements related to rifting of the Pannonian Basin, while the accumulation of lakes was probably also enhanced by increased precipitation during the Miocene Climatic Optimum. The Central Paratethys sea flooded the area in the Badenian and deposited the normal marine Budafa Sandstone Mb. over the lake sediments. The fauna of Lake Mecsek relates it to the Illyrian bioprovince. Considering the biotic data, the sedimentary succession, the structural background and evolution history, the Mecsek area seems to be related to the Dinaride Lake System.

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