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ORIGINAL PAPER

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Evolution of the Bükk Mountains (NE Hungary) during the Middle–Late Triassic asymmetric rifting of the Vardar-Meliata branch of the Neotethys Ocean

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Abstract Based on sedimentological and biostratigraphic investigations of the Middle–Late Triassic successions of the Bükk Mountains, the evolution of an upper plate margin of a rifting area was reconstructed. The Middle Anisian shallow water carbonates are succeeded by terrestrial sediments. Simultaneously with the uplift, volcanic activity starts, indicating the beginning of the rifting. The emersion was followed by rapid subsidence in the Late Anisian–Early Ladinian which corresponds to the synrift stage. Based on facies distribution of Ladinian–Carnian sediments, the half-graben structure of the basement can be outlined. Coeval existence of platforms and basins is characteristic of this period. From the end of the Fassanian, the subsidence slows down: postrift stage. At this time the thermal cooling controls the subsidence of the area. During the Late Triassic, the edges of the platforms were gradually drowned and basins conquered bigger and bigger areas. Sediments deposited on the southern shelf of the opening Vardar-Meliata branch of the Neotethys Ocean show features characteristic to the upper plate part of a rifting area, whereas sediments of the northern shelf show features characteristic to the lower plate. The opening of the Vardar-Meliata branch of the Neotethys Ocean follows the asymmetric rifting model of Wernicke (Can J Earth Sci 22:108–125, 1985) and Dixon et al. (Tectonics 8(6):1193–1216, 1989).

Keywords Middle–Late Triassic · Rifting · Neotethys · Anisian terrestrial sediments · Platform/basin evolution

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Introduction

The Bükk Mountains are located in the NE part of Hungary (Fig. 1) and together with the Aggtelek–Rudabánya Mountains and Darnó Zone, they constitute a part of the Pelso tectonic unit (Haas 2001). There are only few mountains in Middle Europe whose Triassic formations were so little known previously as in the Bükk Mountains. The main reason for this is that the Carboniferous–Jurassic rocks of the mountains were affected by nine tectonic events after their deposition (Csontos 1988). These tectonic events affected mainly the inner part of the mountains. Accordingly, Triassic sections suitable for sedimentological analyses can be found only on the margins of the mountains. Outcrops where heteropic facies could be studied were also missing. Although the structure of the mountains is well known (Csontos 1988) and the geodynamical interpretation of the two Triassic volcanic events was carried out (Harangi et al. 1996), we had only few biostratigraphical data on the Middle–Late Triassic sedimentary series at the beginning of this research, the majority of which was based on macrofossils (Schréter 1935, 1943; Balogh 1964, 1980).

The main objective of this research was the sedimentological and biostratigraphic investigation of the Middle–Late Triassic sequences of the Bükk Mountains, the elaboration of the correlation of the platform–basin facies, and the reconstruction of the Triassic evolution of the Bükk Mountins on the basis of the above results. The Triassic evolution of the Bükk Mountins was compared with that of the other Alpine-Western Carpathian units, and fit into the rifting process of the Neotethys.

In the Triassic sections of the Bükk Mountins, it can be very well demonstrated how the changes inside the Earth (asthenosphere, crust) influence the sedimentation of a rifting area. Naturally, the outer forces, like eustatic sea level changes, the changes in the climate, and the evolutionary trends of the fauna and flora, etc. also have

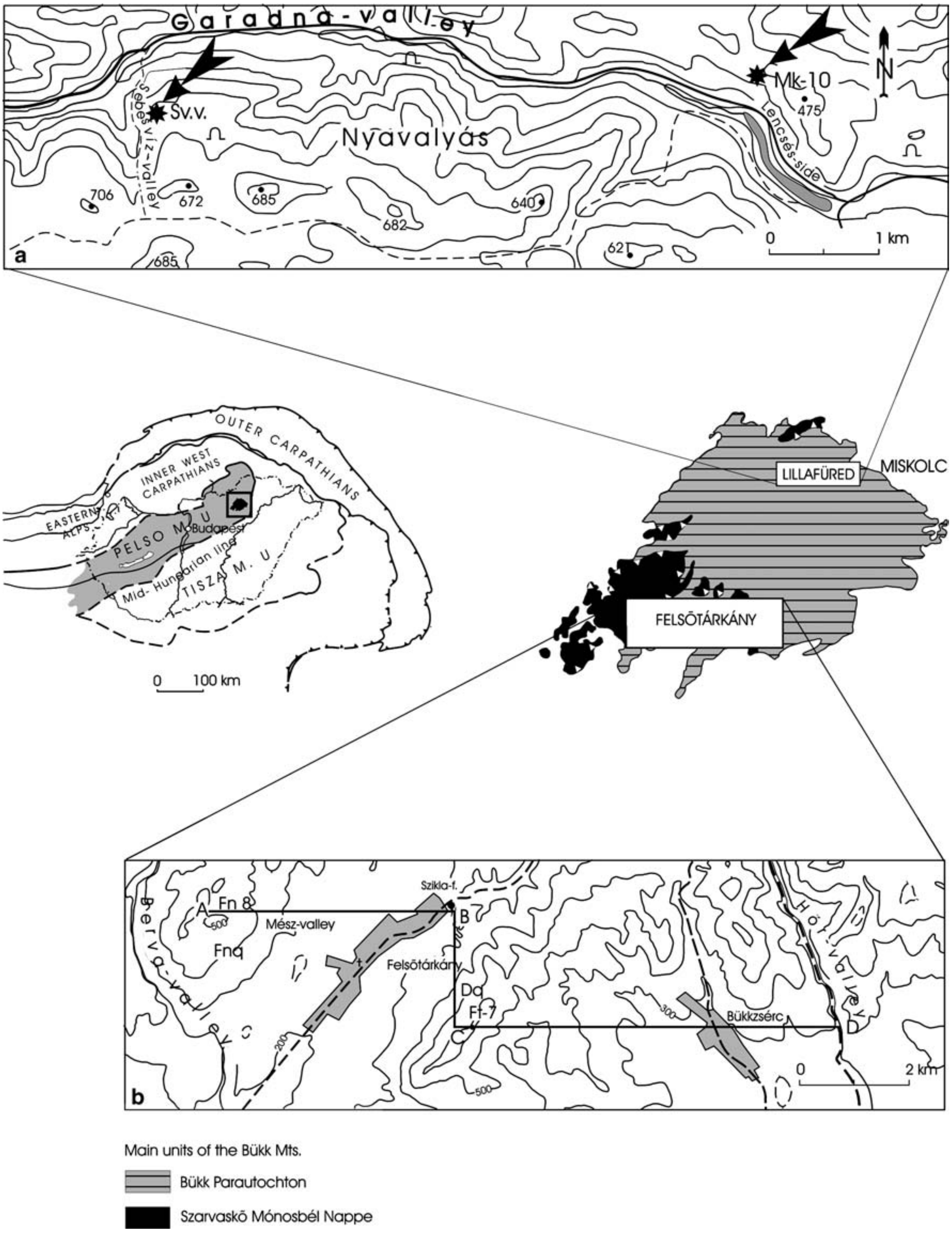


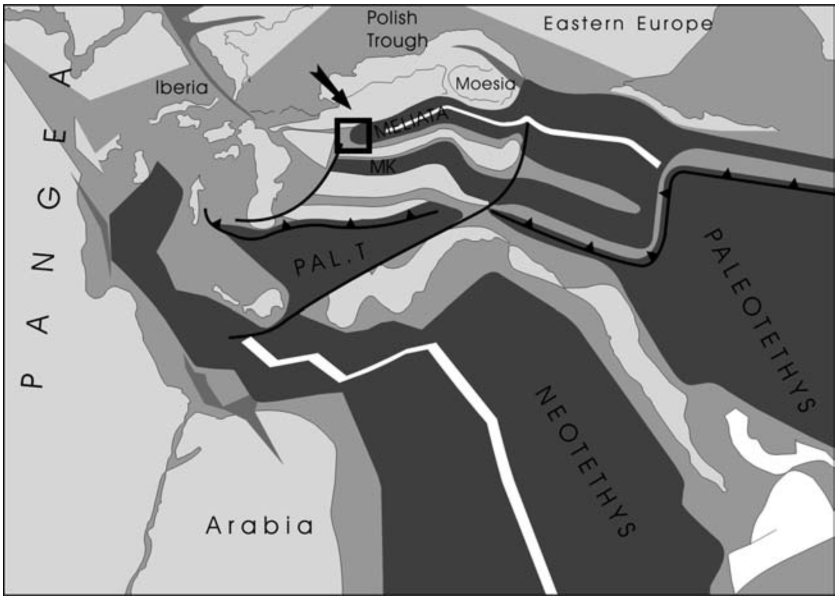
Fig. 1 Location map of the studied areas. **a** Geographic position of the Sebesvíz Valley section (Sv.v.) and borehole Miskolc-10 (Mk-10). **b** Geographic position of the studied outcrops on the S part of the mountains. Legend. *Fnq*, Felnémet Quarry; *Fn-8*, borehole Felnémet-8; *Dq*, dolomite quarry of Vár Hill; *Ft-7*, borehole Felsötárkány-7; *A–B–C–D* trace of the half-graben

an effect. However, they play only a secondary role in the evolution of the Triassic sediments of the Bükk Mountains and in most cases their effects can be traced only with difficulty due to the subsequent tectonics and poor exposure conditions.

Geological setting

The Triassic sections of the Bükk Mountains were deposited on the southern shelf of the opening

Fig. 2 Situation of the continents and oceans in the Middle Triassic. Paleogeographic reconstruction simplified after Stampfli et al. (2001). Legend: *Mk*, Mangyshlak rift. *Rectangle* shows the area discussed in the present paper



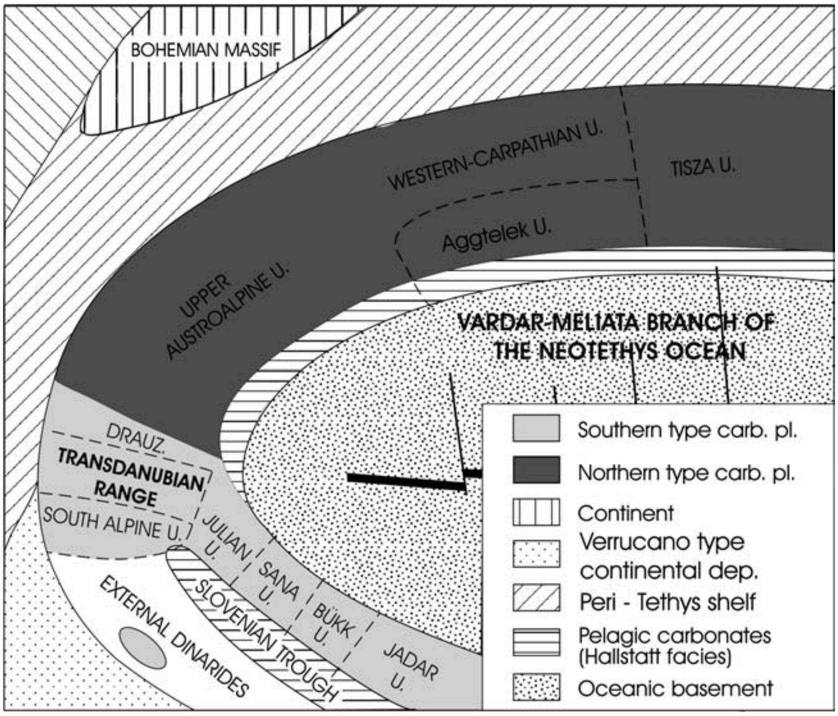
Vardar-Meliata branch of the Neotethys Ocean (Figs. 2, 3). The Carboniferous–Late Triassic sequence of the mountains shows striking similarities to that of the Jadar and Sana–Una units of the Inner Dinarides (Protić et al. 2000). According to the palaeogeographic reconstruction of Kovács (1984), Tollmann (1987) and Haas (2001), the Bükk Mountains were situated adjacent to the Julian Alps and the South Karavank Mountains in the Triassic and came into their present-day position during a several hundred kilometre displacement along the dextral strike slips (Middle Hungarian Lineaments) only in the Late Oligocene–Early Miocene.

Today, the Bükk Mountaains can be found north of the Mid-Hungarian (or Zagreb–Zemplin) Lineament and are part of the ALCAPA (North Pannonian) mega-unit and Pelso mega-unit (Haas 2001).

Two main units build up the mountains (Fig. 1):

1. Parautochthon: a Middle Carboniferous–Late Jurassic volcano sediment series deposited on continental crust. The investigation of its Middle–Upper Triassic sequences is the main subject of this paper.
2. Szarvaskö–Mónosbél Nappe: shale, sandstone series with ophiolites, radiolarites, and olistoliths

Fig. 3 Middle Triassic paleogeographic reconstruction for the Alp-Carpathian units, mentioned in the text. After Tollmann (1987), Kovács (1992), Haas (2001)



(wildflysch) deposited on Jurassic oceanic crust. It was obducted onto the Parautochthon from the northwest (according to present-day co-ordinates) due to the Late Jurassic–Early Cretaceous closing of the Meliata Ocean.

Studied sections of the Bükk Mountains

Investigations covered most parts of the Bükk Mountains. Detailed descriptions of the studied sections and the results were published in various papers (Velledits and Péró 1987; Velledits 1998, 1999, 2004). Only those sections which are highly important from the point of view of the Triassic evolution of the mountains will be described here.

Southern Bükk

In a 12 km long east–west section between the Berva and Hór Valleys (for the track of the section see Fig. 1b), the spatial distribution of the Anisian–Rhaethian facies depicts a half-graben structure of the crust. Both in the eastern and western parts of the area is an island platform (Figs. 4, 5, 7, 9) while between them an intraplatform basin can be found. The half-graben structure can be traced most clearly in the Ladinian–Carnian (Fig. 7), as we have the most information from this period.

Dolomite quarry of Vár Hill

Exposing the footwall of the borehole Felsötárkány-7. This is an abandoned quarry east of village Felsőtárkány, on the SW side of the Vár Hill.

Peritidal (algal domes (Fig. 6a), algal mats, and oncoids (1–4 cm)), as well as subtidal (foraminiferal mudstone–wackestone) sediments build up the dolomites. The rich foraminifer assemblage, found in the latter, represents the Pelsonian age (Velledits 2000) (All the foraminifers mentioned in this paper were determined by A. Bérczi-Makk.)

Borehole Felsőtárkány (Fig. 6)

This was deepened on the NE side of the Vár Hill (Fig. 1b). In its sequence, three sedimentary environments alternate.

Section I. Terrestrial sediments Lacustrine marl (31.8 m thick). The fresh water origin is justified by characean and fresh water ostracodes (Velledits 2004).

In the calcareous marl layers, volcanic material: lava rocks and tuffites are intercalated. In one sample, it can be observed that the volcanic material was still plastic when it arrived in the lake. The matrix of the clast was originally felsitic and contains argillated relicts of plagioclase phenocrysts. According to the extinction of the plagioclase, the grains originated from acidic extrusive rocks (Bagoly-Árgyelán, personal communication). Pumice-bearing tuffs also occur. The size of the pumice fragments does not reach the lapilli realm, referring to distal facies. In certain volcanic tuffs, carbonate grains can be observed.

Section II. Restricted basin: laminite and radiolarite Laminite (Figs. 6c, 7g): 15.5 m thick, dark grey and smaller black dissolution seams (a few millimetres thick) alternate. In the thicker matrix, silt-sized organic matter, quartz, and carbonate grains float, showing a fining upward tendency. Schulz et al. (1996) describe similar laminites from the Arabian Sea, in a water depth of 300–900 m. The origin of the lamination is traced back to the seasonal changes in surface productivity and supply of fine-grained sediment. The black layers, rich in organic matter, are the sediments of the plankton-rich summer. During the diagenesis, they turn into dissolution seams due to pressure solution. The thicker and lighter- coloured layers represent the sediments of the winter period when the sediment is transported into the deeper regions by suspended density currents and episodic turbidity currents. The water is well stratified, its oxygen-content is low, thus there is no bioturbation, so the laminae can be fossilized.

Radiolarite (Fig. 6d) with volcanic intercalations: in between some radiolarite layers, weathered tuff layers are intercalated. From the two thickest radiolarite layers (60 and 40 cm), L.Dosztály determined the latest Fassanian and Longabardian age (Velledits 2000).

Section III. Intraplatform basin with open water circulation (Fig. 6e, f, g) Cherty limestone; age: Late Ladinian–Rhaetian.

The cherty limestone represents the sediments deposited in the basin, on the slope, and at the toe of the slope. Radiolarian, filament, and echinoderm wackestone with some ammonite embryos, sponge spicules, and foraminifers. In certain levels, the quantity of the fossils resedimented from the platform (Tubiphytes, gastropod, peloid) increases. Slumps indicate the sediment movements on the slope. The echinoderm packstone is the sediment of the turbidity current.

Sediments of three gravity mass movements (Fig. 6) form well-separated horizons. The resedimented grains of the two thinner intraclastic limestone layers (echinoderm, peloid mudstone–wackestone) originate from the higher part of the slope. There is no matrix between the grains which is characteristic of the upper part of the slope.

At the end of the Lacian, a third, 13.7 m thick conglomerate–breccia layer also appears (Fig. 6e). The matrix is crinoidal packstone. Its pebbles originate from different depositional environments: from the sand shoal (peloid packstone), from the reef (bindstone), from the toe of the slope (crinoidal wacke-packstone) and from the basin (radiolarian, filament mud-wackestone).

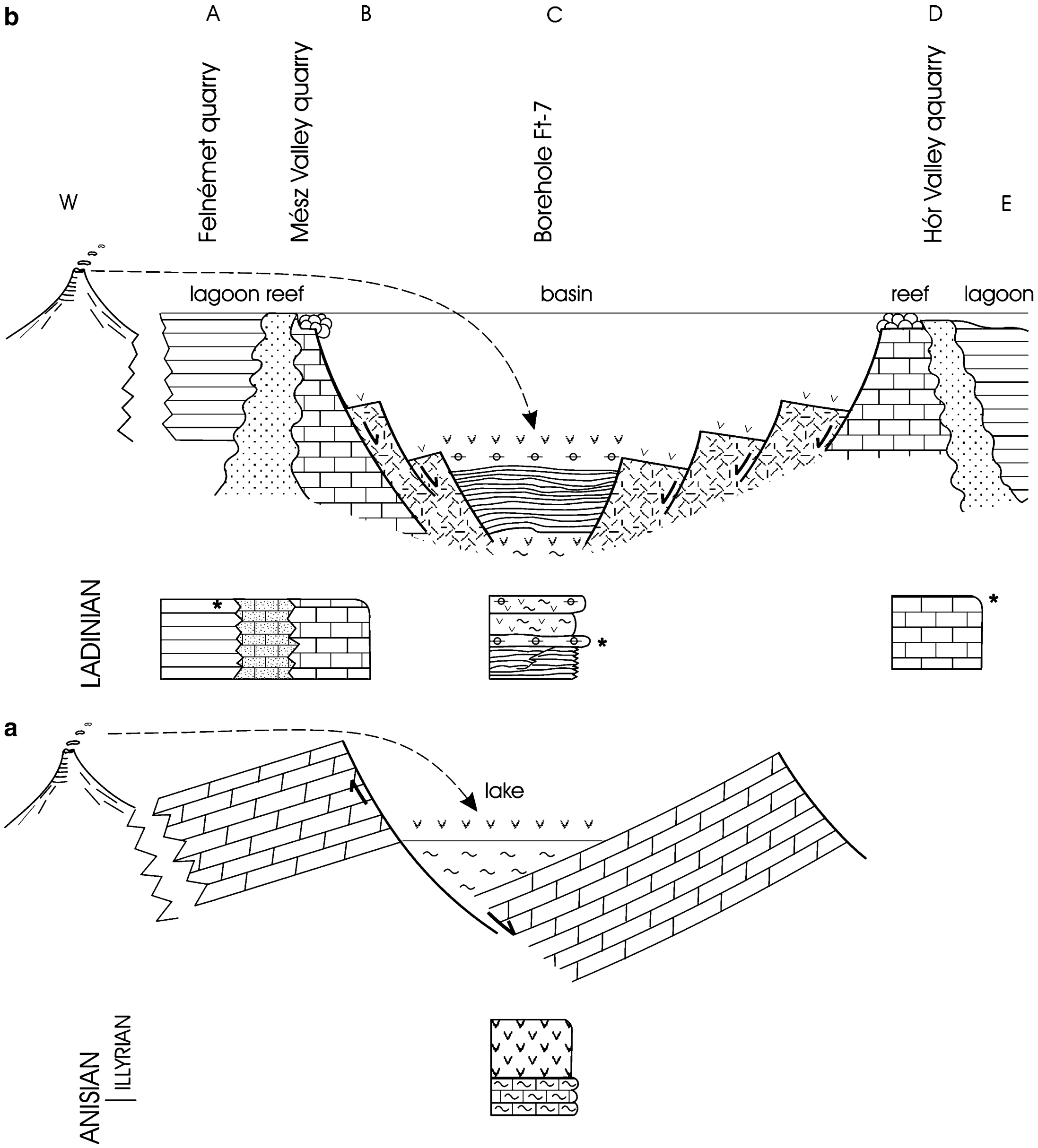


Fig. 4 Evolution of the area between the Berva and Hór Valleys (Southern Bükk). Trace of the cross section can be seen on Figs. 1b and 9. The results of the investigations are depicted in the lower parts of the figures, while the paleogeographic reconstruction of each time interval is shown in their upper parts. On the basis of the facies, the half-graben structure of the basement can be outlined very well. Legend as in Fig. 6. Additional legend: *age data. **a** Upper Anisian lacustrine sediments are known only in borehole Felsötárkány-7. In the Late Anisian, after the deposition of the Hámor Dolomite (dolomite quarry of Vár Hill) the area was uplifted, in its deepest part a lake came into being. At the Anisian/Ladinian boundary, volcanic material appeared within the lacustrine marls, later the volcanic material became dominant (Szentistvánhegy Metaandesite). **b** In the Ladinian, the platforms are well outlined in the eastern and western parts of the area (Figs. 7, 9). Their margins are surrounded by reefs, while in their inner parts different shallow marine facies (lagoon, sand shoal) were formed. At the beginning, the intraplatform basin was restricted. At this time, laminitic calcareous marls were deposited, followed by radiolarites. Traces of the coeval volcanism can be found in the basin even in the Upper Ladinian. In the Early Ladinian, a considerable subsidence must be assumed, because the Upper Anisian lacustrine marls are followed by radiolarite at the Fassanian–Longobardian boundary. Consequently, the territory subsided several hundred metres during a few million years

The characteristic sediments of the slopes and toe of slopes are conglomerates and breccias originating from the debris flow that is induced by the gravitation. In addition, in the rifting zones we have to reckon with the repeated tectonic movements of the crust which contributes considerably to the redeposition of the sediments. Crevello and Schlager (1980) describe a similar phenomenon from an intraplatform basin of the Bahamas, the Exuma Sound, where lithoclasts of shallow water and pelagic origin are also mixed. This is

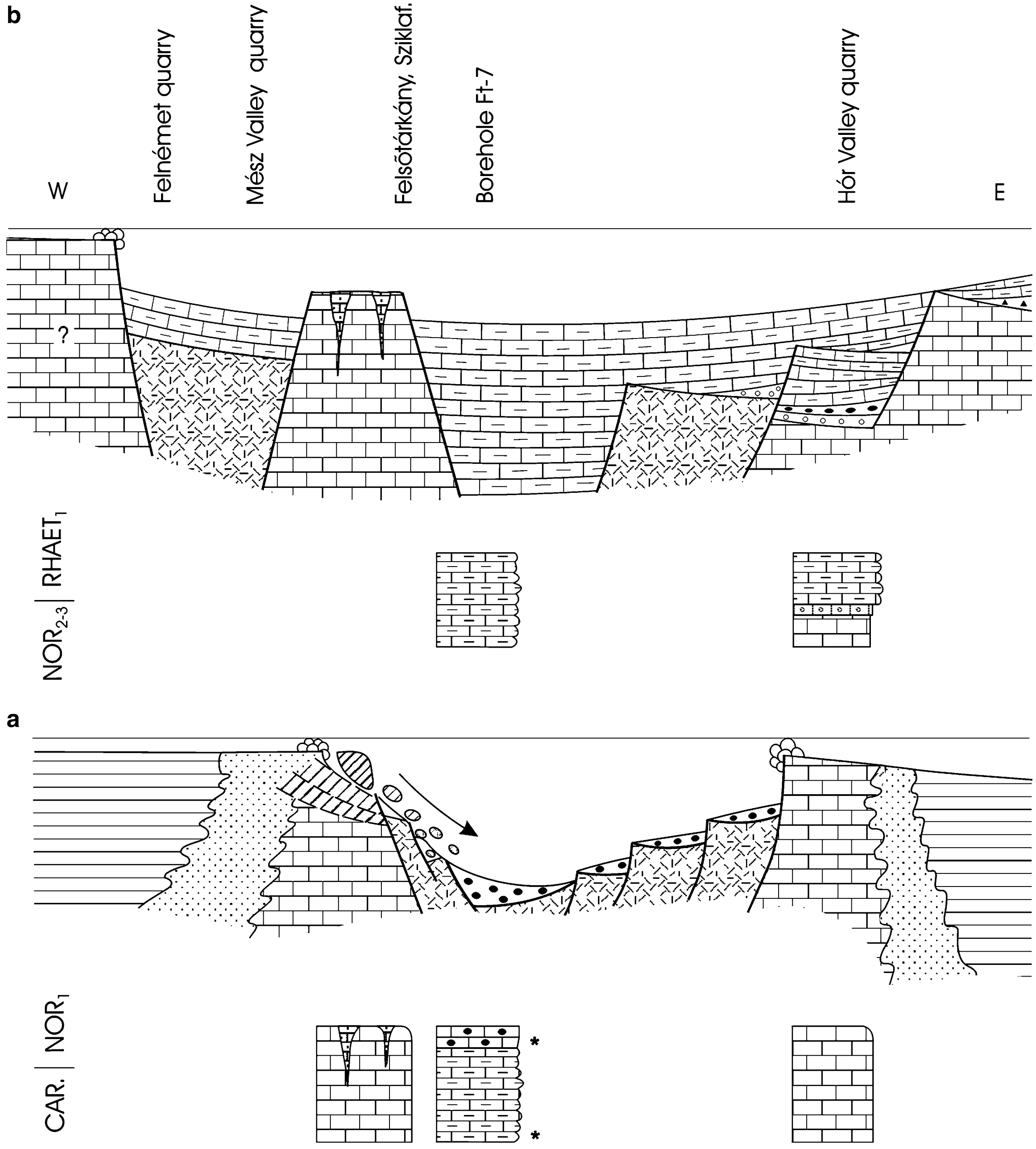


Fig. 5 **a** In the Carnian, the intraplatform basin became well oxygenated. The sediments of anoxic facies are replaced by cherty limestones. The coeval evolution of the platform/basin can be traced both in the Carnian and the Lower Norian in the sequences of the Southern Bükk Mountains. The lithoclast layers, appearing within the pelagic basin sediments, indicate the back stepping of platform margins. Their material derives mainly from the platform. **b** Due to the drowning of different parts of the platforms, pelagic sediments appeared above the platform sediments and the cherty limestone becomes predominant in the Middle and Late Norian and the Early Rhaetian. In the studied sequences, there were no autochthonous reefs found in this period, but the resedimented clasts of the reef building organisms indicate that reefs existed after the drowning of the platform margins even in the Early Rhaetian in the nuclei of the platforms

explained by the detachment of the platform edge and the upper slope. In the course of submarine slidings, the platform edge retrogrades, i.e., large bodies detach from the edge of the platform. Partly, these detaching bodies serve as lithoclasts that are deposited in the deeper parts of the basin together with the intraclasts originating from the basin (Fig. 5a).

Half-graben between Berva- and Hór-Valley

The basin was bordered by platforms to the E and W (Figs. 4, 5, 7). To the W, from W to E in the Berva carbonate platform, different facies (cyclic lagoon (Fig. 7a, b) platform edge moving calcareous sand shoal (Fig. 7c), reef (Fig. 7d, e, f) of a carbonate platform can

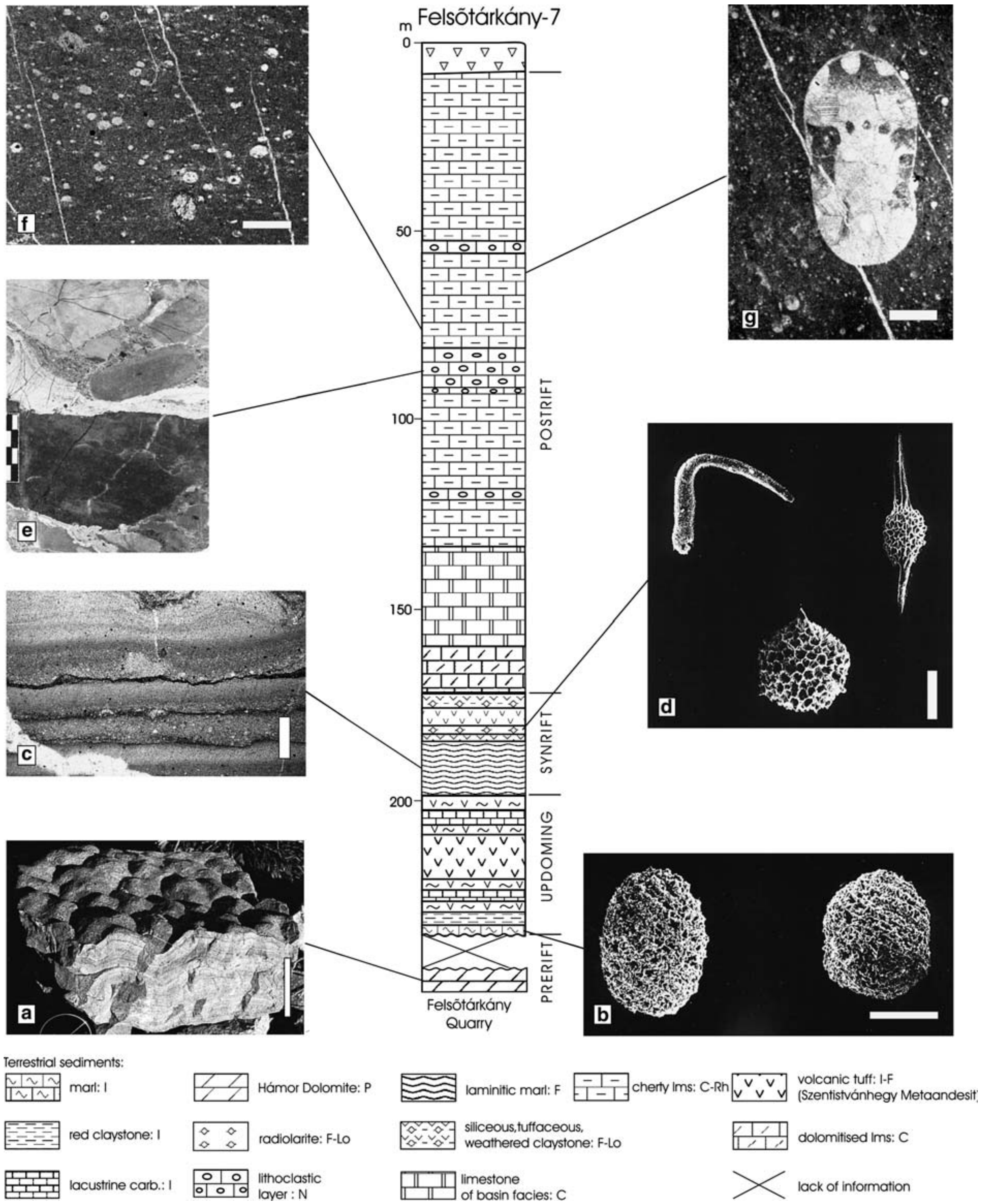


Fig. 6 Borehole Felsötárkány-7 and its footwall reveals the evolutionary phases of the deepest part of the half-graben during the rifting between the Late Anisian and Early Rhaetian. Prerift, **a** Hámor Dolomite, algal laminite, *scale bar* 5 cm. Updoming, **b** lacustrine sediments (chara carpolites), *scale bar* 0.1 mm. Synrift, **c** microfacies of the laminite, *scale bar* 1 mm, **d** radiolarite (Oertlispongus inaequispinosus KOZUR and MOSTLER, Pseudostylosphaera coccostyla–Pseodostylosphaera longispinosa transition, Cenosphaera sp.), *scale bar* 0.1 mm. Postrift: cherty limestone; **e–g**; **e** lithoclastic limestone from the 13,7 m thick resedimented layer. In a matrix of crinoidal debris, limestone grains of different size and origin float. Sediment of toe of slope, *scale bar* 2 cm; **f** radiolarian wackestone, *scale bar* 1 mm; **g** Ammonitic embryo, *scale bar* 1 mm. Legend: *P*, Pelsonian; *I*, Illyrian; *F*, Fassanian; *C*, Carnian; *Lo*, Longobardian; *N*, Norian; *Rh*, Rhaetian

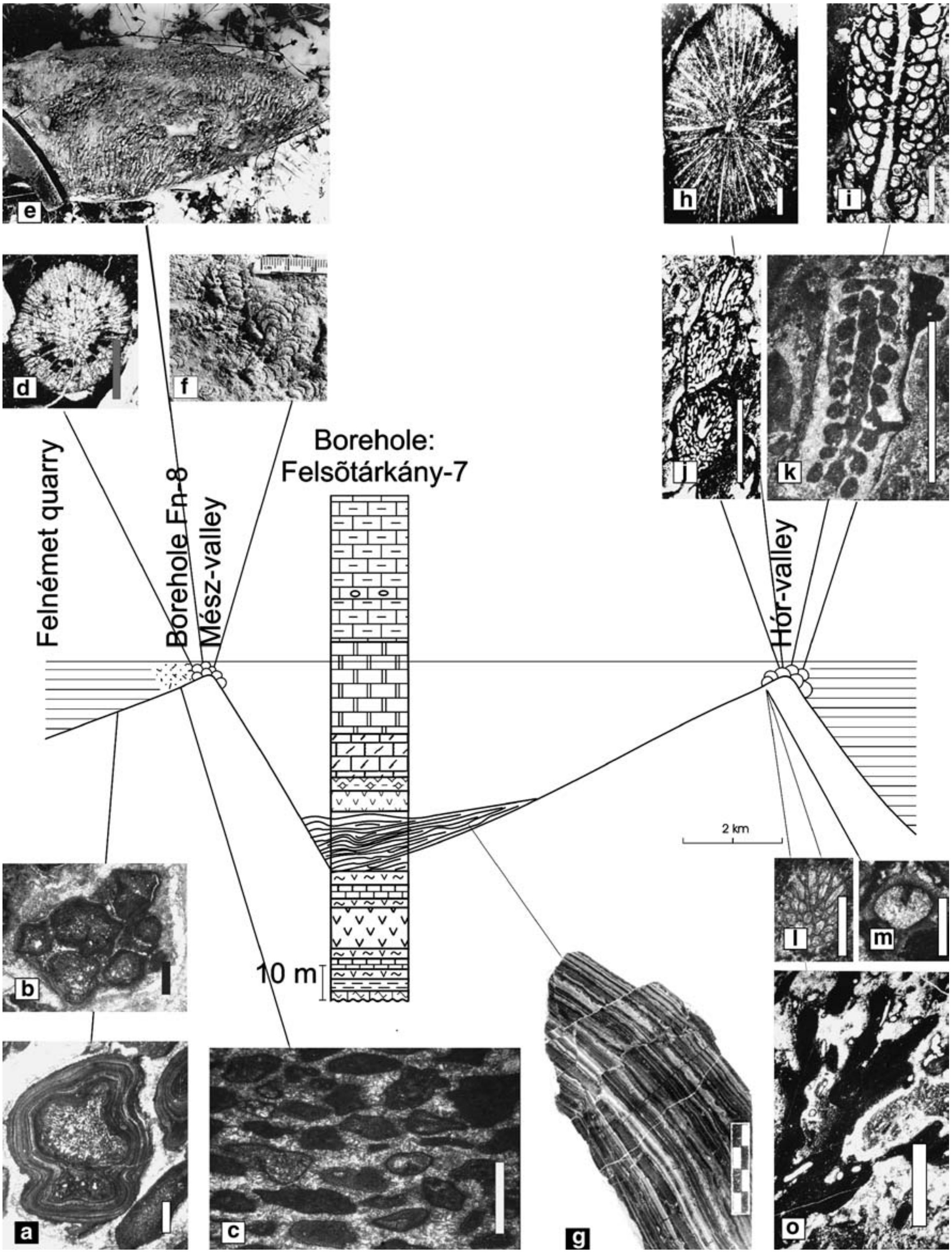


Fig. 7 Early Ladinian half-graben between the Berva and Hór Valleys. To the east and west on the uplifted wings, different platform facies (lagoons, sand shoals, reefs) can be found. Photos depict fossils and microfacies from the different depositional environments. **a–b** pisoid and lump from the lagoon, *scale bar* 1 mm; **c** grainstone from the sand shoal facies, *scale bar* 1 mm; **d–f**, reef; **d** Marganophyllia?, *scale bar* 0.5 cm; **e** weathered surface of a coral colony; and **f** of a Shinctozoa, **g** laminitic marl, *scale bar* 2 cm; **h** Marganophyllia capitata (MÜNSTER), *scale bar* 0.5 cm; **i–k** segmented sponges; **i** Alpinothalamia bavarica (OTT), *scale bar* 0.5 cm; **j** Solenolmia manon manon (MÜNSTER), *scale bar* 0.5 cm; **k** Enoplocoelia armata (KLIPSTEIN), *scale bar* 0.5 cm; **l** bryozoan, *scale bar* 0.5 mm; **m** Radiomura cautica SENOWBARI and SCHÄFER (microproblematicum), *scale bar* 0.5 mm; **o** Tubiphytes sp., *scale bar* 0.5 cm

be found in the Ladinian–Carnian (Velledits and Péró 1987). The eastern edge of the platform was drowned in the Norian. The age of the drowning can be proved on the basis of both the conodonts from the cherty limestone deposited on the platform limestone and the foraminifers in the neptunian dykes of the platform limestone (Velledits 2000). The eastern part of the half-graben is also made up of a platform that was bordered by a reef (Fig. 7h–o) to the W, towards the basin (Flügel et al. 1992). Based on the conodont investigations, this part of the platform was drowned in the upper part of the Middle Norian (Alaunian$_3$). (All the conodonts mentioned in this paper were determined by S. Kovács.)

Evolution of the half-graben

The prerift sediments are represented by the Pelsonian Hámor Dolomite. Due to the updoming lacustrine marls were deposited, indicating the beginning of the rifting. The updoming is accompanied by volcanic activity. The rift lake developed in the deepest part of the half-graben that was formed during the rifting. There is no information on the sediments deposited at this time in the neighbourhood (in the footwall of the Berva and Hór Valley platform), but since the lake developed in the deepest part of the half-graben, the areas to the E and W of the lake were probably also in an elevated position in the Late Anisian. Occasionally, the volcanic activity became so strong in the Late Anisian that the lacustrine marls are missing and the volcanic material becomes predominant.

The laminitic marl of Section II of borehole Felsőtárkány-7 (laminitic marl) were deposited in an euxinic basin that came into being during the increased subsidence following the updoming at the end of the Late Anisian. The laminitic marl is overlain by radiolarite, indicating the deepest sediment of the basin. The sequence of the borehole confirms the view of De Wever and Baudin (1996) that the (dark coloured) radiolarites rich in organic matter were formed in the tectonically active periods of the earth history. The radiolarite together with the laminite was deposited here, in the basin that was formed during the rifting.

In the Ladinian–Carnian, the margins of the Felsőtákány Basin were bounded to the W and E (according to present-day co-ordinates) by two carbonate platforms, bordered by a reef towards the basin (Fig. 7).

In the Late Triassic, the edges of the platforms were drowned step by step. We could prove a drowning event in the Lower Norian (Lacian$_1$) and in the upper section of the Middle Norian (Alaunian$_3$).

Due to the drowning of the platform edges, the basins covered bigger and bigger areas (Figs. 4, 5), while the territory of the platforms gradually decreased. Probably, the cores of the platforms existed for a longer time, since resedimented reef-forming fossils (Tubiphytes) can be found in the basin sediments in the Early Rhaethian.

Sediments of volcanic origin are present continuously from the Late Anisian until the end of the Ladinian, in addition to this holocrystalline quartz appearing in the Early Carnian indicate a distal volcanic activity.

Subsidence history

After the deposition of the Pelsonian Hámor Dolomite, the area was uplifted in the Late Anisian. The updoming was followed first by a rapid and later by a slow/moderate subsidence.

The subsidence was most intensive in the period after the deposition of the terrestrial (lacustrine) and volcanic sediments in the Late Anisian–Early Ladinian. At the end of the Fassanian, radiolarite was deposited in the already several hundred metre deep basin. In the course of around 4–5 million years from the end of the Pelsonian (236.1 Ma according to Gradstein et al. 1995) to the end of Fassanian (231.4 Ma), the area subsided several hundred metres.

At the end of the Fassanian–Longobardian, the subsidence slowed down. During the deposition of the cherty limestone, the depth of the basin did not increase very much or it might even have slightly decreased.

Northern Bükk

Middle–(?)Late Anisian terrestrial sediments were detected in two sections: borehole Miskolc-10 and Sebesvíz Valley (Fig. 1a). These sections do not cover a long time interval (borehole Miskolc-10) or they are metamorphosed due to the subsequent tectonics (Sebesvíz Valley), respectively.

Borehole Miskolc-10

Geographical position: Lillafüred, Lencsés side, 6 km to the NW of the Ómassa–Hollóstető junction (Fig. 1a).

The lowermost 20.1 m of the borehole (Fig. 8a–c) is composed of Steinalm limestone and dolomite (Unit I). Light grey limestone of lagoonal facies and dasycladacean wackestone–packstone and foraminiferal packstone microfacies. Based on dasycladacean and foraminifers, the age is Pelsonian, Early Illyrian? [for detailed description see Velledits (1999), the dasycladacean were determined by O. Piros.]

The lagoonal carbonates are covered by the sediments of a braided river (Unit II) in 12.7 m thickness. Microfacies analysis of the pebbles of the conglomerate revealed that the grains originate mainly from the Hámor Dolomite Formation. Quantity of the limestone pebbles originate directly from the footwall (Steinalm Limestone) is subordinate. The claystone pebbles occurring in small quantities were resedimented from the Ablakoskővölgy Limestone of Olenekian age.

Between the resedimented pebbles of the conglomerate, some mm-sized grains of volcanic origin appear, referring to coeval volcanic activity. Based on the extinction of the plagioclase laths, a basic character of the vulcanite can be excluded (Bagoly-Árgyelán, personal communication).

Fine-grained clastic rocks (Unit III): sandstone, microconglomerate, arkose, crystal tuff follow the fluviatile deposits. The size of the grains decreases to a considerable degree (2–8 mm) and the resedimented volcanic clasts become predominant in their material. The borehole terminates with 59.1 m thick tuffitic sediment.

Interpretation After the deposition of the Steinalm Limestone of lagoonal facies (Unit I) at the beginning of the Illyrian the area was uplifted. As a consequence of the tectonic movements, considerable level differences came into being, providing material for erosion. Due to the uplift of the area on the eroded surface of the Steinalm Limestone fluviatile conglomerates were deposited (Unit II). After the uplift, the volcanic activity began. At the time of the sedimentation of the sandstone (arkose) horizon (Unit III), the diameter of the resedimented grains decreased considerably. Probably, by this time the terrain differences arising from the tectonic movements had already been diminished or disappeared. The volcanic material takes part in the sedimentation in an increasing degree while at the end it becomes predominant (Unit IV).

Anisian–Ladinian layers of the Sebesvíz Valley key section

Geographical position (Fig. 1a): northern part of the Mountains, southern side-valley of the Garadna Valley, western part of the Nyavalyás side, eastern side of the forestry road.

The oldest formation of the investigated sequence is the Hámor Dolomite (Fig. 8) in which no fossils were found in this exposure. Based on its lithostratigraphic position, it belongs to the Pelsonian, its thickness is 31 m in the section.

After an erosion surface, the Sebesvíz Conglomerate (Fig. 8f–i) follows in a thickness of 34 m. Pebbles of 2–15 cm in diameter float in grey, calcareous matrix. In the lower part of the conglomerate, in two (20 and 60 cm thick) horizons, the matrix is red clay, the grains are angular and unsorted. In the matrix of the conglomerate, minerals rich in Al, Al–chlorite and pyrophyllite as well as hematite were pointed out by X-ray diffraction analysis. Probably, the first two minerals were formed by the recrystallisation of kaolinite during the very low grade metamorphism (anchizone). This Al-rich clay mineral assemblage together with the large amount of hematite suggest lateritic weathering (Kovács–Pálffy and Viczián, personal communication). Among the clay minerals, the illite has a double character: a part of it is 2 M-altered, clastic or already metamorphic product while its other part is badly crystallised and has a wide base reflection. The latter one was originally smectite, thus the tuffaceous character of the original material is not excluded (Kovács–Pálffy and Viczián, personal communication).

Microfacies investigations of the resedimented pebbles revealed that they originate from a lagoon of the Aegean–Bithynian age.

In the layer group, a 70×300 cm dish-shaped conglomerate represents fluviatile channel sediments. In the middle part of the Sebesvíz Conglomerate, a maximum 4.8 m thick tuffitic volcanic intercalation can be found whose lower and upper boundaries are tectonic. In the upper part of the conglomerate, claystone pebbles also occur among the resedimented pebbles, accordingly the erosion affected the footwall and the underlying rocks as well. On the conglomerate, vulcanite (Szentistvánhegy Porphyrite) is deposited in 156 m thickness. The vulcanite is followed by dark grey limestone, dissected by laminate clay films (27 m). In the cover, pelagic carbonates, dark grey platy limestone (1.8 m, Fig. 8j) can be found whose microfacies is filament, radiolarian wackestone. It is followed by cherty limestone with siltstone schist and radiolarite intercalations (8 m). Then, red nodular limestone with clay films is deposited (12 m). Its age is Late Fassanian on the basis of the conodonts. The series is closed by white massive limestone with stromatactis and fossils of indistinct contours.

Interpretation The Late Anisian uplift and the subsequent subsidence can be proved in this section, as well. The conglomerate intercalations with red lateritic matrix of the Sebesvíz Conglomerate definitively indicate that here the sedimentation also continued on land after the deposition of the Hámor Dolomite. Coevally with the updoming, volcanism started. After the volcanic activity, pelagic sediments show the deepening. The facies leap between the terrestrial and pelagic sediments is so radical that it cannot be explained only with eustatic sea level change, a radical tectonic subsidence has to be assumed, as well. The youngest massive stromatactis limestone of the section shows that the sedimentation continued on the platform after the pelagic facies. The slowing down of the subsidence made the progradation of the platform possible, so the basin was filled up and the sedimentation continued on the platforms in the Late Ladinian.

Island platforms of the Bükk Mountains

In the structure of the mountains, significant masses are represented by the Middle–Late Triassic platform limestones. In the Ladinian–Carnian, five larger platforms of several ten km^2 area could be reconstructed. Facies distribution and the age of certain platforms are known in different degrees depending on the grade of metamorphism (See Fig. 8).

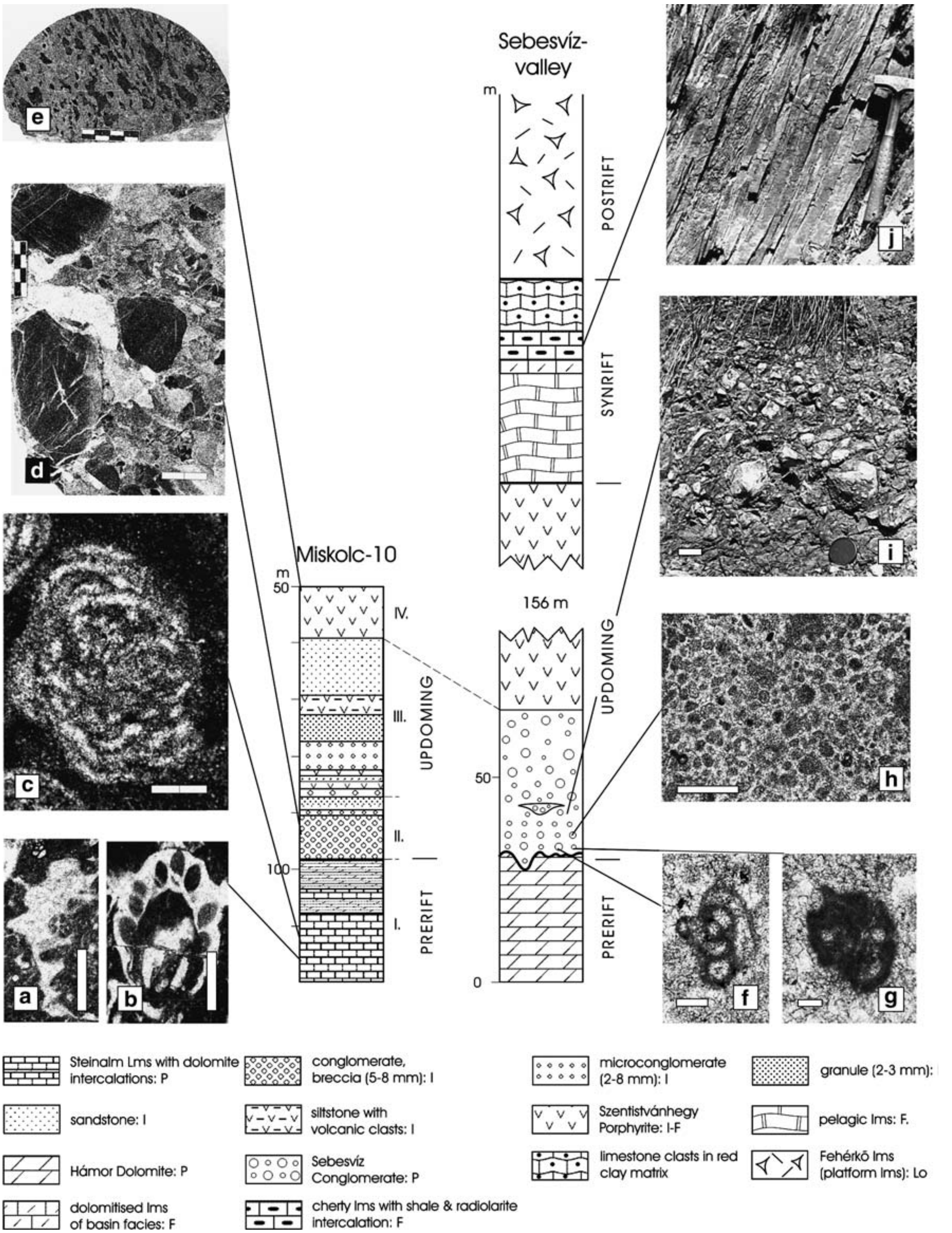


Fig. 8 Two sections of the Northern Bükk with Anisian terrestrial sediments. Borehole Miskolc-10, **a–c** fossils from the Steinalm Limestone; **a** Physoporella pauciforata (GÜMBEL) undulata PIA.; **b** Physoporella pauciforata (GÜMBEL) pauciforata BYSTRICKY; **c** Pilammina densa PANTIĆ, *scale bar* 0.1 mm; **d** conglomerate–breccia, part of the fluviatile sediments. The rock is grain supported, grains of different origin can be distinguished even with an unaided eye; **e** vulcanite with carbonate grains. The rock is the product of a lava flow. The carbonate grains between the volcanic constituents mark the sediments ripped up and incorporated by the lava flow, *scale bar* 2 cm. Sebesvízvölgy, **f–g** two foraminifers from the resedimented grains; **f** Planiinvoluta?, **g** Meandrospira pusilla (HO), *scale bar* 0.1 mm; **h** ooidic grainstone. A resedimented grain from the Lower Triassic Formation, *scale bar* 0.5 mm; **i** Sebesvíz Conglomerate, slightly rounded dolomite pebbles of varying size in red clayey matrix, *scale bar* 5 cm; **j** dark grey pelagic laminitic limestone indicates the deepening of the area

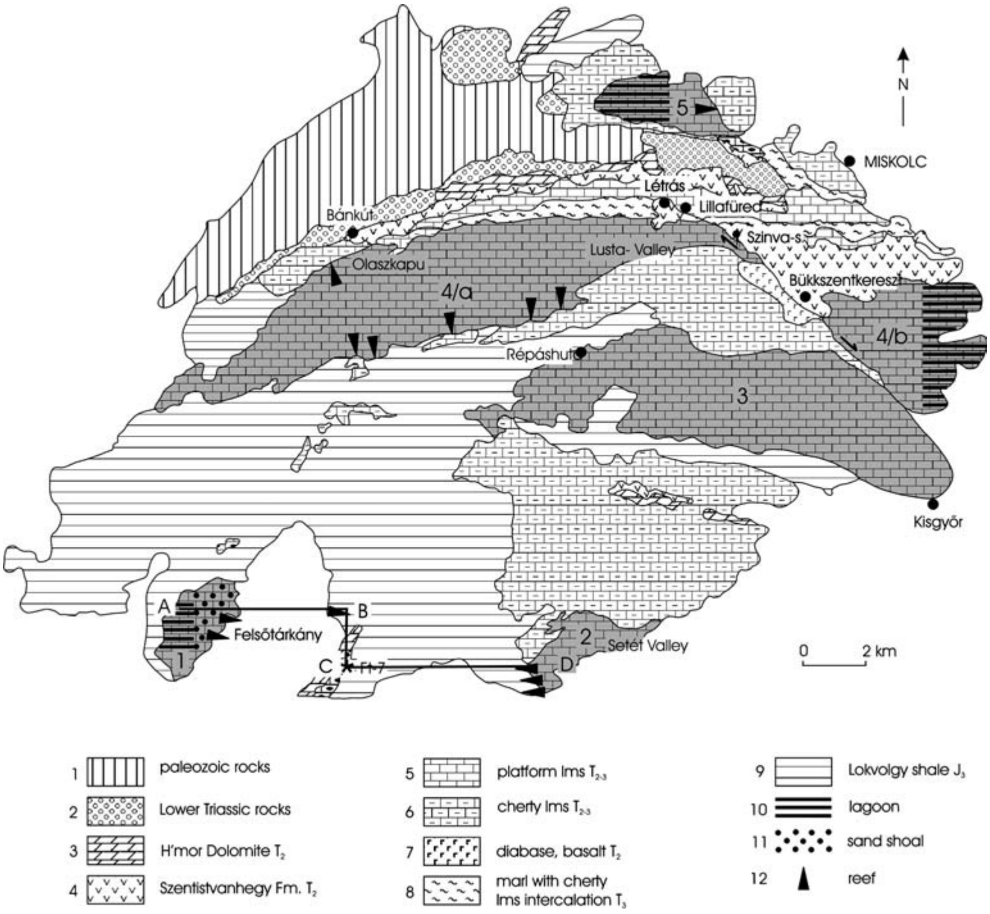


Fig. 9 Geographic distribution of the Middle–Upper Triassic platforms and basins with the known facies. Platforms and known drowning events: *1* Berva Valley; Lacian; *2* Hór Valley; Alaun; *3* platform between Répáshuta and Kisgyör; *4/a* Bükk Plateau; Julian, Cordevolian-Julian *4/b* Nagykömázsa. According to the structural investigations of Csontos (1988), the limestone bodies of the Bükk Plateau and Nagykömázsa were connected in the Triassic and they were separated and came into their present-day position only later due to lateral movements *5* Little Plateau. *A–B–C–D* marks the trace of the section between Berva and Hór Valleys

Sedimentological responses to the rifting of the Vardar-Meliata ocean branch of the Neotethys

Asymmetric rift model

In recent decades, several studies on recent (e.g. Dixon et al. 1989: Red Sea, Wernicke 1981: Basin and Range province) and fossil rifts (Stampfli et al. 1991: Tethys) proved the simple shear model of Wernicke (1985).

In this model, the lithospheric extension is accomplished by displacement on a large, gently dipping shear zone, crosscutting the entire lithosphere. The shear zone transfers the extension from the upper crust of a region to the lower crust and mantle lithosphere of another one. Consequently, there is a separation "of the zone of fault-controlled extension from the zone of upwelled asthenosphere" (Wernicke 1981 in Allen and Allen 2005). According to Wernicke's model, the crust is expected to subside in the upper crustal breakaway zone, while it will lift up above the upwelled asthenosphere. The rocks above the detachment fault are named upper-plate margin, whereas the opposite passive margin is the lower-plate margin (Lister et al. 1986).

Studying the rifting of the Red Sea, Dixon et al. (1989) pointed out that the evolution of the two shelves on the opposite sides of the opening ocean was asymmetric during the rifting in the sense of topography and volcanism. "Tertiary volcanism and uplift characterise the eastern flank of the Red Sea (Saudi Arabia)." Whereas "volcanism is essentially absent on the western flank (Egypt and Sudan)."

According to the above, three areas with a different evolution can be distinguished in the rifting zones (Fig. 10b):

1. Topographic culmination or upper plate. Above the upwelling of the asthenosphere, the crust is updoming, the area lifts up, and erosion starts. This part is characterised by active, often bimodal volcanisms.
2. Upper crustal breakaway or lower plate. This is characterised by the crumbling of the upper crust, the subsidence of the area, and the lack of volcanism.
3. Between these two parts the rift axis can be found. [According to certain theories (Dixon et al. 1989), it comes into being in the pre-existing "weak zones", e.g. along faults.]

In the model of Wernicke (1981), the culmination area comes into being where the detachment fault crosscuts the asthenospere. This area is separated from the rift axis in space. In the case of the Red Sea, it lies 200–400 km to the east. According to Dixon et al. (1989), the areas of maximum uplift and volcanism coincide and so this fact

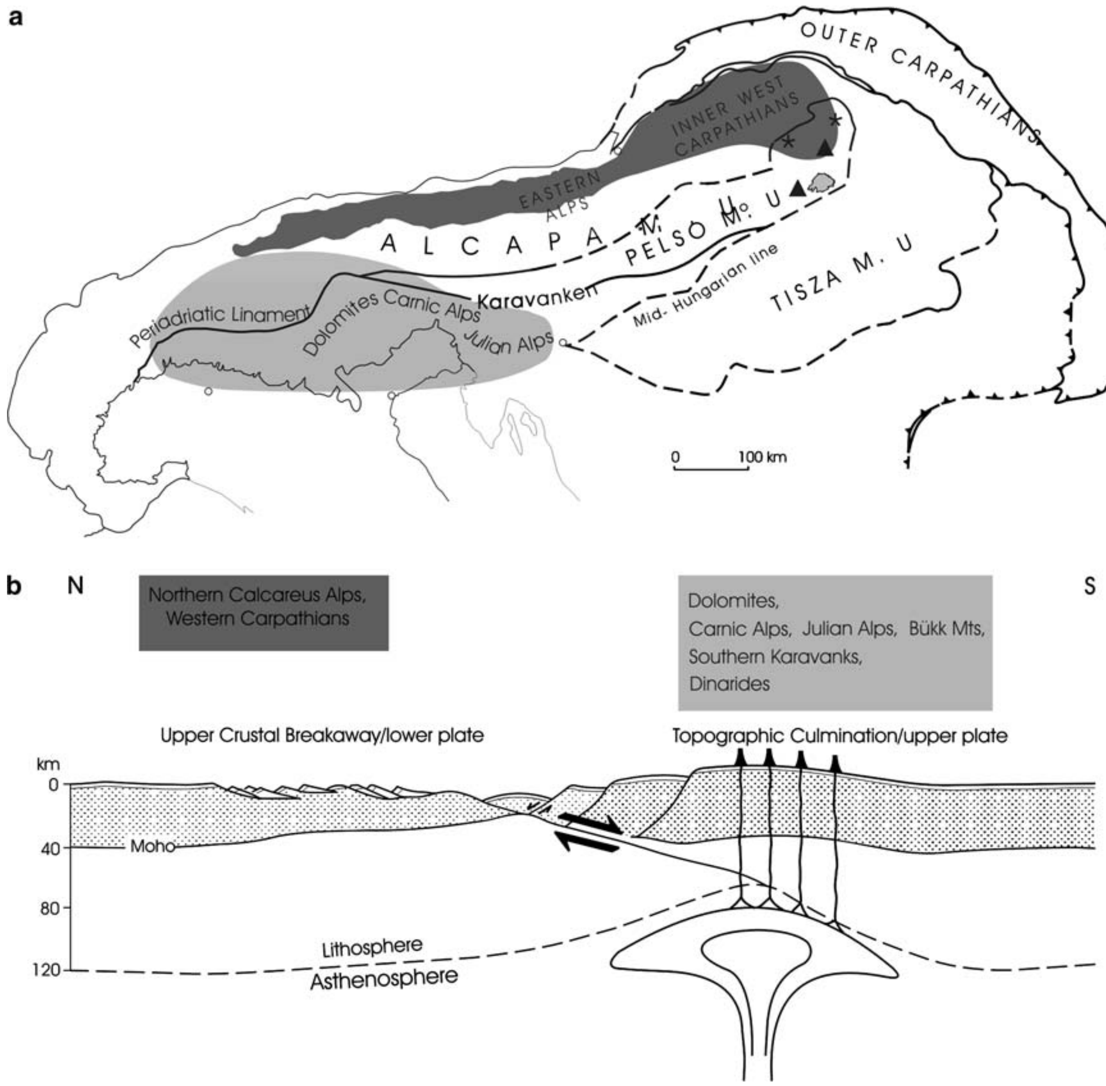


Fig. 10 **a** Distribution of the sections, typical of the northern and southern shelf of the opening Neotethys Ocean. Light raster indicates the Anisian-Ladinian terrestrial sediments and volcanic rocks (southern shelf). The dark raster indicates the sections without them (northern self type). See text for explanation. After Velledits 2004 Fig. 10. Oceanic remnants of the Meliata accretionary wedge are indicated with asterisks, olistoliths of Bódva Valley and Darnó Hill with triangles. **b** Position of the Alpine-Carpathian units during the asymmetric rifting of the Vardar-Meliata branch of the Neotethys Ocean. The lower part of the figure depicts the modified simple shear model (Dixon et al. 1989)

suggests a causal link between uplift and volcanism. In this part of the rifting area, the crust first lifts up then subsides due to the upwelling of the asthenospere and its own thermal expansion. The subsidence is rapid at the beginning: mechanical subsidence stage. At that time, the basin is actively faulted (McKenzie 1978). "If crustal attenuation continues, it will eventually lead to the creation of oceanic crust and to spreading. With this drifting phase, the crust begins to cool and a passive margin develops" (Pigott and Sattayarak 1991). After the extension has ceased, the subsidence slows down: thermal subsidence phase. Then the subsidence is controlled by the thermal evolution of the stretched lithosphere, and is produced by the gradual decay of the thermal perturbation induced by the extension. The cooling is a slow, long process that can last for more than 10 million years.

Bükk Mountains

Evolution of the Middle–Late Triassic formations of the Bükk Mountains shows similarities to that of the updoming/upper plate part of a rifting area.

Prerift stage: Anisian: Pelsonian–Illyrian

The terrestrial sediments indicating the uplift of the area are deposited either on the eroded surface of the Pelsonian Hámor Dolomite (Southern Bükk: borehole Felsőtárkány-7, Northern Bükk: Sebesvíz Valley section) or on the Pelsonian/Illyrian Steinalm Limestone (Northern Bükk: borehole Miskolc-10), consequently the Hámor Dolomite and the Steinalm Limestone represent the prerift sediments.

Updoming

At the beginning of the rifting, the convection in the mantle lifts up the crust. This is completed by the thermal expansion of the crust. The emergence of the Bükk in the Anisian is caused by these phenomena at the beginning of the rifting.

In the Bükk Mountains, the uplifts are indicated by the following terrestrial sediments:

- Alluvial fan and channel sediments (Sebesvíz Valley section), their age is most probably Lower?, Middle? Anisian.
- Fluviatile sediments (Borehole Miskolc-10), their age is Lower Illyrian.
- Lacustrine marls (Borehole Felsőtárkány-7), their age is Lower Illyrian (?).

According to our present knowledge on the sections of the Bükk Mountains, we cannot give a satisfactory answer to the question as to whether one or more terrestrial uplifting events interrupted the marine sedimentation in the Anisian. In the Dolomites, three uplifts of different periods are distinguished in the Anisian: (1) Piz de Peres Conglomerate: Early Bithynian; (2) Voltago Conglomerate: Lower Pelsonian; (3) Richthofen Conglomerate: Early Illyrian (Giannola et al. 1998). Based on the investigations of the sections of the Bükk Mts. a pronounced emergence took place in the Early Illyrian, coinciding in time with the formation of the Richthofen Conglomerate in the Southern Alps. In the Dolomites the Richthofen Conglomerate is represented by ca. 30 m thick fluviatile sediments (De Zanche et al. 1992). Simultaneously, fluviatile sediments appear in the Bükk as well. Their thickness together with the intercalated tuff layers is 28.2 m (borehole: Miskolc-10; Unit II and III).

However, based on the available data from the Bükk Mountains, a smaller, older uplifting event cannot be excluded in the Lower(?), Middle(?) Anisian. A more exact age could not be determined on the basis of the collected foraminifers. It can be correlated with the first or the second uplifting event of the Dolomites (Velledits 2004).

Investigations in the East African grabens show that at the time of the uplift domes and long elongated half-grabens were formed on the surface (Moores and Twiss 1995). In their deepest parts lakes (Leeder and Gawthorpe 1987) came into being or in their axes rivers flowed. In the Bükk Mountains, probably several half-graben systems came into being at the time of the uplifts with lakes in the deepest parts of some of them and with rivers in the axes of others.

In the Triassic, the sedimentation was interrupted twice by volcanic activity. First, around the Anisian–Ladinian boundary. The settling of the uplifting and the more and more intensive volcanic influence can be traced in the Anisian sections of the Bükk Mountains (Fig. 8). For example in borehole Miskolc-10 the coarse-grained sediments, composed mainly of dolomite pebbles, are gradually replaced by volcanic pebble material then by the deposits of the lahar and finally by the vulcanite itself. In the borehole Felsőtárkány-7, the terrestrial (lacustrine) sediments are followed immediately by volcanoclasts (Fig. 6). This is an intermediate–acidic volcanic series (meta-andasite–metarhyolite) mainly on the northern and eastern parts of the mountains (Bánkút and Létrás, and in the neighbourhood of Lillafüred and Bükkszentkereszt). As to the first volcanic series, opinions of the researchers vary. Some of them (Szoldán 1990; Kovács 1992) hold that the volcanic rocks are connected with the subduction while according to Harangi et al. (1996) "the calc-alkaline volcanism may be linked to the early stage of an extensional event when partial melting occurred in the metasomatized lithospheric mantle, resulting in the formation of calc-alkaline magmas".

The latter view reinforces also the opinion that although compressional tectonic activity has been recognised in the Dolomites (Southern Alps) at the Ladinian–Carnian boundary (Doglioni 1984), the general Middle Triassic evolution of the Southern Alps and Dinarides was mainly controlled by extensional tectonism. In addition, folding and nappe structures, metamorphism, and obducted ophiolites that are indicative of a subduction event are not known in this area (Harangi et al. 1996.)

Synrift

The rapid subsidence of the area starts during the later stage of the first volcanic activity (synrift or mechanical subsidence phase). The rate of the subsidence is characterised by the fact that in the borehole Felsőtárkány-7, the Late Anisian lacustrine sediments are followed by Late Fassanian radiolarites. Between the Late Anisian and Late Fassanian, during a few million years, the territory subsided many hundred metres. Similar tendency can be observed in the Sebesvíz Valley section.

The synrift stage lasted from the Pelsonian/Illyrian boundary until the Fassan-Longobardian boundary. Taking into account the dates of Gradstein et al. (1995) it lasted 4.7 million years.

In the Ladinian–Carnian the coeval evolution of the platforms and basins characterises the Bükk Mountains (Figs. 4, 5, 9). The domino structure of the crust, the half-grabens developed during extension determine the sedimentological facies. In the deepest part of the half-graben a lake was formed in the Late Anisian. At the beginning of the Ladinian, during the subsidence, the terrestrial half-graben was flooded, and in its deepest parts basins were formed while in the uplifted wings platforms were formed. The intraplatform basin at Felsőtárkány was restricted in the Early Fassanian, but became well oxygenated later.

Postrift sediments

At the beginning of the Carnian, cherty limestone was deposited in the well oxygenated intraplatform basins. The subsidence of the area was much slower in the Carnian–to Rhaetian-Early Jurassic than in the Late Anisian–Early Ladinian. At that time the subsidence was already influenced by the thermal cooling of the crust. It is in harmony with the statement of Pigott and Sattayarak (1991) that when the extension of an area reaches a level at which formation of the oceanic crust begins, thermal cooling of the crust starts (see later).

In the cherty limestone, intraclast layers are intercalated, which marks the detritus rushing in from time to time from the neighbouring platform margins. This is most probably in connection with the gradual drowning of the platform edges along faults during the platform back stepping.

Drowning in the sections of the Bükk Mountains appears in the following way: the shallow water limestones (reef, lagoon) are covered first by the so-called transitional layers (pink crinoidal limestone) then by pelagic (cherty) limestone. In all probability, the drowning of the five platforms of the Bükk took place not coevally, moreover even different parts of the platforms were drowned heterochronously. Based on conodonts, the following ages could be determined for the drowning events: Julian, Cordevolian–Julian, Lacian$_1$, Alaunian$_3$.

Development of the platforms was interrupted by the second volcanic event in the Late Ladinian–Early Carnian. This series is represented by metabasalt lava and dyke rocks on the eastern side of the Mountains (Létrás, Lusta Valley, Szinva Spring) and on the eastern margin of the Bükk Plateau. Already Dobosi (1986) establishes that these vulcanites are related to extension and this is reinforced by the investigations of Szoldán (1990) and Harangi et al. (1996). According to Harangi et al. (1996), the basalts and metabasalts, formed during the second volcanic event, are within-plate basalts that came into being in the advanced stage of rifting when partial melting of the asthenosphere gave rise to alkaline magma.

In the Middle–Late Triassic, after the second volcanic event, the expansion of the carbonate platforms decreased continuously, while the pelagic basins covered bigger and bigger areas.

In the Early Jurassic sediments of gravitational mass movements occurred. In red micritic crinoidal limestone small and huge olistoliths are accompanied with slumps. Such a sediment is characteristic for passive continental margins (Allen and Allen 2005).

For the duration of the post-rift stage only an estimated value can be given due to the lack of information about the Jurassic sediments of the Bükk Mountains. At the Triassic–Jurassic boundary the subsidence is low, and continuous. It lasted most probably until the Bajocian-Bathonian boundary. The Bükkzsérc Formation (oolitic limestone of Bathonian age) represents the early occurrence of compression. If we consider the boundary between the Bajocian-Bathonian as the end of the post-rift stage, then it lasted for about 50 million years.

Asymmetric rifting of the Vardar-Meliata branch of the Neotethys Ocean in the Middle Triassic

In the Middle Triassic the rifting of the Vardar-Meliata branch of the Neotethys Ocean had a profound influence on the evolution of the Mediterranean region. Coevally with the rifting of the Vardar-Meliata branch the Paleotethys was gradually closed (Fig. 2).

From the point of view of the presence or lack of the Anisian-Ladinian terrestrial sediments and volcanic rocks the Alpine and the Western Carpathian sequences can be divided in two main groups.

In the Triassic sequences of the Dolomites, Carnic Alps, Julian Alps, South Karavank Mountains, Bükk Mountains, and Dinarides terrestrial sediments (alluvial fans, fluviatile conglomerates, lake marls) appear in the Anisian between the thick carbonate formations, indicating the uplift of these areas. These terrestrial sediments were frequently deposited with a significant discordance on Permian or Carboniferous beds (Placer and Čar 1977; Fois and Jadoul 1983; Brandner 1984; Jadoul and Nicora 1986; Gianolla et al. 1998; Velledits 2004). The thickness of the conglomerate may reach even 500 m at some places (Čar and Skaberne 2003). Coevally with the terrestrial sediments, or following them, vulcanites appear in these areas. Their thickness may reach several hundred metres locally.

According to the paleogeographic model of Dercourt et al. (2000), Ziegler and Stampfli (2001) and Haas (2001), these areas were deposited south of the opening Vardar-Meliata branch of the Neotethys Ocean.

If we compare the subsidence histories of the Bükk Mountains and the Dolomites, the following similarities are conspicuous: both areas suffered uplift in the Anisian, followed by a considerable subsidence in the Early Ladinian. Maurer (2000) pointed to the fact that the rate of subsidence considerably accelerated in the Late Illyrian–Early Ladinian (Reitzi, Secedensis, Curioni zones). He estimates 200 Bubnoffs (m/Ma) for this period. According to him the subsidence during the period of Reitzi–Secedensis–Curioni zone was 600–700 m in the western Dolomites, whereas in the central Dolomites and Carnia it was higher 900–1,050 m. In the Bükk Mountains we do not have such exact age determination, but the tendency of the subsidence is quite similar. After the Anisian uplift the subsidence reached 200–300 m/Ma in the Early Ladinian. A further similarity is that at the beginning of the radical subsidence anoxic laminites were deposited in the areas on the basins in both mountains. The laminites of the borehole Felsőtárkány-7 in the Bükk can be well correlated with the Plattenkalk (lower part of Buchenstein Formation) of the Dolomites. Even their thickness is almost the same (10–15 m). The rapid subsidence stopped in the Ladinian in both areas. Bosellini (1991, 1998) has first pointed out, that the rapid subsidence stopped in the Late Ladinian over almost the whole Dolomite Region. According to Maurer (2000) the subsidence slowed down in the Gredleri and Archelaus zones, reaching only 50 Bubnoffs.

In the Bükk Mountains a similar subsidence history can be reconstructed. Uplift in the Pelsonian-Illyrian, which was followed by a rapid subsidence. This rapid subsidence slowed down at the end of Fassanian.

Although in the Anisian-Ladinian sections of the areas deposited on the southern shelf of the opening Vardar-Meliata branch of the Neotethys Ocean exhibit many individual features, they all share the following characteristics: (a) the presence of the Anisian terrestrial sediments. (b) vulcanites of considerable thickness. (c) as to the subsidence in the Anisian to Carnian three distinctive periods can be distinguished: uplift in the Middle–Upper Anisian, rapid subsidence in the Late Anisian–Early Ladinian, and slow subsidence from the Middle Ladinian onward. Such subsidence history is typical of areas which were deposited on the updoming part/upper plate of a rifting areas: namely uplift, rapid subsidence (mechanical subsidence phase), slow subsidence (thermal subsidence phase). Coevally with the uplift (Anisian), erosion and magmatism begins. It is followed by the rapid subsidence in the Late Anisian–Early Ladinian, which radically slows down later, when the cooling of the crust already controls the evolution of these areas from the Middle Ladinian onward.

Triassic sequences of the Northern Calcareous Alps (NCA), and Western Carpathians (WNC) show a quite different character. Terrestrial sediments and vulcanites of considerable thickness are missing. Coeval with the Anisian terrestrial sediments of the above mentioned areas the platforms (or parts of the platforms) were drowned.

In the above mentioned paleogeographic reconstructions the NCA and the WNC were deposited on the northern self of the opening Vardar-Meliata branch of the Neotethys ocean. (The nappe complex of the WNC is the eastern continuation of the nappes of the NCA below the Neogene sediments of the Vienna basin; Fig. 10a.)

In the Northern Calcareous Alps, due to the "Reifling event" a part of the Steinalm platform was drowned during the Pelsonian (Schlager and Schöllnberger 1975; Lein 1987). Due to the block faulting and rapid deepening of some parts of the Steinalm platform, platforms (Wetterstein Formation) and basins were formed. The basins can be subdivided into the Reifling/Partnach basins (intraplatform basins) and the Hallstatt (s.l.) deeper shelf, the latter one bordering the opening Neotethys Ocean (Mandl 2000).

In the WNC the situation is similar. At the beginning of the Illyrian, but locally already in the Late Pelsonian, the first sediments of basin facies appear in the Silicic and Torna Nappes of the Western Carpathians (Mello et al. 1997), indicating the first significant differentiation of the crust. In the Silicic Nappe, platforms (Wetterstein Limestone) and intraplatform basins (Reifling Limestone, Nádaska Limestone, Schreyeralm Limestone) were formed. The platform edge bordering the opening ocean drowned in the Pelsonian, and remained pelagic from the Pelsonian onward (Bódva unit = Hallstatt facies).

In both areas (NCA, WNC), volcanic rocks are not significant. In most cases, they are present only as some cm or some dm thick vulcanite intercalations.

Middle–Upper Triassic evolution of the areas which were deposited on the northern margin of the opening Vardar-Meliata branch of the Neotethys ocean (NCA, WNC) show common characteristics with the upper crustal breakaway/lower plate part of a rifting area: lack of updoming, and vulcanites, and instead of uplift, the platforms drowned.

The evolution of the two opposite shelves of the opening oceanic branch can be correlated very well. Coeval with the uplift of the southern shelf (Pelsonian-Illyrian) large parts of the northern shelf were drowned. Partly intraplatform basins were formed, partly the Hallstatt facies came into being. Approximately 5 million years after the uplift of the southern shelf a new oceanic branch, the Vardar-Meliata branch of the Neotethys Ocean opened in the Late Fassan-Early Longobardian. Remnants of this oceanic branch (Fig. 10b) can be found today in the Meliata accretionary wedge, which is today situated along the southern margin of the West Carpathians in Slovakia (Faryad et al. 2004) and northern Hungary (Réti 1985, 1988; Dosztály and Józsa 1992). Triassic oceanic remnants are the ophiolites of the Bódva Valley and the opiolithes of the Darnó Hill (Boreholes Recsk 131, and Recsk 136). As a consequence of the opening of the new oceanic branch the rapid subsidence of the crust of the southern margin slows down in the Late Fassanian–Early Longobardian.

Consequently, in the Middle Triassic the areas to the south of the opening Vardar-Meliata branch of the Neotethys Ocean follow the evolution of the updoming part, while the areas to the north of it follow the evolution of the break-away part of a rifting ocean. The evolution of these two shelves and the oceanic remnants can be correlated very well. Middle Triassic sequences of the Alpine–West Carpathian region can be easily fitted into the asymmetric rifting model of Wernicke (1985) and Dixon et al. (1989). However we have to note, that whereas the Middle Triassic–Jurassic evolution of the Bükk Mountains was controlled by the opening and closing of the Vardar-Meliata ocean branch, it has no more effect on the evolution of the Dolomites and the NCA from the Upper Triassic onward.

Conclusions

1. In the Middle Triassic–Early Jurassic volcano-sedimentary series of the Bükk Mountains different stages of a rifting process can be demonstrated. The prerift stage is represented by Pelsonian limestones and dolomites. In the Illyrian the area lifted up (updoming). Coevally with the uplift, active volcanic activity began. Late Anisian–Early Ladinian is characterised by very rapid subsidence (synrift/mechanical subsidence), which slowed down in the Middle Ladinian (postrift/thermal subsidence). At that time the cooling of the crust controls the subsidence.
2. Middle Triassic sediments of the Southern Alps, Carnic Alps, Julian Alps, Southern Karavanks, Dinarides show similar features: uplift, volcanic activity, which is followed by rapid, and later slowly subsidence. Such characteristics are typical of the upper plate margin of a rifting area.
3. Sediments of the NCA and WNC show a strikingly different evolution: absence of the terrestrial sediments and volcanic rocks. Coeval with the uplift of the southern shelf the platforms were drowned in the Late Anisian. These are characteristic to the lower plate of a rifting area.
4. The evolution of the northern and southern shelves can be correlated very well. Coeval with the uplift of the southern shelf (Late Anisian) large parts of the northern shelf were drowned. Approximately 5 million years after the uplift of the southern shelf a new oceanic branch, the Vardar-Meliata branch of the Neotethys Ocean opened in the Late Fassan–Early Longobardian.
5. The opening of the Vardar-Meliata branch of the Neotethys Ocean follows the asymmetric rifting model of Wernicke (1985) and Dixon et al. (1989).
6. Whereas the Upper Triassic–Jurassic evolution of the Bükk Mountains was strongly influenced by the birth and death of the Vardar-Meliata branch of the Neotethys Ocean, from the Upper Triassic onward they had no effect on the evolution of the areas situated to the west of the Bükk Mountains (eg. Dolomites, NCA).

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