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Reconstruction of Middle Triassic platform drowning and basin evolution of the Balaton Highland: new micropaleontological constraints

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A Balaton-felvidéki középső triász platformok megfulladásának és medencefejlődésének rekonstrukciója új mikropaleontológiai adatok alapján

Összefoglalás

A Balaton-felvidék és a Veszprémi-fennsík területén az anisusi emelet középső részét egymással heteropikus fáciesű képződmények alkotják (*1.* és *2. ábra*): a sekélytengeri, karbonátplatform-fáciesű Tagyoni Formáció és a hemipelágikus medencefáciesű Felsőörsi Mészkő. A két heteropikus fácies elterjedése alapján három pelsoi szigetplatform rekonstruálható: a Balaton-felvidék középső részén lévő Tagyoni-platform, az attól északra lévő Barnagi-platform és a Veszprémi-fennsíkon lévő Kádártai-platform (*9. ábra, A*). A korábbi részletes ammoniteszvizsgálatok szerint (VÖRÖS 1998, 2018; VÖRÖS & BUDAI 1993a, b; VÖRÖS et al. 1996, 2003a, b) a közöttük lévő medence üledékképződése folyamatos volt, a Felsőörsi Mészkő és Vászolyi Formáció rétegsorában elkülöníthető az összes ammoniteszzóna a középső anisusitól (Balatonicus Z.) a ladin elejéig (Curionii Z.). Ezzel szemben a pelsoi platformok területén üledékhézag és jelentős fáciesváltozás figyelhető meg a Tagyoni Formáció sekélytengeri, ciklusos rétegsora és a fölötte éles határral települő, felső anisusi medencefáciesű karbonátokból és vulkanitból álló Vászolyi F. között (BUDAI & HAAS 1997, VÖRÖS et al. 1997, BUDAI et al. 1999b), ami a platformok megfulladásaként értelmezhető (BUDAI & VÖRÖS 2006).

A platformok megfulladását előidéző folyamatok korának pontosabb meghatározása céljából mikropaleontológiai vizsgálatot végeztünk mindhárom platform egy-egy szelvényében. Az Akol-domb rétegsorában (*4. ábra*) a Tagyoni F.-ra települő Vászolyi F. krinoideás mészkövének conodonta-együttese a Paragondolella bulgarica Zónába tartozik, ami igazolja a Barnagi-platform peremi részének késő pelsoi megfulladását. A fölötte települő ammoniteszes mészkő (VÖRÖS et al. 2022) conodonta-együttese késő illyr korú, az ostracoda-együttes mély neritikus környezetre utal. A szentkirályszabadjai kőfejtőben (*7. ábra*) a Tagyoni F.-t metsző neptuni telér *Paragondolella bulgarica*, *P. bifurcata* és *P. hanbulogi* conodonta-együttese a Balaton-felvidéki kora anisusi karbonátrámpa feldarabolódását eredményező, extenziós tektonikai esemény pelsoi korát igazolja. Itt a Tagyoni Mészkő fölött éles határral települő Vászolyi F. bázisrétegeiből *P. bifurcata*, *P. hanbulogi* és *Ne. cornuta* conodonta-együttes került elő, amely a Kádártai-platform peremi részének kora illyr megfulladását támasztja alá (BUDAI & HAAS 1997, VÖRÖS 1998). A Dörgicse Drt–1 térképező fúrás a Tagyoni-platform rétegsorát reprezentálja (*8. ábra*), amelyben a Tagyoni F.-ra települő krinoideás mészkő conodonta-együttese a platform kora illyr megfulladására utal.

A platformok megfulladásának árnyaltabb értelmezése céljából az új adatokat együtt elemeztük a korábban publikált Balaton-felvidéki és alpi–dinári kutatási eredményekkel. Megállapítottuk, hogy a három Balaton-felvidéki platform – illetve azokon belül egyes részterületek megfulladásának időpontja területenként bizonyos fokú eltérést mutat (*9. ábra, A, B*), és ezt igyekeztünk összefüggésbe hozni a lehetséges kiváltó okokkal. A legkorábbi megfulladási esemény a pelsoi idejére rögzíthető a Barnagi-platform peremén (*10. ábra, A*). Ezzel egy idejű a Kádártai-platform peremi részén feltárt neptuni telér felnyílása, továbbá megegyezik az Aggtelek–Rudabányai-egység (VELLEDITS et al. 2011, PÉRÓ et al. 2015), az Északi-Mészkőalpok (VELLEDITS et al. 2017, GAWLICK et al. 2021), a Dolomitok (FARABEGOLI & GUASTI 1980) és a Dinaridák (SUDAR et al. 2013) legidősebb középső triász telérjeinek korával. Ez az esemény tehát egyértelműen kapcsolatba hozható a Neotethys nyugati selfjének számos részén megfigyelt, extenziós blokktektonikával (*11. ábra*). A Tagyoni-platform mindhárom korábban vizsgált szelvényében (Szentantalfa, Dörgicse, Vászoly) a pelsoi sekélytengeri karbonát fedőjében települő, legidősebb medenceüledék középső illyr korú (Trinodosus kron, Camunum szubkron) az ammoniteszek alapján (VÖRÖS & BUDAI 1993a, b; VÖRÖS 1998). A Dörgicse Drt–1 esetében a conodonta-fauna ennél valamivel idősebb, kora illyr kort jelez. Időpontját és jellegét tekintve ez a megfulladási esemény egyértelmű korrelációt mutat az Aggtelek–Rudabányai-egység Steinalmi-rámpájának megfulladásával (Szár-hegy; VÖRÖS 2010). A Kádártai-platform DNy-i pereme (Szentkirályszabadja) ugyancsak a Camunum szubkron idején fulladt meg (BUDAI & HAAS 1997), a platform belsőbb részei felé azonban a folyamat kezdete fiatalodást mutat (*9. ábra, A, B; 10. ábra, B*). A kádártai kőfejtő szelvényében a medencefáciesű rétegsor legidősebb conodonta-együttese az illyr végét jelzi (Paragondolella trammeri Z.; KARÁDI et al. 2022). Ez összhangban van a hajmáskér–sólyi területen tapasztaltakkal, ahol a megfulladási felszín fölötti legalsó rétegek ammoniteszfaunája a Reitzi Zóna legfelső, Avisianum szubzónájába tartozik (VÖRÖS 1998, BUDAI et al. 2001). Értelmezésünk szerint a megfulladási esemény időbeli eltolódása elsősorban a Kádártai-platform ÉK felé terjeszkedő tektonikus feldarabolódásával magyarázható, de a megfulladást elősegíthette a tengerszint eusztatikus emelkedése és az egyre intenzívebbé váló vulkanizmus is a késő illyr során (*10. ábra, B*). Az ostracoda-együttesek szerint mély, neritikus, tenger alatti hátsági környezet alakult ki a platformok illyr megfulladását követően. A ladin során az üledékgyűjtő további mélyülését igazolja a batiális (ún. „psychroszferikus") ostracoda-taxonok megjelenése és arányának növekedése az együttesekben.

Ajánlás

Jelen publikációt a szerzők Vörös Attila és Galácz András paleontológusok tiszteletére ajánlják, akik úttörők voltak a szinszediment tektonikai események felismerése és rekonstrukciója terén a Dunántúli-középhegység mezozoos fejlődéstörténetében.

Kulcsszavak: extenziós tektonika, platformmegfulladás, medencefejlődés, conodonta, kagylósrák

Abstract

Three Middle Anisian carbonate platforms (Barnag, Tagyon and Kádárta Platforms) surrounded by the hemipelagic Felsőörs Basin have been reconstructed in the Balaton Highland. The truncated surface of all platforms is covered by basinal carbonates and volcanic rocks of the Vászoly Formation. Based on conodont investigations these platforms were subject to drowning at different times. The earliest drowning was recognized in the late Pelsonian on the southern edge of the Barnag Platform (Paragondolella bulgarica Zone). This date correlates well with the opening of a neptunian dyke encountered near the southwestern margin of the Kádárta Platform and also with the age of the dykes cutting through Pelsonian platforms in the Northern Calcareous Alps, Aggtelek Hills, Dinarides and Dolomites. Drowning of the Tagyon Platform and the marginal area of the Kádárta Platform occurred in the early Illyrian (Paragondolella bifurcata and Neogondolella constricta Zones). However, the Kádárta Platform shows a trend of decreasing age for the timing of the drowning from the edge towards the inner parts of the platform during the late Illyrian. This can be explained by tectonically forced backstepping of the downfaulted marginal blocks and/or by eustatic sea-level rise accompanied by increasing volcanic activity that may have caused the decrease of transparency of the sea-water. Later on, as a result of intensifying sea level rise bathyal environment formed during the Ladinian that can be confirmed by the appearance and increasing dominance of deep-water 'psychrosphaeric' forms in the ostracod assemblage.

Dedication

The authors dedicate the present publication in honor of paleontologists Attila Vörös and András Galácz, who were pioneers in the recognition and reconstruction of synsedimentary tectonic events in the Mesozoic history of the Transdanubian Range.

Keywords: extensional tectonics, platform drowning, basin evolution, conodonts, ostracods

Introduction

During the last geological mapping project of the Balaton Highland several sections were sampled for micropaleontological investigations but only a few of the results on the conodont and ostracod studies were published (KOVÁCS 1993, 1994; KOVÁCS in VÖRÖS 2003b; MONOSTORI 1995; MONOSTORI & TÓTH 2013; TÓTH & MONOSTORI 2015; KARÁDI et al. 2022). In the last years micropaleontological investigations continued to produce important stratigraphic and paleoecologic data. The aim of this paper is to display these results and based on these new inferences to provide a more accurate reconstruction of the evolution of the Middle Triassic carbonate platforms and basins than the previous ones (BUDAI & VÖRÖS 1992, VÖRÖS et al. 1997, BUDAI & VÖRÖS 2006).

Geological setting

The Balaton Highland is located on the southeastern limb of the SW–NE oriented syncline of the Transdanubian Range. It is made up of a very low to low grade metamorphic Paleozoic suite that is unconformably overlain by Permian and Triassic formations. This succession is cut through by the SW–NE oriented Litér thrust; the main structural element of the Balaton Highland. The Middle Anisian formations occur on both the northwestern and southeastern sides of this thrust (*Fig. 1*) showing significant lateral facies change. In a predominant part of the northern thrust-sheet the Middle Anisian is represented by hemipelagic cherty limestones of the Felsőörs Fm. and by the shallow marine platform carbonates of the Tagyon Fm. on the Veszprém Plateau (it was referred to as Szentkirályszabadja Platform

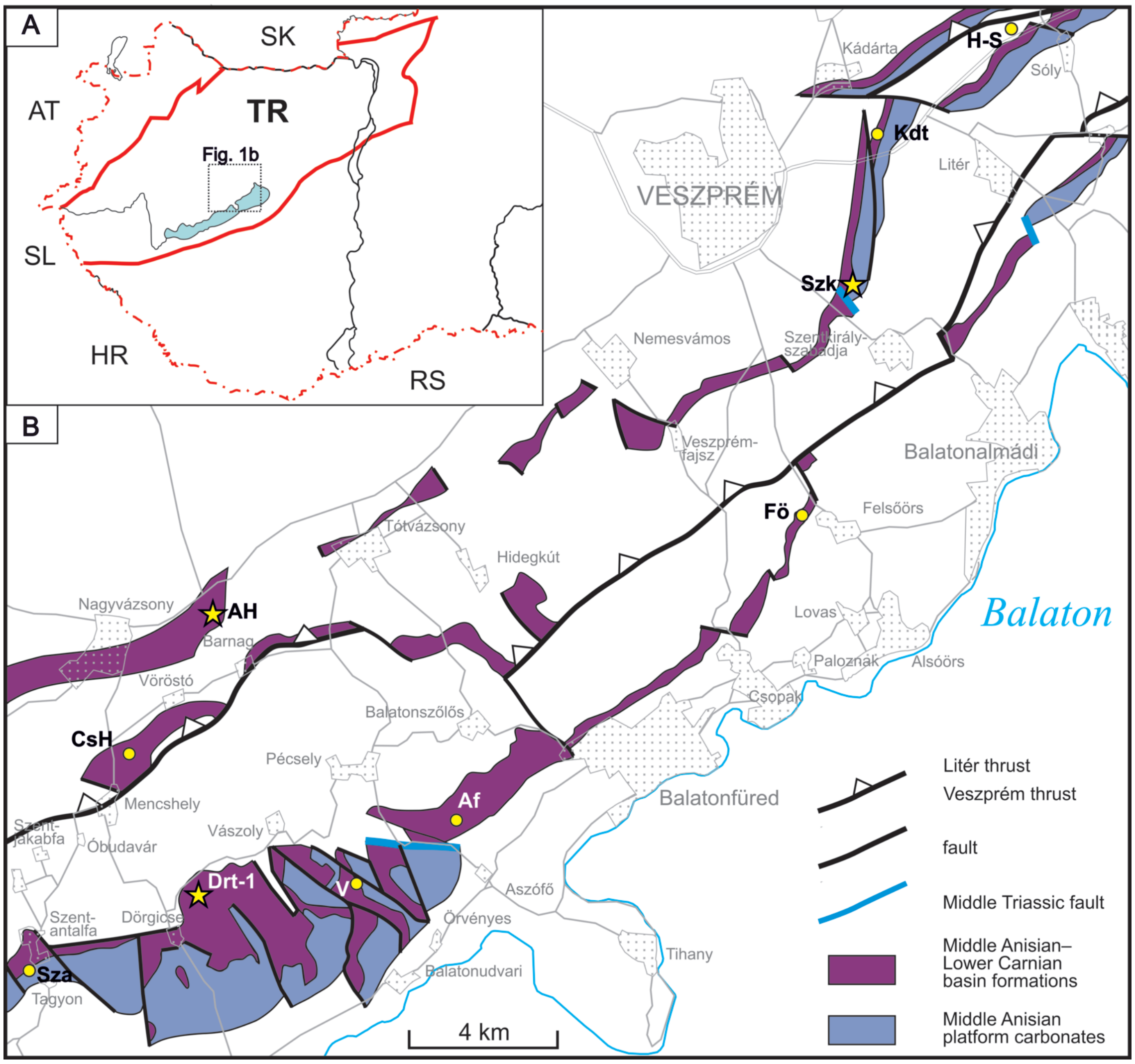


Figure 1. Geographic position of the Transdanubian Range Unit (A) and simplified Pre-Cenozoic geological map of the Balaton Highland (B) showing the areal extension of the Middle Anisian platform carbonates (Tagyon Fm.) and the Middle Anisian–lowermost Carnian basinal formations (Felsőörs, Vászoly, Buchenstein and Füred formations) (after Budai et al. 1999a, 2000). Studied localities (yellow asterics): AH: Akol Hill, Barnag; Drt-1: Dörgicse well; Szk: airport quarry, Szentkirályszabadja. Referred localities (yellow dots): Af: Aszófő; CsH: Cser Hill, Mencshely; Fö: Felsőörs, Forrás Hill; Kdt: Kádárta quarry; H-S: Hajmáskér–Sóly; Sza: Szentantalfa; V: Vászoly, Öreg Hill

***1. ábra.** A Balaton-felvidék prekainozoos földtani térképének helyzete a Dunántúli-középhegységi-egység (TR) területén (A). A középső anisusi platformkarbonátok (Tagyoni F.) és a középső anisusi – alsó karni medencefáciesű képződmények (Felsőörsi Mészkő, Vászolyi F., Buchensteini F., Füredi Mészkő) elterjedése (B). A vizsgált (sárga csillag) és hivatkozott szelvények (sárga pötty) helyének feltüntetésével (Budai et al. 1999a, 2000 nyomán)*

by Budai & Vörös 2006, Haas et al. 2014; and as Kádárta Platform by Karádi et al. 2022). A very small part of another platform was also encountered near Barnag (it was referred to as Vöröstó Platform by Budai & Vörös 2006; and as Barnag Platform by Vörös et al. 2022). In the area of the southern range the Middle Anisian is represented by platform carbonates in the middle part of the Balaton Highland (Tagyon Platform, Budai & Vörös 2006, Haas et al. 2014), and partly by coeval hemipelagic carbonate deposits (lower part of the Felsőörs Fm). Based on the increasing thickness of the Felsőörs Fm. from the NE to the SW (*Fig. 2*) a tectonically controlled halfgraben basin was reconstructed for the Pelsonian to early Illyrian (Budai & Vörös 1993, 2006; Budai & Haas 1997; Budai et al. 1999b). The Pelsonian platforms are covered by Middle–Late Illyrian pelagic carbonates and volcanic tuffs of the Vászoly Fm. Deep marine nodular cherty limestones and radiolarite of the Buchenstein Fm. were formed both above the previous platform and basin areas in the Ladinian (Budai et al. 1999b, 2017).

Material and methods

For conodont biostratigraphic investigations three samples from the dolomite of the airport quarry at Szentkirályszabadja (Szk in *Figs 1* and *2*) and four samples from the lilac-red carbonate of the Akol Hill section were collected (AH in *Fig. 1*). The samples weighed 3 kg each, and were dissolved in hot acetic acid at 10% dilution in the Department of Palaeontology at the Eötvös Loránd University (Budapest). The washing residue was collected using a 125 µm mesh-size sieve. All seven samples contained conodont ele-

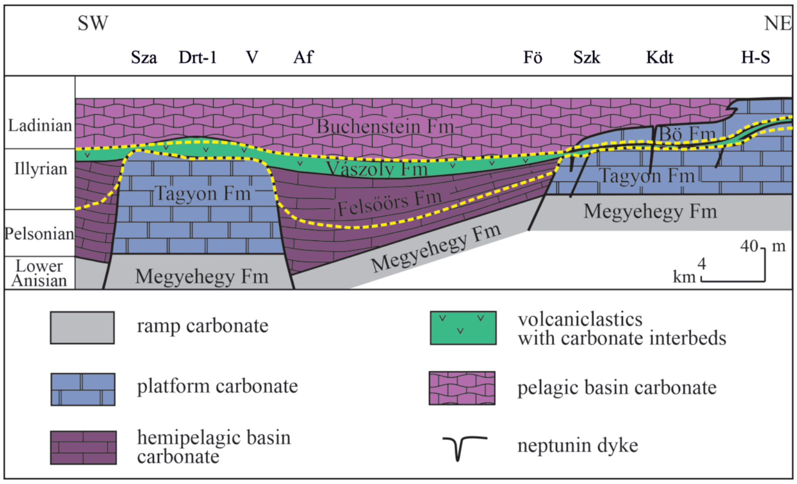


Figure 2. Simplified geological profile from the Veszprém Plateau (NE) to the middle part of the Balaton Highland (SW), showing the lateral and vertical relationship of the Middle Anisian–Ladinian formations (after Budai & Vörös 2006, simplified). For abbreviations see Fig. 1. Bö Fm: Budaörs Dolomite Fm

2. ábra. *Vázlatos földtani szelvény a Veszprémi-fennsíktól a Balaton-felvidék középső részéig a középső anisusi – ladin litosztratigráfiai egységek feltüntetésével (Budai & Vörös 2006 nyomán, egyszerűsítve). Rövidítéseket lásd az 1. ábrán. Bö Fm: Budaörsi Dolomit Formáció*

ments along with fish remains (teeth and placoid scales). Ostracods were recovered from one conodont sample of Szentkirályszabadja. For additional ostracod studies of Akol Hill, the samples (200–300 g air-dried hard limestones) were treated by acetolysis following a protocol originally developed by Lethiers & Crasquin-Soleau (1988) with a slight modification to extract the calcareous microfauna. Only one sample provided suitable ostracod fauna along with few foraminifers, gastropods, bivalves, echinoderm fragments and fish teeth.

Scanning electron micrographs were taken of selected specimens at the Szentágothai Research Centre of the University of Pécs and at the Department of Petrology and Geochemistry of the Eötvös Loránd University. All recovered specimens are stored at the Department of Palaeontology of the Eötvös Loránd University. The microfossils from the Dörgicse Drt–1 core (*Figs 1* and *2*) were studied in the Hungarian Natural History Museum where the material is housed. Conodonts were present in 19 samples and ostracods in 6 samples. Other faunal elements in the samples are represented by foraminifers, holothuroid sclerites, echinoid spines and warts, inarticulated brachiopods, fish teeth and placoid scales. The palaeoecological interpretation of ostracods is based mainly on the qualitative analyses and the semi-quantitative (percentage distribution) analyses of the specimens of the different taxa or groups.

Results

The studied sections yielded abundant and well preserved conodont faunas characterized by a CAI value of 1 that indicates negligible thermal alteration. Biostratigraphic evaluation of the conodonts was based on the studies by Kovács et al. (1980), Kovács (1993, 1994, 2011), Kozur (2003) and Brack et al. (2005). Nomenclature of Kozur (2003) and Muttoni et al. (2004) is followed here. Conodont zones were correlated with the ammonite zonation (*Fig. 3*) of Vörös (1998, 2018) and Vörös et al. (2003). Conodont zones and correlation is mainly based on Kozur (2003) with slight modifications. The Paragondolella trammeri praetrammeri and the subsequent Paragondolella trammeri trammeri zones of Kozur (2003) are merged, because even Kozur (2003: 61) notes that the differences between the two subspecies are not easy to recognise. Therefore, the suitability of *P. trammeri praetrammeri* as an index fossil is debatable. There is an option for distinguishing a Neogondolella pseudolonga zone with a base correlatable to the Avisianum Subzone of the Reitzi Zone where the nominal taxon first appeares (Kozur 2003: 61), but *N. pseudolonga* is stated to be a rare species in the conodont assemblages (Kozur 2003) and thus it is not included in the present zonal scheme. *Neogondolella praehungarica* is often used as marker conodont species for the base of the Ladinian, however, the FAD of this taxon is recorded already in the upper Secedensis Zone (Kozur 2003: 59; Brack et al. 2005).

The ostracod specimens are represented by articulated carapaces suggesting 'in situ' preservation according to Boomer et al. (2003). In hard limestones, the preservation potential of the carapaces strongly depends on the diagenetic processes. The extracted ostracod carapaces from the studied Triassic samples are moderately preserved, recrystallized and sometimes broken.

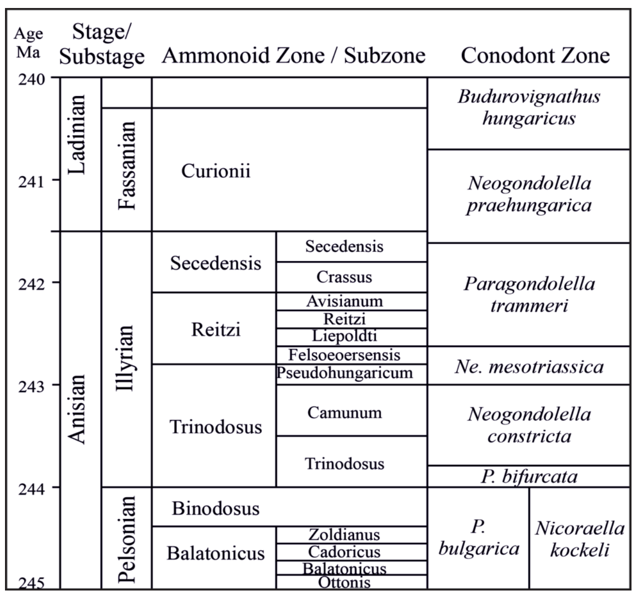


Figure 3. Middle Anisian–Lower Ladinian biostratigraphy of the Balaton Highland after Vörös et al. (2003), Vörös (2018) and Karádi et al. (2022)

3. ábra. *A Balaton-felvidéki középső anisusi – alsó ladin biosztratigráfiai tagolása Vörös et al. (2003), Vörös (2018) és Karádi et al. (2022) nyomán*

Barnag, Akol Hill

The Akol Hill at Barnag (AH in *Fig. 1*; N46°59.419'; E017°44.180') is located north of the Litér thrust where the Middle Anisian succession is unusually thin (*Fig. 4*). The Lower Anisian bituminous dolomite of the Megyehegy Fm. is overlain by a few-metres-thick shallow marine limestone containing oncoids and dasycladalean algae (*Physoporella pauciforata, Oligoporella* sp.) that can be assigned to the Tagyon Fm. (Vörös et al. 2022). It is overlain by the beds of a purple-grey crinoidal hard limestone with a few brachiopods, forming the basal part of the Vászoly Fm. Above it follows a reddish, slightly clayey limestone that contains ammonoids and nautiloids in a rock-forming quantity. In the Illyrian ammonite assemblage (Camunum and Pseudohungaricum Subzones) some species of the Pelsonian Balatonicus Zone also occur in the lower layers. Detailed description of the succession and the cephalopod fauna, together with some vertebrate remains were recently published by Vörös et al. (2022).

In the Akol Hill section the lowermost samples (Ad–7, Ad–6) from the crinoidal limestone (lower part of the Vászoly Fm.) contained the conodonts *Paragondolella bulgarica*, *P. bifurcata*, *P. hanbulogi*, *Nicoraella germanica* and *Ni. kockeli*. This assemblage (*Fig. 5*) is indicative of the late Pelsonian. The species *Neogondolella cornuta* and *P. excelsa* from sample Ad–3 suggest Illyrian age. The fauna characterized by *Ne. cornuta*, *Ne. pseudolonga*, *Ne. mesotriassica* and *P. liebermani* from sample Ad–4 places this level in the late Illyrian.

The sample Ad–4 yielded benthic ostracod assemblage in low abundance. Four taxa (*Hungarella problematica*, *Bairdia bicostata*, *B. cassiana* and *Bairdiacypris triassica*) were identified (*Fig. 6*). The presence of smooth healdoids such as *Hungarella* in the fauna indicate water depth below 30–50 m (Kozur 1991). The composition of the ostracod assemblage (smooth healdoids and bairdioids), the absence of shallow neritic forms (e.g., ornate bairdiids) and 'paleopsychrosphaeric' ostracods suggest most probably open marine deep neritic depositional environment below the storm wave base (according to Karádi et al. 2022).

Szentkirályszabadja, airport quarry

North of the Litér thrust on the rim of the Veszprém Plateau at Szentkirályszabadja a small abandoned quarry (Szk in *Fig. 1*) exposes the shallow marine cyclic platform carbonate of the Tagyon Fm. (Budai et al. 1993, 1999b, 2001). Subtidal beds, containing dasycladalean algae (*Physoporella* div. sp., *Anisoporella, Pontecella, Teutloporella*), gastropods and oncoids, alternate with peritidal stromatolites and pisoidic intercalations. A lucky find of *Balatonites balatonicus* in a subtidal bed (*Fig. 7, A*) proves early Pelsonian age (Balatonicus Zone) of the formation (Budai & Haas 1997, Vörös et al. 2003).

The Tagyon Fm. is cut by a nearly vertical neptunian dyke (*Fig. 7, a, b*) in the southern yard of the quarry (N 47°04'22.36'', E 17°57'29.22''). It is filled by reddish micritic crinoidal packstone (Vörös et al. 1997).

To determine the age of the opening of the dyke a sample was taken for micropaleontological study from the dolomitized crinoidal limestone of the neptunian dyke (Szk–3 in

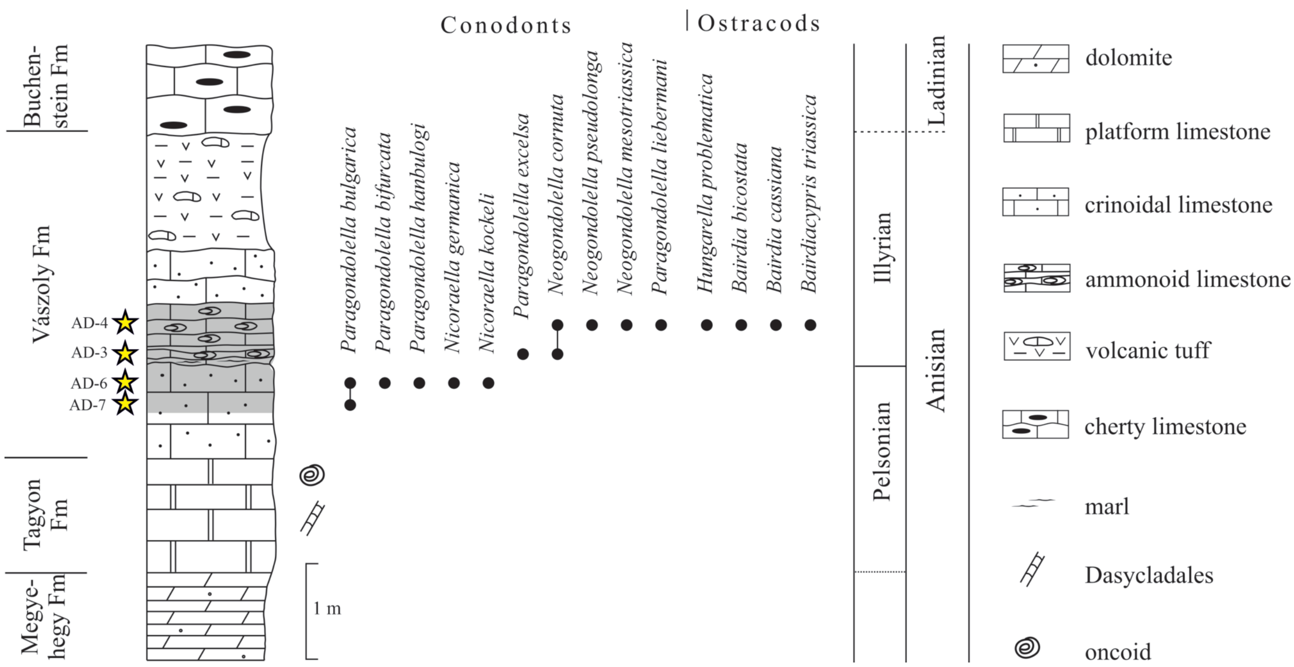
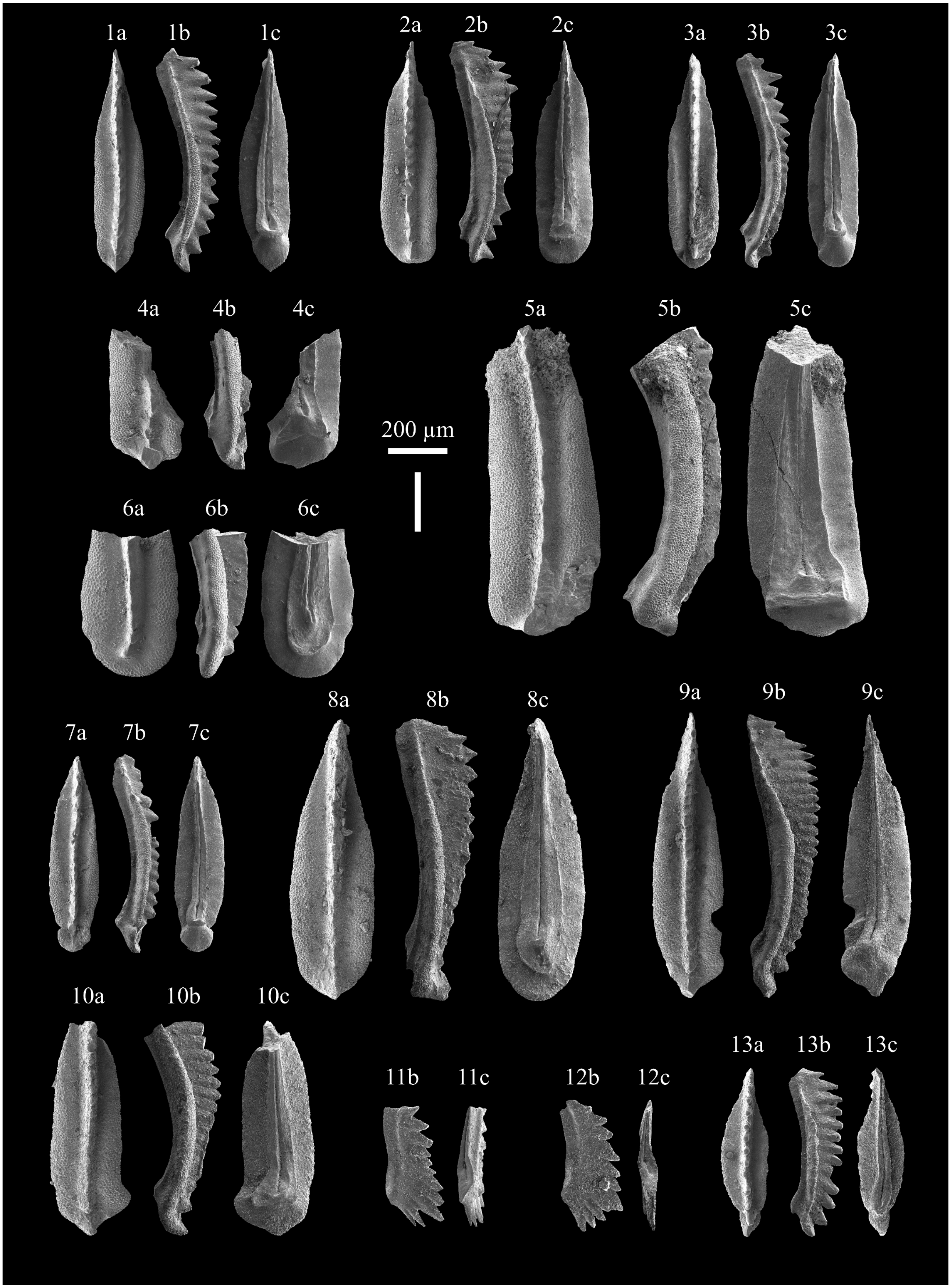


Figure 4. Stratigraphic column of the Akol Hill at Barnag (after Vörös et al. 2022) with the sites of micropaleontological samples (yellow asterisk). Grey shading marks the exposed and studied part of the site

***4. ábra.** A barnagi Akol-domb rétegoszlopa (Vörös et al. 2022 nyomán) a mikropaleontológiai minták feltüntetésével (sárga csillagok). A rétegsor feltárt, vizsgált részét a szürke kiemelés mutatja*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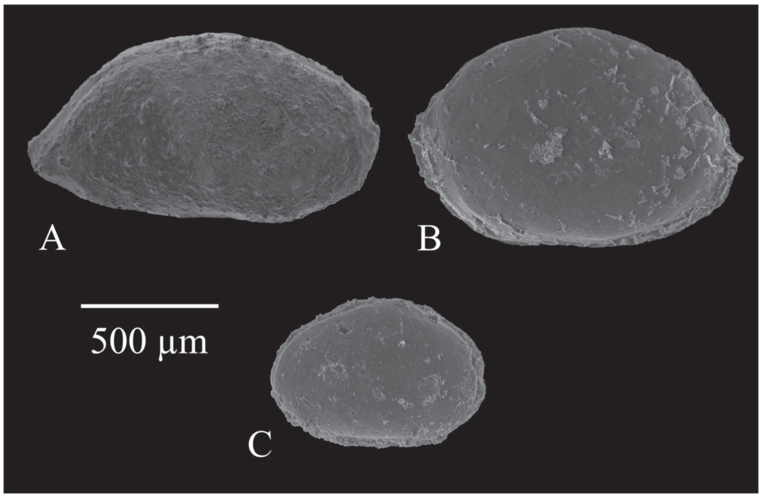

Figure 6. Ostracods from the Akol Hill and the Szentkirályszabadja airport quarry. A) *Bairdia cassiana*, carapace in right view, Akol Hill, sample Ad-4; B) *Hungarella problematica*, carapace in left view, Szentkirályszabadja, sample Szk-2; C) *Hungarella* sp., carapace in right view, Szentkirályszabadja, sample Szk-2

6. ábra. *Kagylósrákok a barnagi Akol-domb szelvényéből és a szentkirályszabadjai repülőtéri kőfejtőből. A)* Bairdia cassiana*, kettősteknő jobb oldali nézetben, Akol-domb, Ad-4 minta; B)* Hungarella problematica*, kettősteknő bal oldali nézetben, Szentkirályszabadja, Szk-2 minta; C)* Hungarella sp.*, kettősteknő jobb oldali nézetben, Szentkirályszabadja, Szk-2 minta*

Fig. 7). The infilling of the dyke contained the conodont species *P. bulgarica*, *P. bifurcata* and *P. hanbulogi*. This assemblage is Pelsonian in age.

In the northern yard of the quarry (N 47°04'25.03'', E 17°57'25.66'') the Tagyon Formation is overlain by a reddish-brown dolomite with a sharp boundary (basal beds of Vászoly Fm., *Fig. 7, A*), that contains a relatively poor ammonite assemblage of the lower Illyrian Camunum Subzone (Vörös 1998, 2018). We took samples (Szk–1, Szk–2) just above the sequence boundary from the basinal dolomite to specify the age of the drowning event. In sample Szk–1 *P. bifurcata*, *P. hanbulogi* and *Ne. cornuta* were found. This assemblage is characteristic for the lowermost Illyrian. *Neogondolella cornuta* and *P. liebermani* from sample Szk–2 are indicative of the Illyrian (but not lowermost Illyrian). This latter sample also yielded ostracods (Fig. 6). Only a few specimens of *Hungarella* were found in the sample from the Vászoly Fm. suggesting a depositional environment below 30–50 m water depth (Kozur 1991).

←**Figure 5.** Conodonts from the Akol Hill section. 1) *Neogondolella pseudolonga*, sample AD-4; 2) *Paragondolella liebermani*, sample AD-4; 3) *Neogondolella cornuta*, sample AD-4; 4) *Neogondolella mesotriassica*, sample AD-4; 5) *Neogondolella cornuta*, sample AD-3; 6) *Paragondolella excelsa*, sample AD-3; 7) *Neogondolella cornuta*, sample AD-3; 8) *Paragondolella hanbulogi*, sample AD-6; 9) *Paragondolella bulgarica*, sample AD-6; 10) *Paragondolella bifurcata*, sample AD-6; 11) *Nicoraella germanica*, sample AD-6; 12) *Nicoraella kockeli*, sample AD-6; 13) *Paragondolella bulgarica*, sample AD-7. a: upper view, b: lateral view, c: lower view. Scale bar: 200 μm

←***5. ábra.*** *Az Akol-domb szelvényének conodontái. 1)* Neogondolella pseudolonga*, AD-4 minta; 2)* Paragondolella liebermani*, AD-4 minta; 3)* Neogondolella cornuta*, AD-4 minta; 4)* Neogondolella mesotriassica*, AD-4 minta; 5)* Neogondolella cornuta*, AD-3 minta; 6)* Paragondolella excelsa*, AD-3 minta; 7)* Neogondolella cornuta*, AD-3 minta; 8)* Paragondolella hanbulogi*, AD-6 minta; 9)* Paragondolella bulgarica*, AD-6 minta; 10)* Paragondolella bifurcata*, AD-6 minta; 11)* Nicoraella germanica*, AD-6 minta; 12)* Nicoraella kockeli*, AD-6 minta; 13)* Paragondolella bulgarica*, AD-7 minta. a: felülnézet, b: oldalnézet, c: alulnézet. Skála: 200 μm*

Dörgicse Drt–1 well

The Dörgicse Drt–1 well (N 46°55'31.68", E 17° 43'45.93") exposed the Middle Anisian to lowermost Carnian succession of the middle part of the Balaton Highland (Drt in *Fig. 1*). The cyclic platform carbonate of the Tagyon Fm. is overlain with a sharp contact by a light brownish crinoidal limestone of the Vászoly Fm. (*Fig. 8*), which contains ammonites of the lower Illyrian Camunum/Pseudohungaricum Subzone (Vörös 1998, 2018). It is overlain by a colourful (green reddish or lilac) tuffitic limestone and volcanic tuff ("pietra verde"). The upper part of the formation consists of bedded light grey limestone ("Vászoly Limestone Mb", Vörös et al. 1997). The overlying Buchenstein Fm. is formed by a colourful (reddish, greenish or lilac) succession of nodular limestone with chert nodules and marl intercalations, alternating with volcanic tuff layers. Radiolarians in the upper part of the formation (*Fig. 8*) belong to the Upper Ladinian (Longobardian) *Muelleritortis cochleta* Zone (Dosztály 1993). The Füred Limestone Fm. is made up of light grey micritic limestone, with a 10-centimetres-thick marly interlayer in the lower part, containing many thin-shelled bivalves (e.g. *Halobia*) on the bedding surface.

The lowest samples (75.4–75.2 m, 74.6–74.4 m) from the Vászoly Fm. of the Drt-1 core (*Fig. 8*) yielded a conodont fauna characterized by *P. bifurcata* and *P. hanbulogi*. This assemblage is either uppermost Pelsonian or lowermost Illyrian. Somewhat higher, from the samples at 72.8–72.6 m and 69.2–69.0 m a rather poor assemblage was recovered consisting of the species *Ne. cornuta* and *Gladigondolella tethydis*, which indicates Illyrian substage. The following interval (from 68.8 to 61.8 m) can be assigned either to the uppermost Illyrian or to the lowermost Fassanian based on the conodonts *Ne. praehungarica*, *Ne. cornuta*, *Ne. mesotriassica*, *P. fueloepi*, *P. trammeri*, *P. alpina*, *P. excelsa* and *Gl. tethydis*. The lower part of the Fassanian is represented by *Ne. cornuta*, *Ne. pseudolonga*, the *Ne. bakalovi*-group, *Ne. praehungarica*, *Ne. transita*, *P. trammeri* and *Gl. tethydis* from 61.8 m to 55.6 m. In the sample at 53.6–53.4 m a conodont specimen assignable to the genus aff. *Budurovignathus* sensu Chen et al. (2016) was found. The sample at 47.7–47.4 m contained an assemblage consisting of *P. trammeri*, *Budurovignathus mungoensis* and *Gl. tethydis*, which suggests uppermost Fassanian or Longobardian substage. The conodont *Paragondolella* cf. *inclinata* in sample at 23.7–23.5 m is indicative of the Longobardian or the Julian (Lower Carnian). In the highest positive sample of the core (22.4–22.1 m) only long-ranging *Gl. tethydis* and *Gl. malayensis* were found.

The ostracod fauna found in the samples between 74.6 to 57.4 m from the nodular limestone of Vászoly Fm. is very similar to the assemblage of Akol Hill. Smooth healdoids

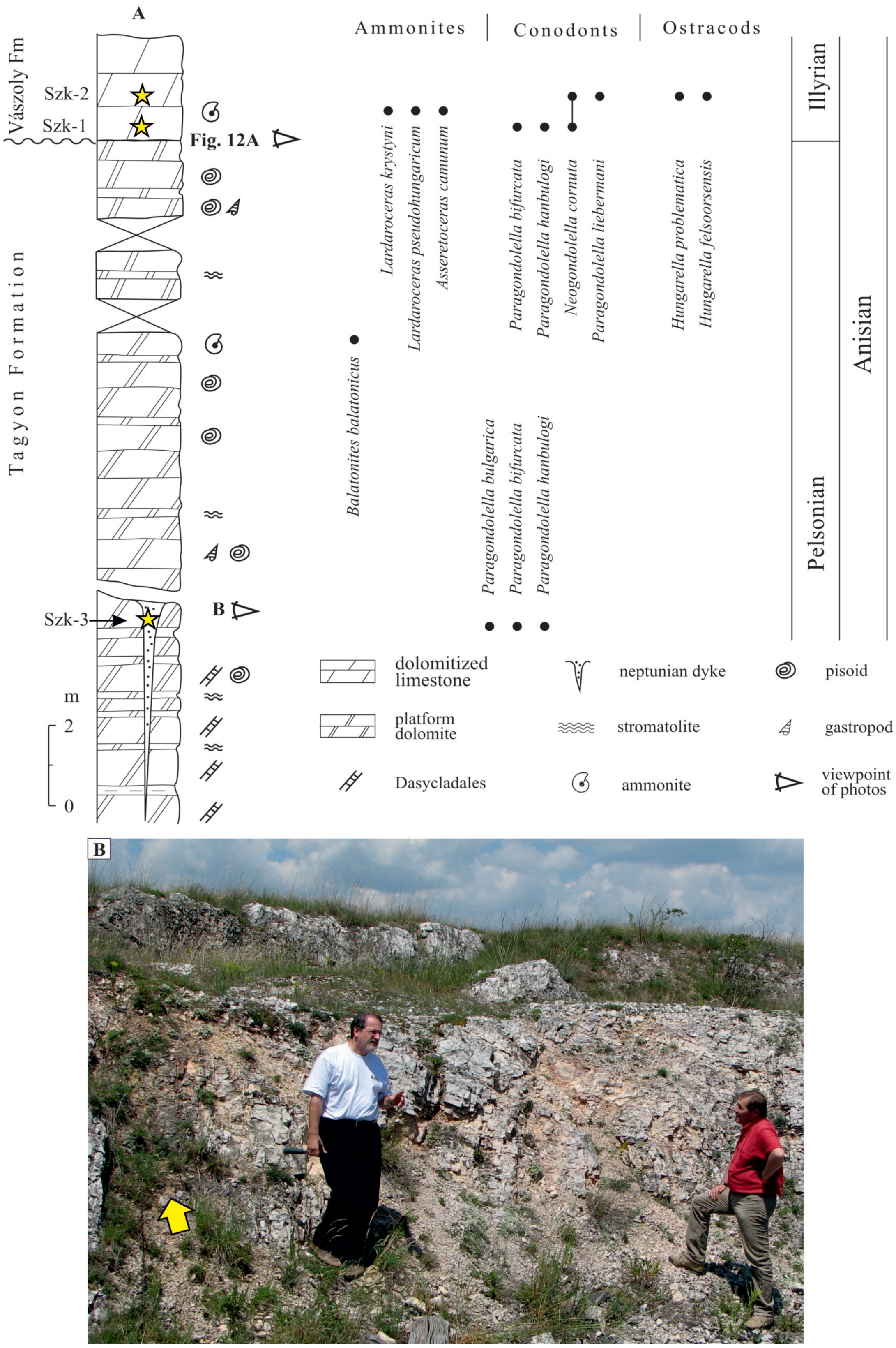

Figure 7. Stratigraphic column (A) of the airport quarry at Szentkirályszabadja (after BUDAI et al. 2001) indicating the sites of the samples for micropaleontology (yellow asterisk). Ammonoid data after VÖRÖS (1998, 2018) and VÖRÖS et al. (2003). Photograph (B) shows the two jubilant paleontologists in 2007 on a field-trip, studying the neptunian dyke (yellow arrow) that penetrates the Tagyon Fm. (photo: Zs. KERCSMÁR)

7. ábra. *A szentkirályszabadjai repülőtéri kőfejtő rétegoszlopa (A) (BUDAI et al. 2001 nyomán), feltüntetve a mikropaleontológiai minták helyét (sárga csillag). Ammoniteszadatok VÖRÖS (1998, 2018) és VÖRÖS et al. (2003) nyomán. A fényképen (B) a két ünnepelt paleontológus látható egy kiránduláson 2007-ben a Tagyoni Formációt harántoló neptúni telér (sárga nyíl) tanulmányozása közben (fotó: KERCSMÁR Zs.)*

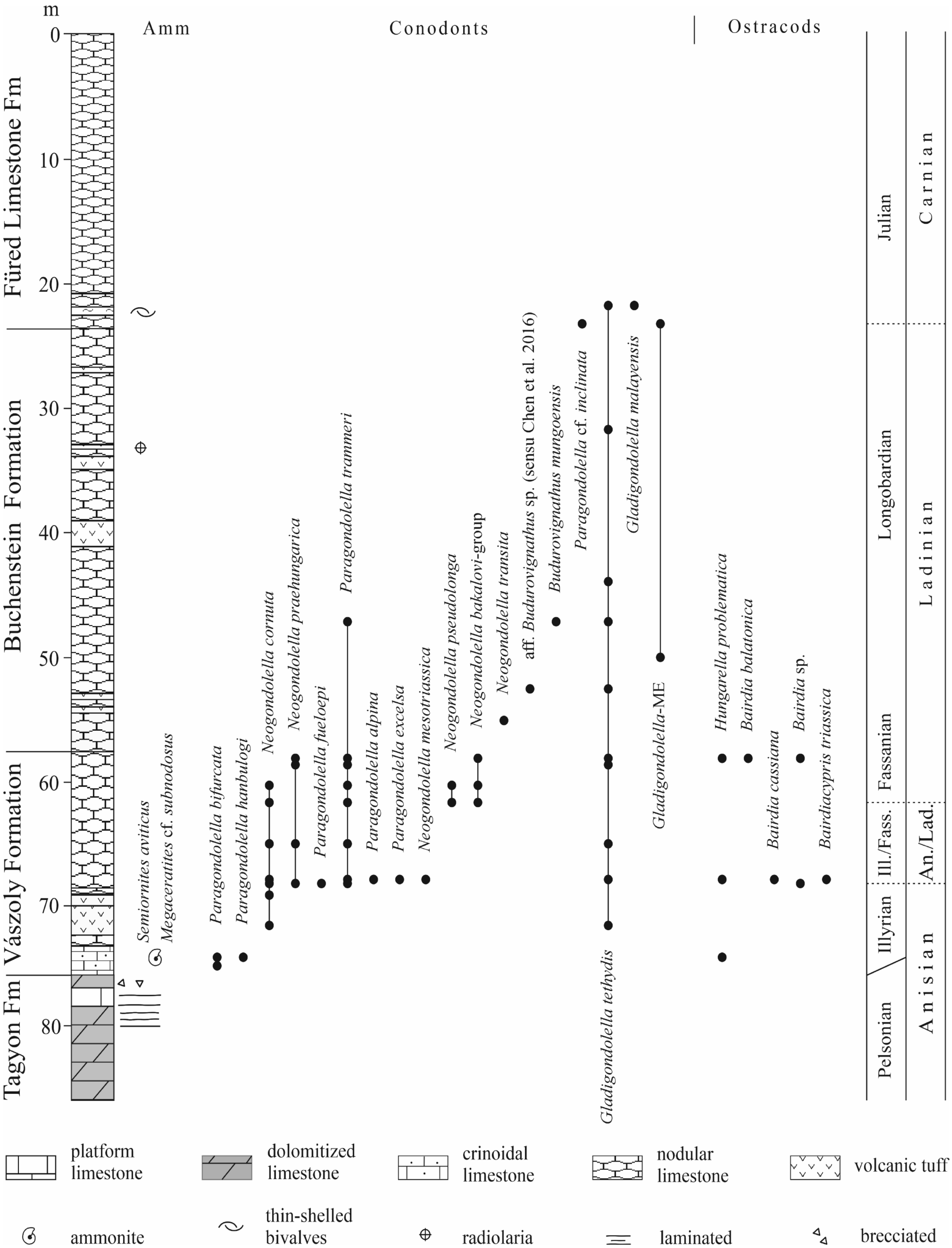

Figure 8. Stratigraphic column of Dörgicse Drt–1 drill core (after BUDAI et al. 1993, 1999b) showing the stratigraphic position of the conodont and ostracod taxa. Ammonoid data are based on VÖRÖS (1998)

8. ábra. *A Dörgicse Drt–1 fúrás rétegoszlopa (BUDAI et al. 1993, 1999b nyomán), feltüntetve a conodonta és ostracoda taxonok rétegtani elterjedését. Ammoniteszadatok VÖRÖS (1998) nyomán*

(*Hungarella problematica*), smooth bairdiacypridiids (*Bairdiacypris anisica*) and bairdiids (*Bairdia cassiana*) form the ostracod assemblage. The fauna suggests open marine deep neritic depositional environment below the storm wave base like in the Akol Hill section. Unrepresented numbers of *Hungarella problematica* and *Bairdia* sp. were recovered from the samples (23.7–23.5 m and 22.4–22.1 m) of Füred Limestone.

Discussion

In the studied region, the Pelsonian platform carbonates (Tagyon Fm.) are directly overlain by ammonite bearing crinoidal limestone/dolomite beds representing the basal part of a deeper-water hemipelagic basin succession (Vászoly Fm.). Accordingly, examples for the platform drowning could be encountered and studied here and the new micropaleontological investigations provided new data for the exact dating and better understanding the process of this drowning event.

The previously published biostratigraphic data (VÖRÖS et al. 1997, VÖRÖS 1998, BUDAI & VÖRÖS 2006, VÖRÖS 2018, KARÁDI et al. 2022) and our new conodont stratigraphic results confirmed that ages of the base of the post-drowning successions above the Pelsonian platforms are different (*Fig. 9, A*).

Three Pelsonian platforms were recognised in our study area (Barnag, Tagyon and Kádárta Platforms; *Fig. 9, B* and *Fig. 10*) although only a small part of the Barnag platform was explored.

Extensional tectonics

To determine the timing of the extensional tectonic activity we obtained data from the margin of the Kádárta Platform. The conodont fauna of the neptunian dyke in the Szentkirályszabadja quarry (*Fig. 7*) proves Pelsonian age.

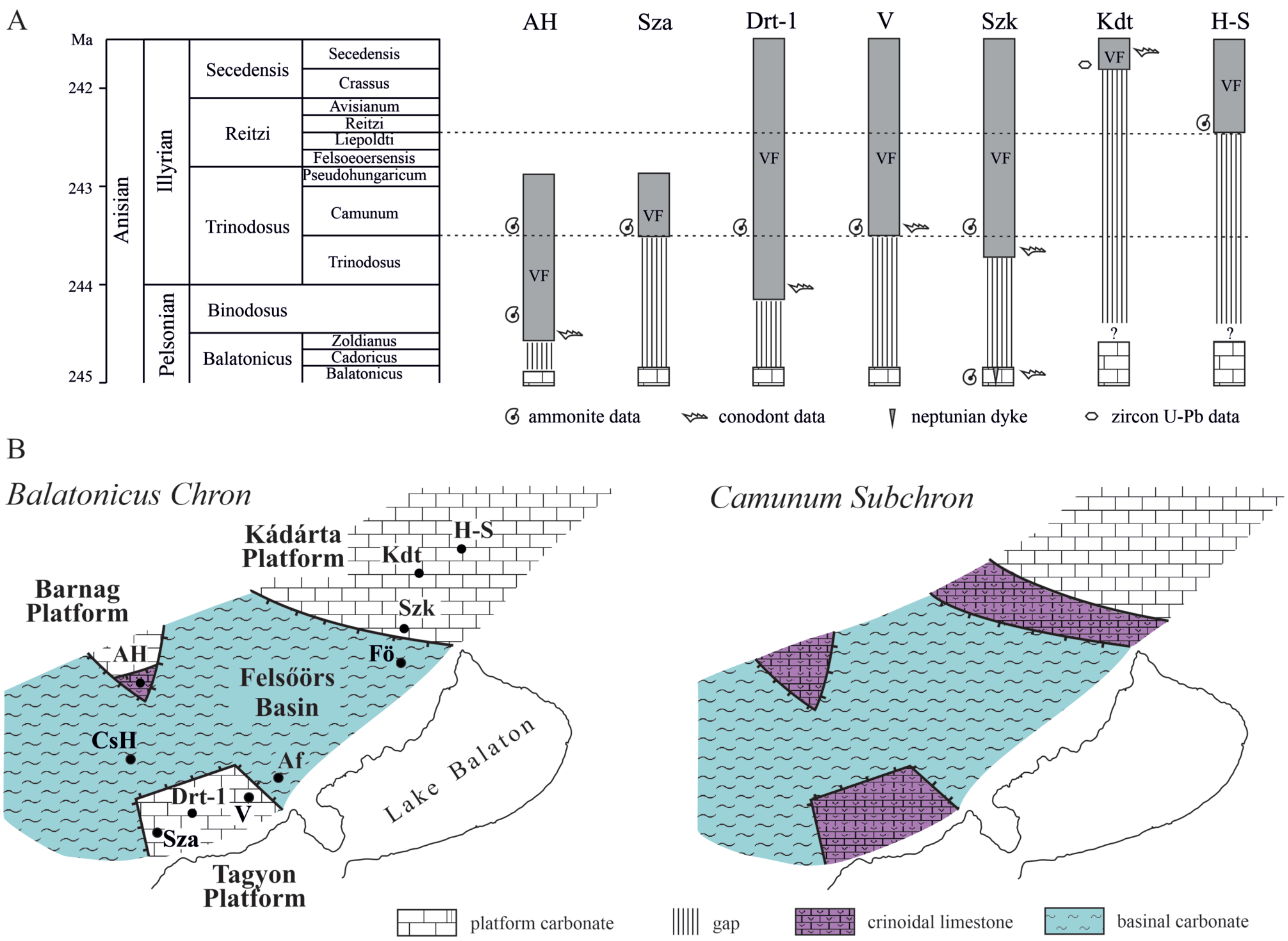

Figure 9. A) Simplified stratigraphic charts of the studied sections showing the gap between the Pelsonian platform carbonate (Tagyon Fm.) and the overlying oldest basin sediments (VF – Vászoly Fm.). AH: Akol Hill (VÖRÖS et al. 2022); Sza: Szentantalfa (VÖRÖS 2018); Drt–1: Dörgicse drill core (VÖRÖS 2018; conodonts this paper); V: Vászoly (VÖRÖS 2018; conodonts KOVÁCS 1994); Szk: Szentkirályszabadja (VÖRÖS 2018; conodonts this paper); Kdt: Kádárta (KARÁDI et al. 2022); H–S: Hajmáskér–Sóly (VÖRÖS 2018). B) Palaeogeographic sketch of the Balaton Highland for the Pelsonian and for the early Illyrian showing the reconstructed position of the three isolated carbonate platforms and the hemipelagic basin between them (after BUDAI & VÖRÖS 2006; modified)

9. ábra. *A) A vizsgált és hivatkozott szelvények egyszerűsített rétegtani táblázata, a pelsoi platformkarbonátok és a legidősebb medencefáciesű fedő üledékek (VF – Vászolyi F.) közötti üledékhézag feltüntetésével. B) A Balaton-felvidék ősföldrajzi vázlata a pelsoi és a kora illír korszakban, a három karbonátplatform és a közöttük lévő, hemipelágikus medence rekonstruált helyzetével (BUDAI & VÖRÖS 2006 nyomán, módosítva)*

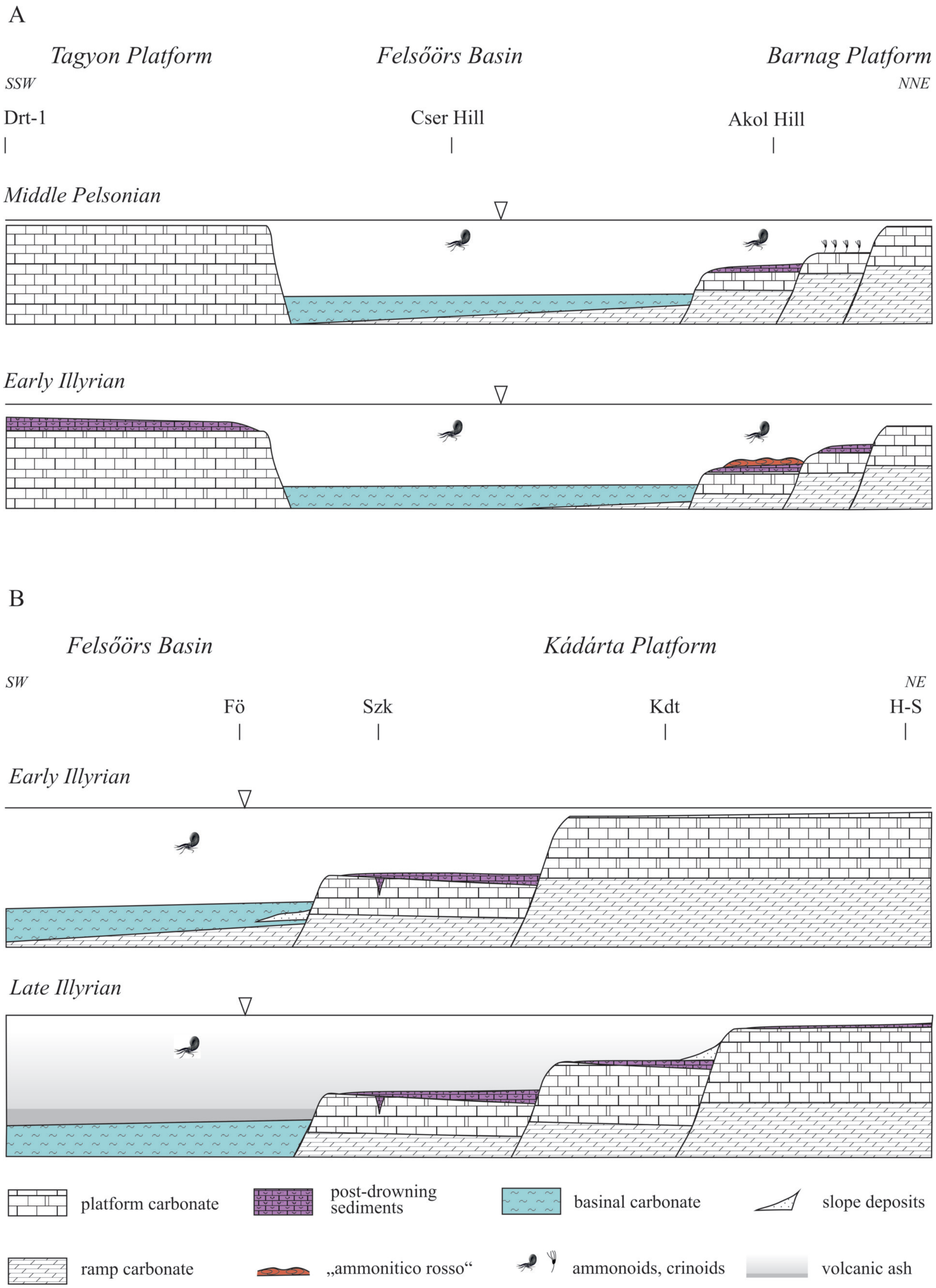

Figure 10. Palaeogeograhic profile A) between the Barnag and Tagyon platforms through the Felsőörs Basin and B) across the transition of the Felsőörs Basin and the Kádárta Platform. For the name of the studied/referred sections see Fig. 1.

10. ábra. *Ősföldrajzi szelvény A) a Barnagi- és a Tagyoni-platform között, a Felsőörsi-medencén keresztül; valamint B) a Felsőörsi-medence és a Kádártai-platform érintkezésén keresztül. A vizsgált/hivatkozott szelvények nevét lásd az 1. ábrán*

This date corresponds well with adjacent parts of the western Neotethys shelf (*Fig. 11*). In the Monte Rite area of the Southern Alps (SA in *Fig. 11*) Farabegoli & Guasti (1980) reported three generations of neptunian dykes that penetrate the Pelsonian Upper Serla Platform. In the Aggtelek–Rudabánya Unit (A–R in *Fig. 11*) the Middle Anisian Steinalm Ramp is dissected by neptunian dykes, filled by red pelagic limestone rich in fragments of thin-shelled bivalves ("filaments"). Based on conodont assemblages, Late Pelsonian and Early–Middle Illyrian dyke generations were identified (Velledits et al. 2011). Similar dual dyke generations were observed in the Schreyeralm area of the Northern Calcareous Alps (Austroalpine Units in *Fig. 11*; Velledits et al. 2017; Gawlick et al. 2021). In the Dinarides (OD in *Fig. 11*) the neptunian dykes that penetrate the Pelsonian platform carbonate (Ravni Fm.) started to form in the Late Pelsonian (Sudar et al. 2013). In the Late Illyrian the tectonic activity intensified again and the dykes cross-cut not only the platform carbonates but the older post-drowning basinal deposits (Bulog Limestone), as well (Gawlick et al. 2023).

Platform drowning

In the Akol Hill section at Barnag (*Fig. 4*, AH in *Fig. 9, A, B*) above the extremely thin Tagyon Limestone the conodont fauna constrains Pelsonian age for the basal crinoidal limestone beds. This indicates a relatively early flooding above the block-faulted margin of the Barnag Platform in the Middle Anisian (*Fig. 10, A*). The Early Illyrian ammonite fauna of the overlying condensed "ammonitico rosso" limestone also contains Pelsonian forms (Vörös et al. 2022). The dissolved specimens coated by Fe–Mn oxide crust suggest very slow and episodic sedimentation in a current dominated environment.

In the area of the Tagyon Platform, on the basis of the ammonite fauna, the basal beds can be assigned to the Early Illyrian (Camunum Subchron, Vörös 1998; Budai & Vörös 2006; Vörös 2018) in both the Szentantalfa (Sza in *Fig. 9, A, B*) and in the core Dörgicse Drt–1 (*Figs 8* and *9, A, B*). It has to be mentioned that in the case of conodonts the Early Illyrian age of the lowermost layers of the Vászoly Fm. in Dörgicse Drt–1 core is only based on the lack of the Pelsonian *P. bulgarica*. However, this can easily be a bias caused by the very limited material available for conodont investigation. Since *P. bifurcata* and *P. hanbulogi* are also present prior to the Illyrian, a Late Pelsonian age of the basal beds cannot be excluded. In the marginal Vászoly section (V in *Fig. 9, A, B*) the age of the oldest post-drowning sediment is Early Illyrian (Camunum Subchrone) based on ammonoids (Vörös 1998, 2018) and conodonts (Kovács 1994), as well.

In the Szentkirályszabadja section (*Fig. 7*, Szk in *Figs 9, A, B* and *10, B*), which may have been located near the western margin of the Kádárta Platform, the basal post-drowning hemipelagic carbonate beds (*Fig. 12, A*) can be assigned to the Early Illyrian (Camunum Subchron). However, conodonts found in the dyke prove earlier, Late Pelsonian drowning as a result of downfaulting of the platform margin. In the section of the Kádárta quarry (*Fig. 12, B*), representing the internal part of this platform (*Fig. 9, B*), based on conodont and zircon age data (*Fig 9, A*; Karádi et al. 2022) latest Illyrian age (Secedensis Chron) of the volcaniclastic beds of the Vászoly Fm. was pointed out. In the internal platform area at Hajmáskér–Sóly, based on ammonoid data (Vörös 2018), somewhat older age (Reitzi Subchron) was determined for the oldest post-drowning sediments.

We must note that the age data for the base of the post-drowning succession provide information on the age of first record of the post-drowning deposition, which is not necessarily identical to the timing of the drowning event. In many cases the drowning is followed by a period of non-deposition leading to a short- or long-term stratigraphic gap (Read 1982, 1985; Schlager 1989, 1991, 2005). The drowning is commonly preceded by subaerial exposure and erosion of the platform that resulted in the apparent increase in the duration of the gap. Various factors (in many cases combination of several factors) may lead to the drowning of carbonate platforms. In exten-

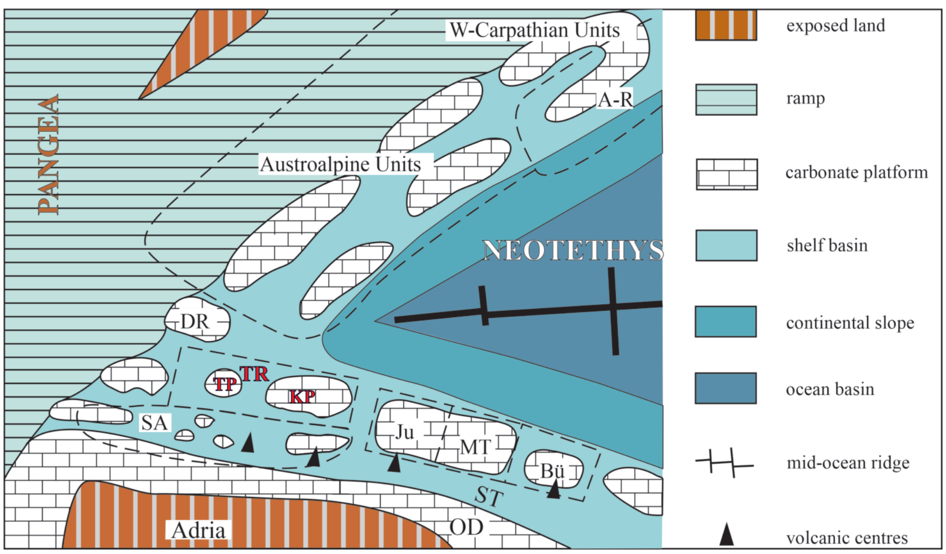

Figure 11. Palaeogeographic setting of the Tagyon Platform (TP) and the Kádárta Platform (KP) within the Transdanubian Range Unit (TR) during the Middle Triassic in the western part of the Neotethys (Budai et al. 2017, Karádi et al. 2022)

A–R: Aggtelek–Rudabánya Unit; Bü: Bükk Unit; DR: Drau Range; Ju: Julian Alps; MT: Mid-Transdanubian Unit; OD: Outer Dinarides; SA: South-Alpine Units; ST: Slovenian Trough

11. ábra. *A Tagyoni-platform (TP) és a Kádártai-platform (KP) középső triász ősföldrajzi helyzete a Dunántúli-középhegység-egységen (TR) belül a Neotethys nyugati selfjén (Budai et al. 2017, Karádi et al. 2022)*

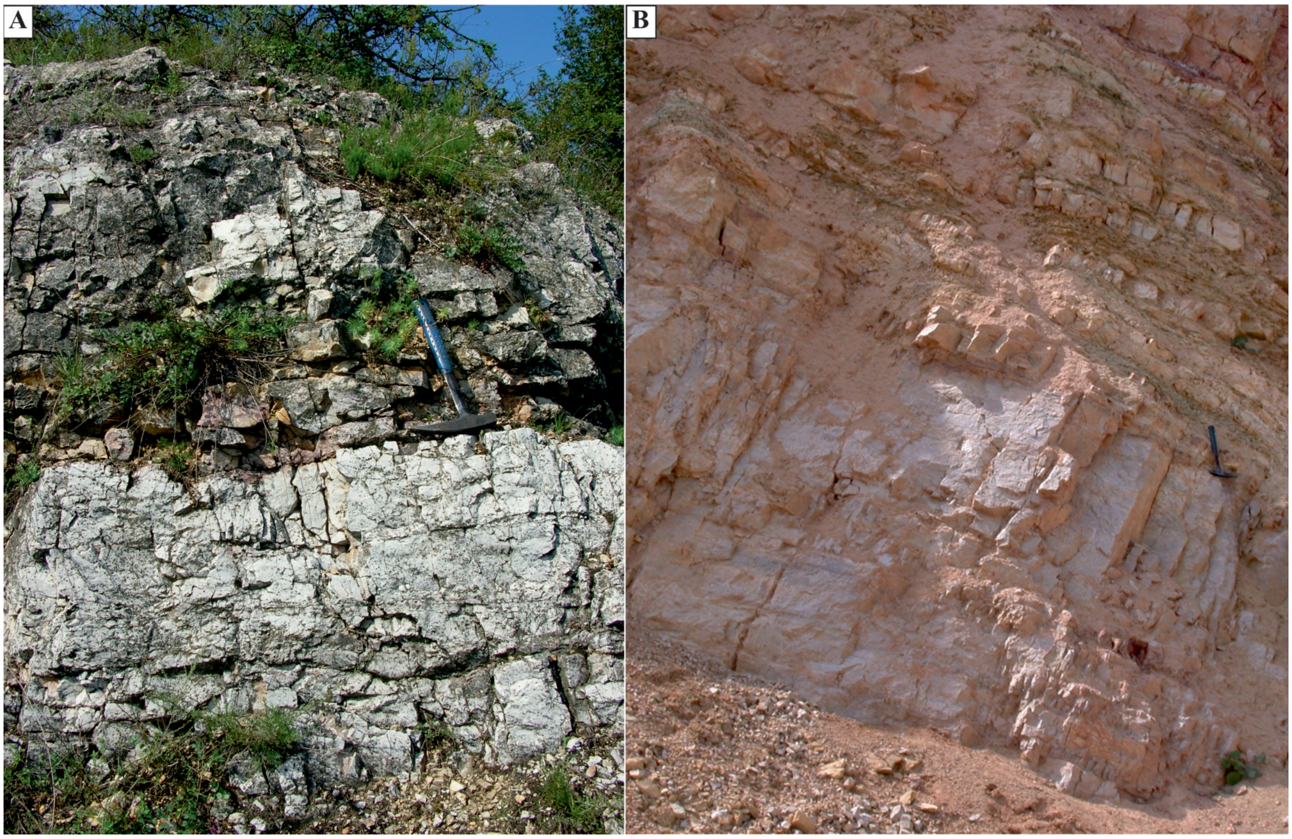

Figure 12. Drowning unconformity on the top of the Pelsonian Tagyon Fm. (at the hammer), that is covered by A) dolomitized ammonitic Lower Illyrian limestone (Camunum Subzone) in the quarry at Szentkirályszabadja; and B) uppermost Illyrian volcaniclastic layers (Secedensis Zone) in the quarry at Kádárta

12. ábra. *Megfulladási diszkordancia felszín a pelsoi Tagyoni F. felső határán (kalapács a képeken), amelyre A) ammoniteszes, dolomitosodott alsó illyr mészkő (Camunum Szubzóna) települ a szentkirályszabadjai kőfejtőben; és B) legfelső illyr vulkanoklasztit rétegsor (Secedenis Zóna) települ a kádártai kőfejtőben*

sional structural regimes the tectonically forced retrograding of the margin may result in an exceptionally fast subsidence of the downfaulted blocks and, accordingly, the end of the production of the euphotic carbonate factory (*Fig. 10, B*). Coeval acceleration of subsidence and an intense eustatic sea level rise may also lead to drowning. Decreasing water transparency and, consequently, the shallowing of the light-saturated zone may also be a dominant factor in the drowning or may contribute to this phenomenon. Influx of large amount of suspended terrigenous material (clay and/or fine organic material) or extreme proliferation of planktonic organisms may be responsible for the reduced transparency.

At the beginning of the Pelsonian, the Akol Hill section was located in the external belt of the Barnag Platform (*Fig. 9, B*). Here, the Pelsonian drowning can be attributed to downfaulting of the platform margin when a fault-controlled and probably step-like slope may have come into being (*Fig. 10, A*). The drowning was likely followed by a period of non-deposition due to high-energy currents. Resedimented fragments of crinoids in the basal bed of the post-drowning succession may have been derived from higher terraces of the slope (*Fig. 10, A*), similar to the sedimentation model proposed by Galácz & Vörös (1972) and Galácz (1988) for the Early Jurassic deposition of the Hierlatz-type limestones. The overlying condensed bed-set with a rich but partly reworked, mixed ammonite fauna reflects high-energy depositional conditions allowing only ephemeral sediment deposition and preservation.

In the area of the Tagyon Platform the drowning took place prior to the Early Illyrian (Camunum Subchron) both in near margin setting that is represented by the Vászoly sections (V in *Fig. 9, A, B*), and also in the central part of the isolated platform that is represented by the Szentantalfa section (Sza in *Fig. 9, A, B*) and the Dörgicse Drt–1 drill core (*Fig. 9, A, B* and *Fig. 10, A*). To determine the cause of the drowning we must take into account the facies of the basal beds of the post-drowning succession. They are made up of carbonate layers rich in radiolarians, fragments of thin-shelled bivalves, crinoids, ammonites and brachiopods and volcanic tuff interlayers. This bed set is punctuated by phosphoritic horizons along the NE plaform margin represented by the Vászoly section (Budai et al. 2017). These litho- and biofacies characteristics suggest that along with the accelerated subsidence of this block and the coeval eustatic sea-level rise the reduced transparency as a result of enhanced productivity and input of volcanic dust might have played a critical role in the drowning. The radiolarians are indicators of high productivity of the surface waters, which depends on the fertility controlled by the availability of limiting nutrients (e.g. P, Si) (De Wever & Baudin 1996, De Wever et al. 2014). Due to common abundance of radiolarians in pyroclast-bearing successions, the role of input of volcanic dust in the fertilization of sea-surface was also put forward (LIN et al. 2011, ABDI et al. 2016). Considering the palaeogeographic constrains, a monsoon-driven local upwelling and/or the input of volcanic material seems to be the source of the limiting nutrients along the margin of the Tagyon Platform (BUDAI et al. 2017).

In the marginal area of the Kádárta Platform (Szentkirályszabadja quarry, Szk in *Fig. 9, A, B* and *10, B*) pedogenic crusts or stromatolitic horizons (akin to those in the core Drt–1) occur between the thick beds of the platform carbonate containing a rich shallow marine fossil assemblage. Accordingly, this succession reflects periodically changing depositional conditions; shallow marine lagoon and peritidal environments alternated as a consequence of the high frequency sea-level oscillation (HAAS et al. 2014). In contrast, in the inner part of the Kádárta Platform (Kádárta quarry, Kdt in *Fig. 9, A, B* and *10, B*) at least in the upper part of the Tagyon Formation, the peritidal horizons are subordinate suggesting permanency of the subtidal depositional setting even during the periods of lowest sea level (HAAS et al. 2022). According to biostratigraphic constrains, the age of the basal part of the post-drowning succession is Illyrian in both sections (*Fig. 9, A*); however, it does not mean that the drowning took place at the same time. It is more probable that, due to downfaulting of the platform margin zone, the drowning happened earlier in the Szentkirályszabadja area (*Figs 9, A* and *10, B*), although on the top of the downfaulted block the intense current activity hindered sediment deposition for a while, which could only accumulate in the fissures. Conversely, in the more internal part of the platform, which is represented by the Kádárta quarry section, the shallow marine conditions may have been prolonged during the Early Illyrian, although there are no exact biostratigraphic data for this. Nevertheless, the latest Illyrian was already characterized by deep-water sedimentation in this area as well (*Figs 9, A* and *10, B*; KARÁDI et al. 2022). The thick sedimentary breccia bed set, occurring above the post-drowning pelagic tuffaceous dolomite layers, can be interpreted as a platform foreslope deposit indicating the presence of the coeval platform margin near this place (*Fig. 9, C*). Further northeast in the Hajmáskér–Sóly sections (H-S in *Figs 9, A, B* and *10, B*) the oldest post-drowning layers are somewhat older; based on ammonoid biostratigraphic data they belong to the Reitzi Subzone of the Reitzi Zone (VÖRÖS 2018). In this area the intense volcanic activity, i.e. the related reduced water transparency, may have been the major controlling factor of the drowning since thick tuff layers were deposited at that time in the Felsőörs basin (BUDAI & VÖRÖS 1993, BUDAI et al. 2001). However, the role of tectonic retrograding cannot be excluded either, which continued even during the Ladinian as it was proven by a neptunian dyke in the Litér quarry containing a Ladinain ammonite assemblage (BUDAI et al. 2001, BUDAI & VÖRÖS 2006).

Drowning of the Middle Triassic platforms may have taken place at different times also in other parts of the western Neotethys shelf (KARÁDI et al. 2022 and references therein). For example, in the Aggtelek–Rudabánya Unit (AR in *Fig. 11*) the Steinalm Limestone is overlain by the post-drowning sequence of the Schreyeralm Limestone of Late Pelsonian age in the Baradla Cave section (VELLEDITS et al. 2011, PERÓ et al. 2015), while the basal part of the red pelagic ammonitic limestone belongs to the lower Illyrian Trinodosus Zone in the Szár Hill section (VÖRÖS 2010). On the southern shelf of the rifting Neotethys (*Fig. 11*) the volcanic activity was much more intense (VELLEDITS 2009) and, accordingly, it played a more decisive role in the basin evolution from the Pelsonian until the Ladinian (SMIRCIC et al. 2020, KUKOC et al. 2023).

The palaeoenvironmental reconstruction based on ostracod palaeoecology reflects well the deepening of the Felsőörs Basin (KOZUR 1970, MONOSTORI 1995) and the flooding of the Middle Anisian isolated platforms during the Late Anisian. Very similar ostracod faunas (dominance of smooth bairdiids, bairdiacypridids and healdoids) were identified above the platform carbonates in the Illyrian beds (Vászoly Fm.) of the studied sections in Szentkirályszabadja quarry, Akol Hill and the Drt–1 core. The ostracod assemblages indicate deep neritic open shelf environment with water depth below 30–50 m (below the storm wave base) supporting the deepening of the basin above the former Kádárta, Barnag and Tagyon platforms during the Illyrian. The appearance of the thin-shelled 'palaeopsychrosphaeric elements' with long spines such as bairdiid *Acratia*, beecherellid *Acanthoscapha*, tricorninid *Nagyella* and macrocypridid *Praemacrocypris* in the Ladinian ostracod fauna of the Litér and Kádárta quarries suggests the climax of the deepening of the basin with water depth below 200 m (upper bathyal zone). This represents the maximum flooding of the Kádárta Platform during the Longobardian (MONOSTORI & TÓTH 2013, KARÁDI et al. 2022).

Conclusions

Drowning of the Middle Anisian platforms of the Balaton Highland was mostly controlled by the onset of block-faulting during the Pelsonian. Accordingly, the earliest drowning and post-drowning deposition may have taken place in the Pelsonian at the edge of the Barnag Platform (Akol Hill).

On the Tagyon Platform (Szentantalfa, Dörgicse and Vászoly), where the first post-drowning basinal layers were deposited during the Late Pelsonian or Early Illyrian, the drowning was probably governed by the accelerated relative sea-level rise, although the reduced water transparency, triggered by enhanced productivity in the upwelling zone and input of volcanic dust, may also have played some role in it.

The marginal area of the Kádárta Platform (Szentkirályszabadja) faulted down in the Pelsonian, however, the post-drowning deposition occurred in the Early Illyrian. In the inner parts of this platform (Kádárta and Hajmáskér–Sóly area) pelagic sediments deposited from the Late Illyrian indicating a step-by-step faulting of the platform.

During the Ladinian bathyal environment was established everywhere in the study area as a result of continuing sea level rise.

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