S. Kövér *et al. Swiss Journal of Geosciences* (2025) 118:3
https://doi.org/10.1186/s00015-024-00474-3

Swiss Journal of Geosciences

RESEARCH **Open Access**

From Middle Jurassic extension to Late Jurassic obduction: sedimentary records from the Greater Adriatic margin of the Neotethys Ocean in NE Hungary

Szilvia Kövér[1,2*], János Haas[2], Nevenka Djerić[3], Ottilia Szives[4], Péter Ozsvárt[5] and László Fodor[1,2]

Abstract

A displaced segment of the Late Triassic–Late Jurassic Greater Adriatic margin of the Neotethy Ocean was investigated in NE Hungary. In this area, the Mesozoic basement is largely covered by the Palaeogene—Miocene infill of the North Hungarian Palaeogene Basin and the Pannonian Basin. Micropaleontological, sedimentological and structural investigation of more than thirty wells resulted in the detailed characterisation and 3D depositional model of the area, which may have formed in the eastern continuation of the Slovenian Basin or in a similar sub-basin. The sedimentation in its Bajocian–early Callovian extensional half-grabens was characterised by pelagic limestones followed by dark shales with sandstone intercalations. Mass-flow deposits derived from both the footwalls of graben-bounding normal faults and the Adriatic Carbonate Platform were frequent. The most basin-ward segment of the latter one was penetrated by the south-westernmost well of the area. Both the Middle Jurassic extension of the formerly extended continental crust and the lower plate source of the sediments have great importance, while they change the tectonic interpretation of the basins. In the overlying Tarna olistostrome sedimentation lasted at least until the Tithonian, as indicated by nannofossils. This is the oldest possible age for the overthrusting of the ophiolite nappe over this segment of the Greater Adriatic continental margin. The now eroded ophiolite nappe is underlain by the Darnóhegy Mélange, a typical sub-ophiolitic mélange, which was formed further to the south-east during the Callovian–Oxfordian, at an earlier, intraoceanic stage of the Neotethyan subduction.

Keywords Middle Jurassic extension, Bükk, Darnó, Greater Adria, Margin evolution, Neotethys

Handling editor: Wilfried Winkler.

*Correspondence:
Szilvia Kövér
koversz@gmail.com
[1] Institute of Earth Physics and Space Science, HUN-REN, Csatkai Endre út 6-8, 9400 Sopron, Hungary
[2] Department of Geology, Institute of Geography and Earth Sciences, ELTE Eötvös Loránd University, Pázmány Péter sétány 1/C, 1117 Budapest, Hungary
[3] Faculty of Mining and Geology, University of Belgrade, Kamenička 6, 11000 Belgrade, Serbia
[4] Department of Collections, Geological Survey, Supervisory Authority for Regulatory Affairs, Stefánia út 14, 1143 Budapest, Hungary
[5] Research Group for Paleontology, HUN-REN-MTM-ELTE, P. O. Box 137, 1431 Budapest, Hungary

1 Introduction

The two most interesting moments in the life-cycle of oceanic margins are the end of rifting (the onset of break-up), thus the first moment of becoming a passive margin, and then the transformation into an active margin due to the closure of the oceanic basin. This latter crucial event is the target of our investigation regarding the Greater Adriatic margin facing the Neotethys Ocean during the Middle Triassic–Late Jurassic interval. Greater Adria is a relatively large continental lithosphere fragment of Gondwanian (African) origin, which is separated from Precambrian Africa by the oceanic lithosphere of the southeast Mediterranean basin (Gaina et al., 2013).

It collided with the Eurasian Plate during the Alpine orogeny.

Reconstructing the exact time steps between the subduction initiation and the final collision is a great challenge, and a lot of contributions are needed starting from e.g. the analysis of the possible weakness zones for subduction initiation (Maffione et al., 2015) through the age of the metamorphic sole (Bortolotti et al., 2013), the direction of the intra-oceanic subduction (Robertson, 2012; Bortolotti et al., 2013), the obliquity of the margin (Schmid et al., 2008; Tremblay et al., 2015), the first moment of obduction (Saccani et al., 2004; Bortolotti et al., 2013; Tremblay et al., 2015), the spatiotemporal evolution of the overthrusting ophiolite nappe, the evolution of the connected foreland basins (Scherreiks et al., 2014), the timing, kinematics, deformation style of the imbricated continental margin (Schefer et al., 2010; Porkoláb et al., 2019), and finally the timing, kinematics and magmatic events of the final collision (Ustaszewski et al., 2009, 2010). The reconstruction of this complex history is difficult at straight subduction zones and even more challenging at curved ones or at the termination/transfer zones of oceanic systems. This is the case with suture zones in the northernmost part of the Dinarides and its displaced segment in NE Hungary. The relationships of the thrust sheets with Greater Adriatic origin and the overriding sub-ophiolitic mélange and ophiolite nappe are well described in the mountainous areas of the Dinarides, Albanides and Hellenides (Karamata et al., 2005; Schmid et al., 2008, 2020; Placer, 2008; Handy et al., 2010; Gawlick & Missoni, 2019; Stojadinović et al., 2022). However, it is much more problematic to define different successions and the overriding sub-ophiolitic mélange nappe in Northern Hungary, because the original contact zones have been displaced ca 300 km northeastward by the Mid-Hungarian Fault Zone (Tari, 1994; Csontos & Nagymarosy, 1998; Fodor et al., 1998) during Cenozoic strike-slip movements (Fig. 1a). In addition to this large-scale deformation, the poor outcrop conditions, and the overprinting Miocene extensional tectonics and sedimentary basin formation hamper the recognition of any pre-Eocene boundaries. However, this area is composed both of continental margin successions originating from different segments of Greater Adria, and obduction-related units, so it may provide a lot of information regarding the imbrication of the continental margin, the migration of foreland basins

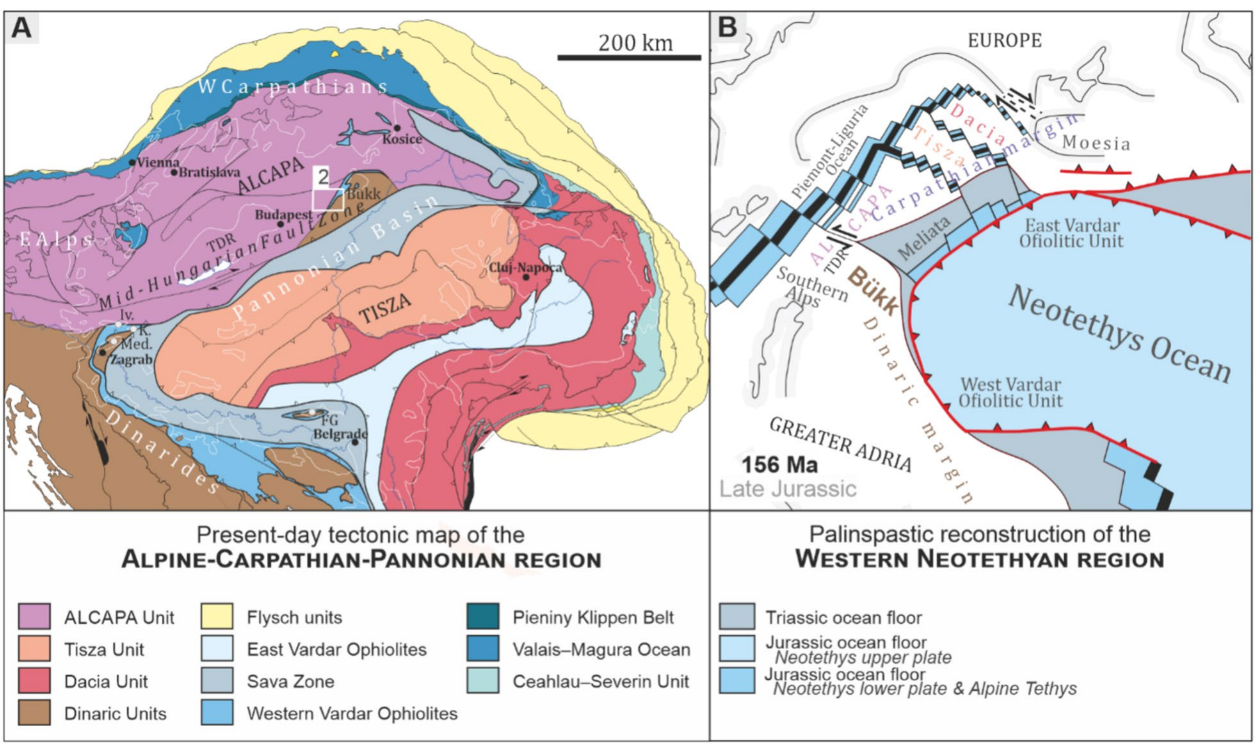

Fig. 1 **a** Position of the investigated units on the present-day tectonic map of the Alpine–Carpathian–Dinaric–Pannonian region (modified after Schmid et al., 2008). **b** Position of the investigated units on a palinspastic reconstruction of the western termination of the Neotethys Ocean. Timeslice: Late Jurassic (modified after Schmid et al., 2008) *FG* Fruška Gora, *Iv.* Ivanščica Mt., *K.* Kalnik Mt., *Med.* Medvednica Mt., *TDR* Transdanubian Range

and the obduction of the ophiolite nappe. The study investigates the Recsk and Darnó areas, where the Mesozoic basement is covered by thick Paleogene to Miocene succession (Fig. 2), which was Palaeogene by more than hundred deep wells, part of which is still available in the repository of the Mining and Geological Survey of Hungary (now Supervisory Authority of Regulatory Affairs).

The aim of this paper is to summarise the results of the previous studies and the new investigations of this key

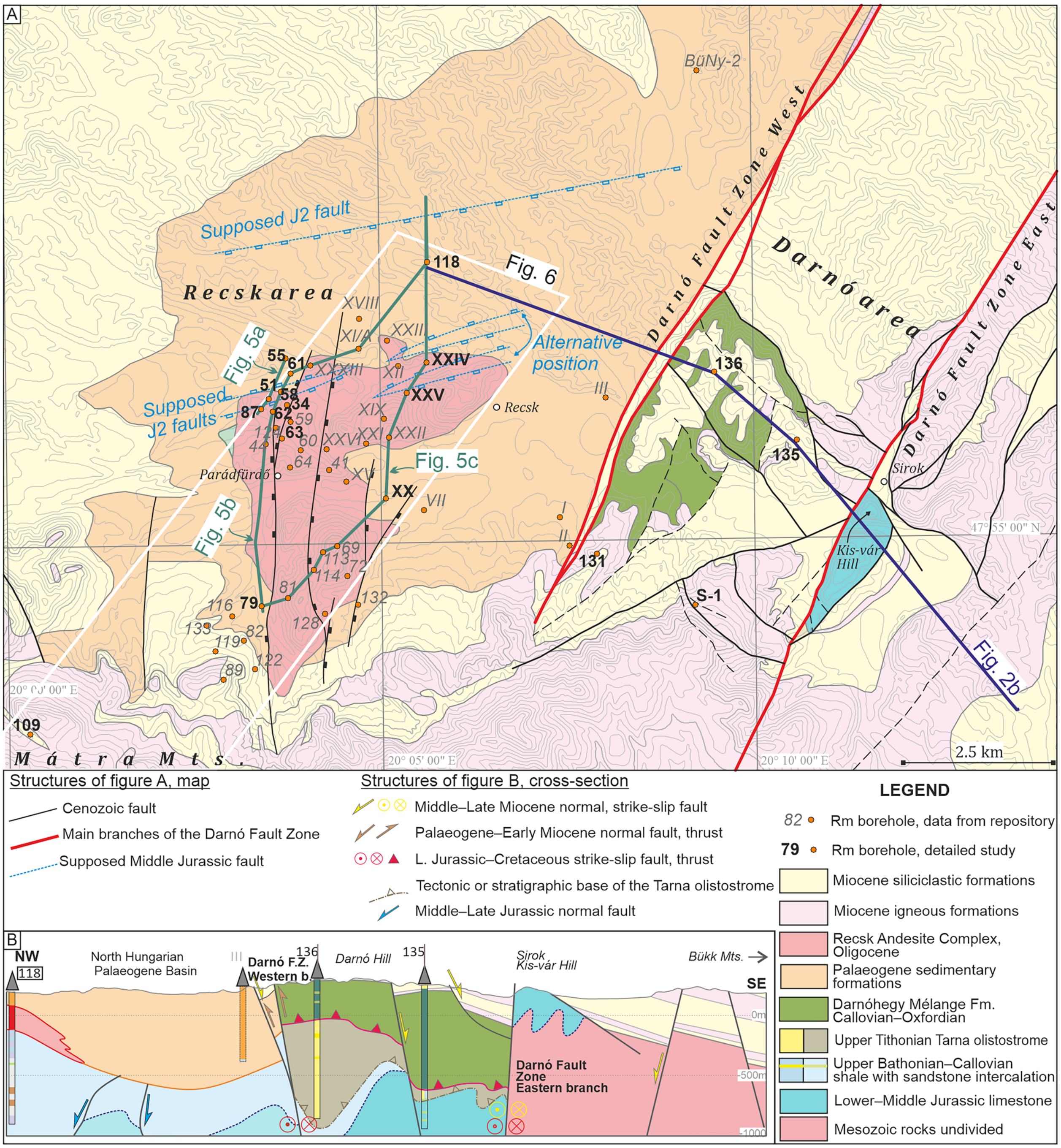

Fig. 2 **a** Simplified pre-Quaternary geological map of the investigated area. Compiled from Less and Mello (2004), the 1:100,000 scale geological map series of Hungary, sheet Eger (Gyalog & Síkhegyi, 2005), and from Gál et al. (2021). **b** NW–SE oriented cross-section of the Recsk and Darnó areas (Haas et al., 2024)

area. Sedimentological and structural observations and interpretation of the data resulted in a three dimensional reconstruction of the depositional area in the Middle Jurassic as an extensional graben system, perpendicular cross-sections showing the present-day relationships and geometries of the defined structural units, and enabled us to draw conclusions regarding the change from extension to subduction-related shortening between the Callovian and Tithonian.

2 Geological setting

2.1 Darnó area

2.1.1 Darnóhegy Mélange Formation (DM)

The Darnó Hill and its surroundings (Fig. 2), east of the Darnó Fault is an area of critical importance for the analysis of the relationship of several units. The surface exposures and the upper parts of exploratory wells (Rm-131, -135, -136) are composed mostly of redeposited clasts and large blocks of basalts with minor amount of gabbros (Harangi et al., 1996; Józsa et al., 1996) surrounded by shale and radiolarite matrix (Józsa, 1999; Dosztály et al., 1998, Haas et al., 2024) that can be assigned to the Darnóhegy Mélange Formation (Kovács et al., 2008, 2011a; Józsa et al., 2024). The age of the basalt blocks is latest Anisian–Ladinian on the basis of conodonts and radiolarians dissolved from those sedimentary rocks, which were closely associated with one group of the basalt blocks (Kozur & Krahl, 1984; De Wever, 1984; Haas et al., 2011, 2024). On the other hand, the radiolarian assemblage associated with either the matrix of the mélange or with basalt blocks of different geochemical characteristics (Kiss et al., 2012) showed Bajocian–Callovian (Kozur, 1991), Callovian (Gawlick et al., 2012) or Callovian–Oxfordian age (Haas et al., 2024). These age intervals can be interpreted as minimum ages for the mélange formation. Previous researches considered this mélange as a true ophiolite-derived mélange nappe (Schmid et al., 2008; Haas et al., 2024) and correlated it with the Dinaric counterparts (Haas & Kovács, 2001; Dimitrijević et al., 2003; Kovács et al., 2011b).

2.1.2 Tarna olistostrome (Taro)

Below the DM, the exploratory wells exposed dominantly sedimentary rocks which were previously assigned to the Mónosbél succession (Haas et al., 2006, 2011; Kovács et al., 2008). However, recent analyses of Haas et al. (2024) defined a new unit, the Tarna olistostrome (Taro). The Taro is intersected by wells Rm-131, Rm-135(?) and Rm-136 (Figs. 2, 3, 4) in a remarkable thickness (200 m to 900 m, respectively), comprises dark grey and red shale, siliceous shale, sandstone, radiolarite, pelagic, occasionally cherty limestone, with gravitational mass deposits including large blocks (olistoliths).

The identified large blocks include Upper Permian, Carnian (Kovács et al., 2013) and Lower Jurassic limestones (Haas et al., 2024) and Ladinian radiolarite (Dosztály & Józsa, 1992, Haas et al., 2024). Late Tithonian age of the Taro has recently been determined on the basis of nannofossils (Haas et al., 2024). A deep marine basin was suggested for the depositional environment, where carbonates and fine siliciclastic mud were deposited as "background" sediments and were also supplied by mass flows. The upper part of the series is truncated by the basal thrust of the overriding DM nappe (Figs. 2, 3).

2.2 *Recsk area and northern foreland of the Mátra Mts.*

The Mesozoic basement of the area west of the Darnó Fault is the second sub-area of our work (Fig. 2). It incorporates the northern foreland of Miocene volcanites of the Mátra Mountains and the hilly area around the Oligocene Recsk Andesite Complex (Fig. 2, Arató et al., 2024). There are no surface exposures of the pre-Cenozoic rocks in this region, but numerous continuously cored ore exploratory wells reached the Mesozoic rocks below Oligocene volcanic and sedimentary formations providing data on the geological characteristics of the basement. A number of very detailed publications prepared a thorough lithological, microfacies and micropalaeontological characterization of the penetrated basement rocks (Dosztály & Józsa, 1992; Kovács et al., 2008, 2013; Haas et al., 2013, 2024).

Upper Carnian–lower Norian, grey cherty limestone with marl interlayers (Felsőtárkány Limestone Fm.) is the oldest penetrated formation (Figs. 3, 4). The same lithology continues upwards for ~150 m with lack of conodonts, which may refer to Early Jurassic age (Kovács et al., 2013). In some successions lower Norian grey, cherty dolomite (i.e. pervasively dolomitized pelagic carbonate) was encountered, which shows similarities towards the Bača Dolomite Fm. of the Slovenian Basin both in lithofacies and in age (Buser, 1986, 1989; Rožič et al., 2009; Gale, 2010; Goričan et al., 2012). Both the limestone and the dolomite is overlain by grey, occasionally cherty limestone, with claystone and marl intercalations. The majority of the observed microfacies types are mudstones with sponge spicules and radiolarian molds, however, wackestones with thin-shelled bivalves and radiolarian packstone are also present (Haas et al., 2024). These microfacies types are indicative for pelagic depositional environments. The age of this lithofacies unit is Lower Jurassic (lower Sinemurian–lower Toarcian) to lower Bathonian (Haas et al., 2024).

There is a gradual lithological transition from the grey micritic limestone to grey marl and shale, which pass upward to grey shale with sandstone intercalations. The sandstone intercalations are fine- to coarse-grained; the

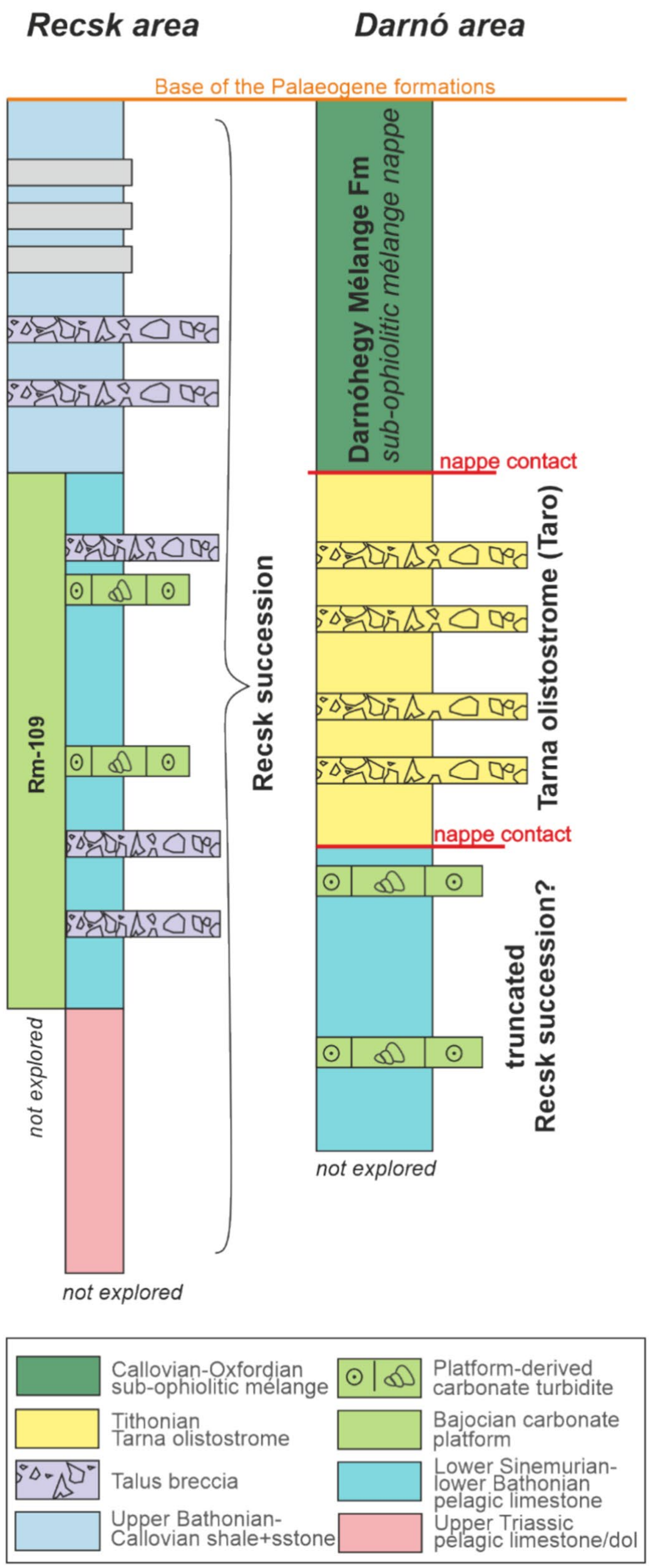

Fig. 3 Simplified lithostratigraphic columns of the Recsk and Darnó areas (simplified and modified after Haas et al., 2024)

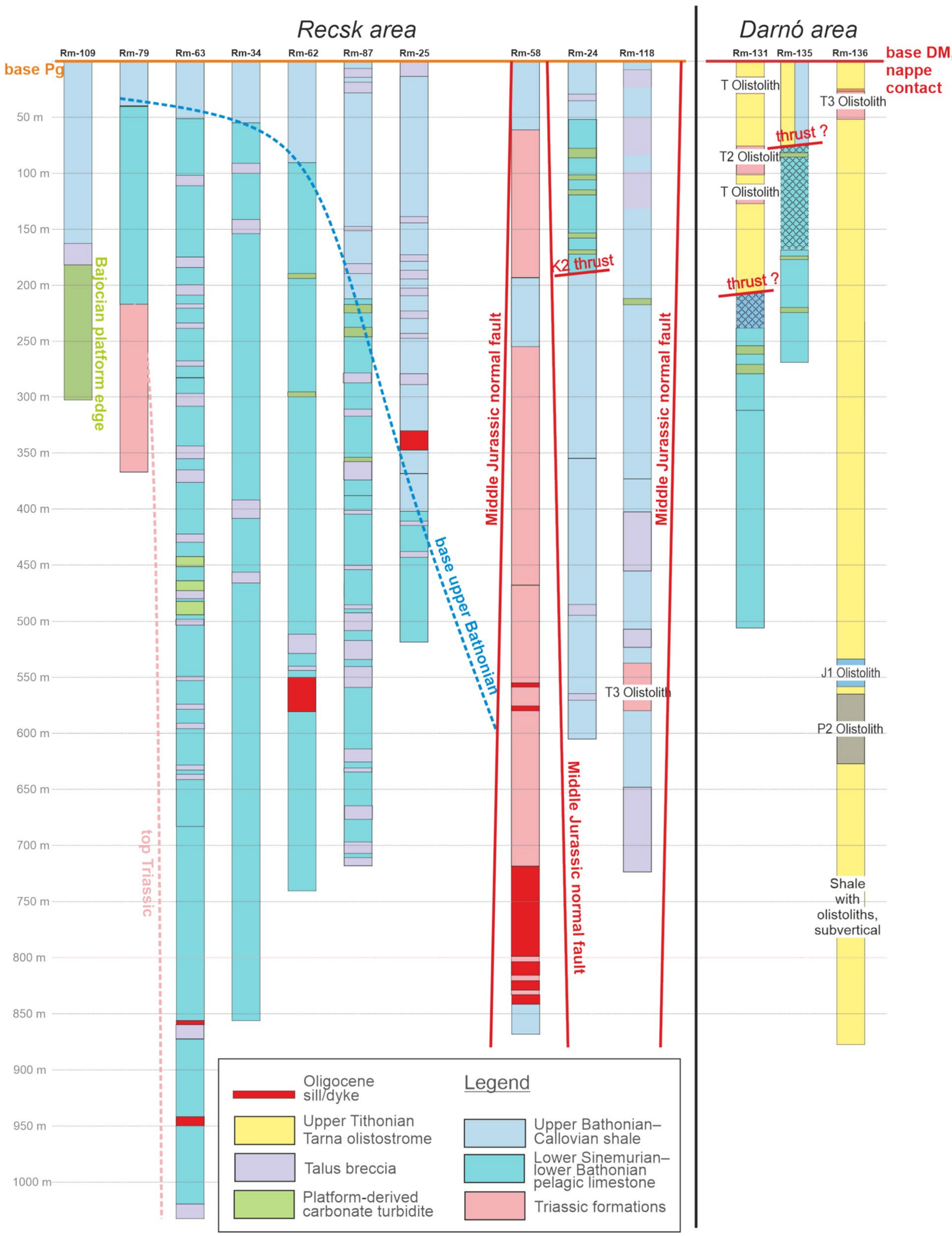

Fig. 4 Simplified lithostratigraphic columns of the key wells in the Recsk and Darnó areas (simplified and modified after Haas et al., 2024). Diagnostic breccia horizons and platform-derived carbonate turbidites are marked separately. Diagonal pattern indicate tectonic zones

dominant minerals are quartz, muscovite, plagioclase and chlorite (Haas et al., 2024). The age of this lithofacies unit was determined to be upper Bathonian–lower Callovian thus the cessation of carbonate deposition, and gradual change into the siliciclastic sedimentation may have taken place during the Bathonian (Haas et al., 2024). Intensive silicification of both the limestone and shale is quite common, especially at the upper part of the succession, where radiolarite also occurs locally.

Within this pelagic limestone and shale succession two types of redeposited bed intercalations are present (Haas et al., 2024). Microfacies and microfossil content for the first type indicated shallow-marine environment, most probably a coeval carbonate platform as source of the clasts. The other type of redeposited layers are breccias containing cm-sized to mm-sized un-rounded to sub-rounded lithoclasts (micro-breccia) (Haas et al., 2024).

Based on lithological and age similarities the whole Lower–Middle Jurassic succession was suggested to be in close relationship with the Oldalvölgy Formation of the Bükk Mts. (Pelikán et al., 2005; Haas et al., 2013, 2024; Pelikán, 2024).

The above described succession built up by Upper Triassic cherty limestone/dolomite, lower Sinemurian to lower Bathonian pelagic limestone and upper Bathonian to Callovian shale with sandstone intercalations was named Recsk succession (Rs) (Haas et al., 2024), and will be referred accordingly through this paper.

A unique succession was explored in borehole Rm-109 in the south-westernmost part of the area (Fig. 2). Here, in contrast with all the other boreholes, a lower Bajocian platform carbonate succession was found directly below the upper Bathonian to lower Callovian dark grey shale. (Haas et al., 2006, 2024). The microfossil assemblage and microfacies analysis suggested platform margin as site of deposition.

3 Observations

3.1 Breccia layers within the Middle–Upper Jurassic sedimentary successions

The penetrated successions at the Recsk and Darnó area contain two basic types of gravitation mass deposits: carbonate turbidites and breccias, micro-breccias. The latter ones occur in three stratigraphic levels: (a) within the Bajocian–lower Bathonian part of the pelagic limestone succession, (b) in the upper Bathonian-Callovian shale and (c) in the upper Tithonian Taro (Figs. 3, 4). The gravitation mass deposits of (a) and (b) are usually dm to few m thick breccia and micro-breccia layers. They are clast-supported breccias with mm to cm sized, angular to sub-rounded lithoclasts and calcite or silica cement. The main clast types are pelagic to hemipelagic limestones, shale, silicified shale, fine-grained sandstone, radiolarite and occasionally ooidic limestone. Detailed description of the redeposited layers and their composition is found in Haas et al. (2024). Angular geometry of the lithoclasts suggest short transportation. All the identified clasts can be correlated with members of the local Upper Triassic–Middle Jurassic succession (Fig. 3), thus the simplest solution is to suppose an intrabasinal source for the clasts. However, submarine exposure of the deeper stratigraphic levels is essential for clast supply. The kinematics of the exposure will be discussed in the next chapter.

The upper Tithonian gravitation mass deposits (c) usually have different characteristics. They either form coarse-grained breccias (olistostromes) of various limestones and radiolarite or m to tens of metres scale individual limestone blocks. However, finer-grained breccias are also present with similar clast-composition within the shale, sandstone and pelagic limestone “background” sedimentary rocks. In core Rm-135 (Figs. 2, 4) only this finer part was penetrated in ~ 70 m thickness. In the lack of age data, the classification of this part of the section is questionable. It may belong to the upper Bathonian–Callovian shale succession or to the upper Tithonian Taro. The other difficulty of having only well data, is the question of intercalations/large olistoliths. It is not always straightforward, if a penetrated pelagic limestone section is a few metre-thick limestone intercalation or represents an olistolith. At some occasions microfossils proved the olisthOlitic nature of Upper Permian, Middle Triassic, Upper Triassic, Lower Jurassic intervals (Dosztály & Józsa, 1992; Kovács et al., 2013; Haas et al., 2024). The clasts of the olistostromes and individual olistoliths derived from that part of the exposed passive margin, which contained shallow marine Late Permian, pelagic Ladinian to Norian cherty limestones with radiolarite intercalations and Lower Jurassic pelagic limestone. The upper part of this source succession is present locally in the Recsk area, while both pelagic Ladinian limestone and Late Permian shallow marine sedimentary rocks can be supposed in the underlying strata or in the surrounding areas of the former Greater Adriatic margin.

3.2 Origin of the Middle Jurassic and late Tithonian basins

3.2.1 Middle Jurassic structures of the Recsk area

While we have only sporadic one dimensional information, exact location, geometry and kinematics of the supposed structures are rather speculative. However, arguments supporting the existence of active Middle Jurassic faults will be presented. A general northward thickening trend can be recognised within the penetrated Recsk succession (Figs. 4, 5b, c). This northward tilting of the Triassic basement is interpreted to be the effect of a southerly facing normal fault, which can be the boundary fault of the Recsk half-graben containing the Recsk

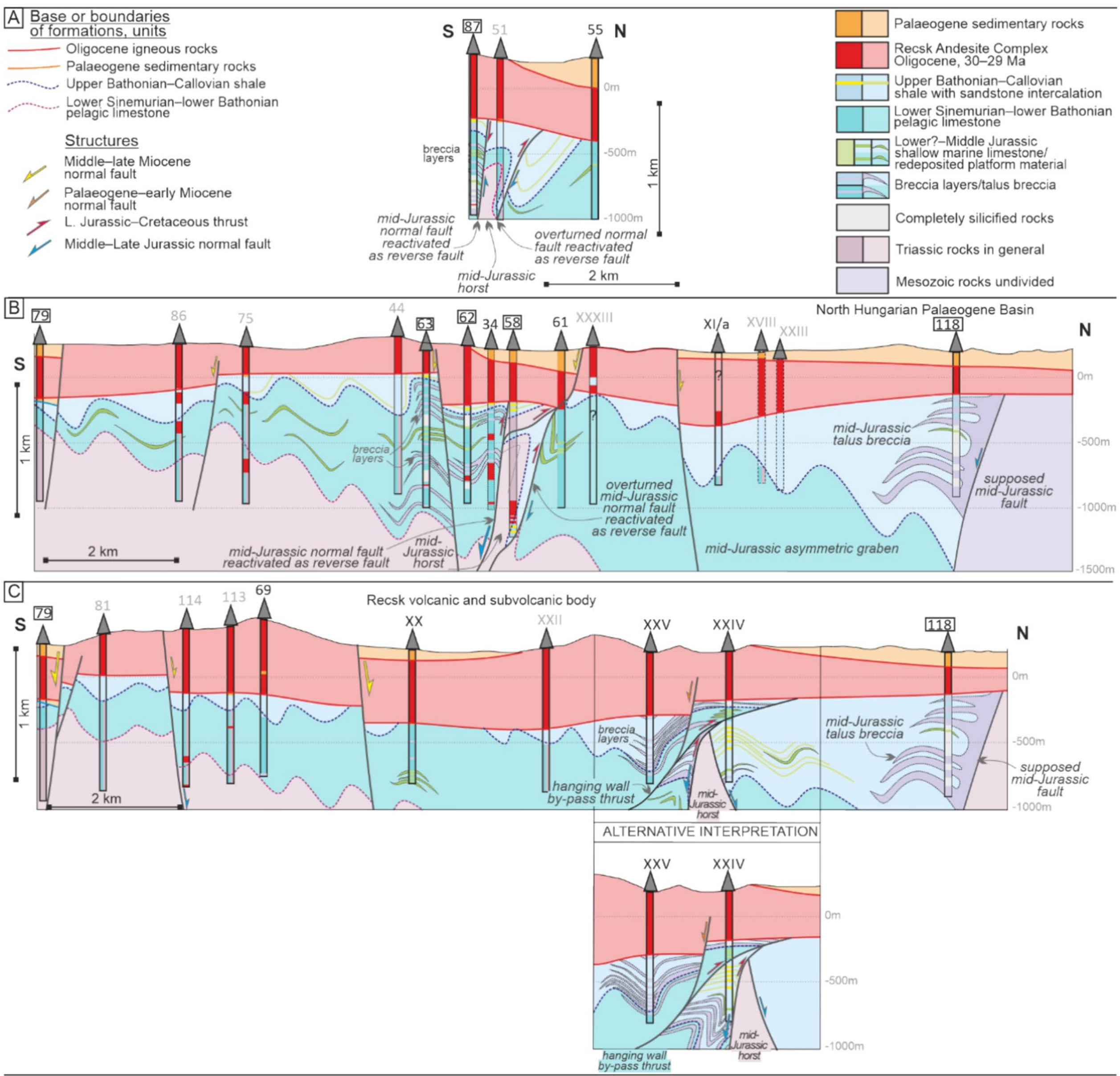

Fig. 5 Geological cross-sections of the Recsk area. The locations of the sections are indicated on Fig. 2. Note 2× vertical exaggeration. Folded character of the succession is projected from surface observation (like on the Kis-vár Hill on Fig. 2a). Boreholes with framed numbers were investigated in detail by Haas et al. (2024)

succession. The fault should be located further north of well Rm-118 (Figs. 2, 5b, c).

The only exception from the northward thickening trend is in the vicinity of well Rm-58, Rm-51 and Rm-XXIV (Figs. 2, 4, 5). The first one penetrated the repetition of Upper Triassic pelagic limestone/dolomite and the upper Bathonian–Callovian shale (Figs. 4, 5b). The lower Sinemurian–lower Bathonian pelagic limestone succession is missing; however, it is rather thick in the neighbouring wells Rm-34, -61, -62, -63, -87 both on the northern and southern side (Figs. 4, 5a, b). The missing of more than 1000 m of pelagic limestone cannot be the result of Cenozoic normal faulting while the base of the Recsk Andesite is not dissected. It is rather suggested that the incomplete succession represents a mid-Jurassic horst with reduced sedimentation. Similar, reduced succession was penetrated in well Rm-51 east of Rm-58 (Figs. 2, 4, 5a). The eastern continuation of the horst can be in the vicinity of Rm-XXV and XXIV while the latter one also has an anomaly in the expected sequence:

~ 130 m lower pelagic limestone is present above the shale (Figs. 4, 5c). This extra element is interpreted as a repetition by a hanging wall by-pass thrust, connected to the Cretaceous shortening (Fig. 5c). In a map view, two highs can be interpreted from the three parallel cross-sections: Rm-51, Rm-58 and between Rm-XXV and Rm-XXIV or north of this latter (Figs. 2, 6). From these point-like observations, the orientation of the horst is postulated to have a trend of WSW-ENE (Figs. 2, 6). We tentatively used the same orientation for the northern edge of the northern half-graben.

These structural arguments are strengthened by sedimentological data. Those successions, which are in the vicinity of the supposed horst, have numerous breccia intercalations (Figs. 4, 5, 6), which are interpreted as talus breccias, connected to the movement of coeval faults. Soft-sediment deformation features like slumps are also common in these cores (Haas et al., 2024), indicating the existing slopes. More intensive silicification of the breccia bodies and connected sediments may refer to elevated fluid circulation in the vicinity of the faults. The frequency of the platform-derived intercalations shows an interesting spatial distribution: it is generally present south to the horst in the immediate southern hanging wall of the horst, while only a few intercalations are detected on the north (Figs. 5, 6). Thus the suspected mid-Jurassic horsts have another important effect on the sedimentation: they formed a barrier or confinement for the platform-derived turbiditic currents coming from the S- or SW, from the direction of Rm-109, representing the edge of the carbonate platform (Figs. 4, 6). A small part of the platform-derived material got through the horst, potentially along stepovers of the horst-bounding normal faults (Figs. 2, 6).

3.2.2 Kinematics of the late Tithonian basin

In the lack of direct or indirect structural data, the only observation to determine the character of the original basin would be the coarsening or fining upward trend of the sedimentary record (Einsele, 1992). The upper part

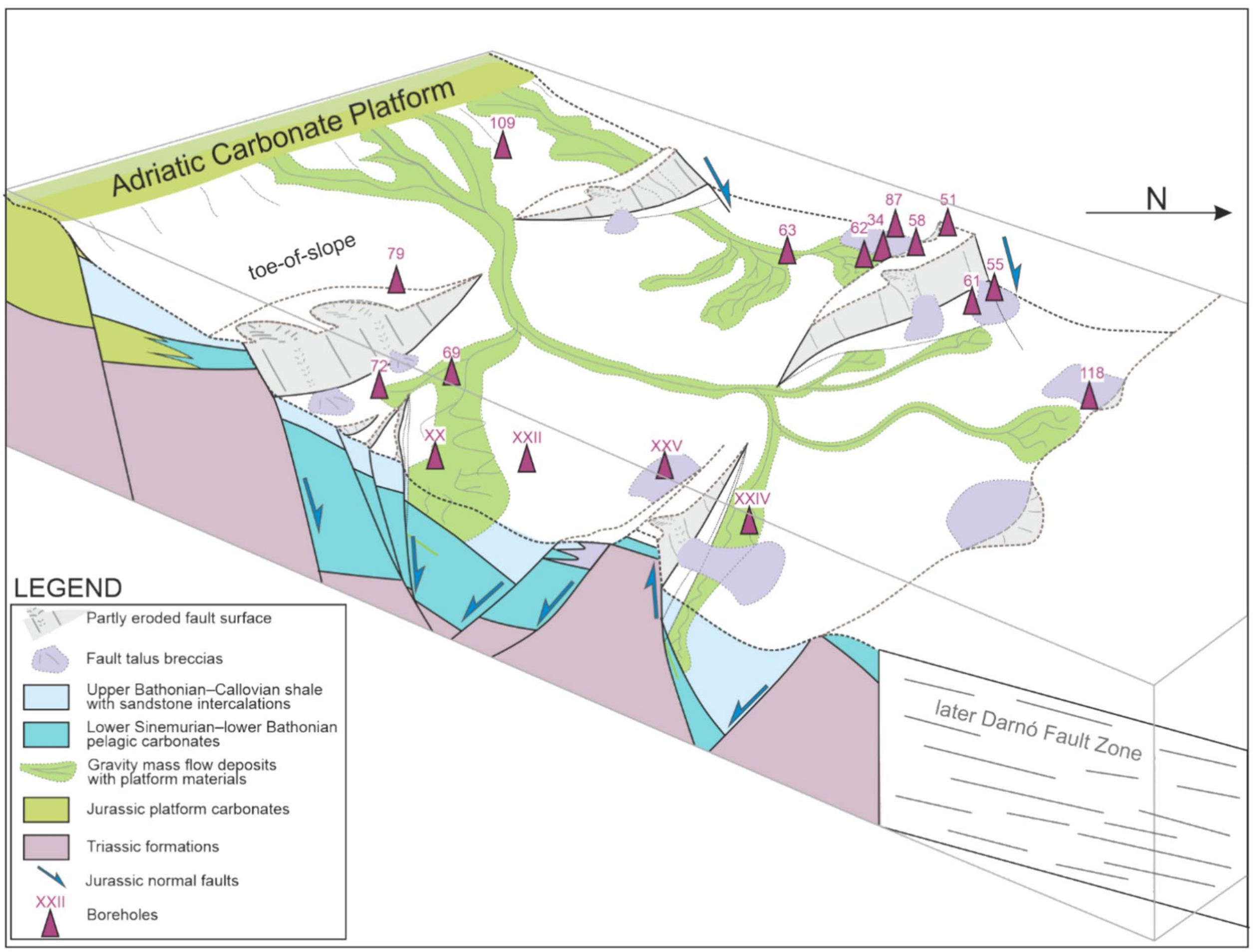

Fig. 6 3D model for the Middle Jurassic paleogeography of the Recsk area. Note that the gravity mass flow deposits occur on different surfaces

of the Taro is truncated by the basal thrust of the DM. The lower contact was penetrated in wells Rm-131 and Rm-135; it is separated from the underlying pelagic limestone succession by a thick brecciated and sheared zone (Fig. 4). There is a considerable age gap at the boundary (lower Toarcian vs. Tithonian and lower Bathonian vs. upper Tithonian, respectively, Haas et al., 2024). The upper Bathonian–Callovian shale succession, which is the general stratigraphic cover of the pelagic limestone, is missing. The presence of the brittle shear zones and the age gap suggest a tectonic origin of the contact. Accordingly, the Taro most probably forms a thin thrust-sheet between the sub-ophiolitic DM and the lower passive margin sequence. While the Taro is truncated at both the upper and lower contact, the coarsening trend cannot be observed.

4 Discussion

4.1 Connections towards the Bükk, the Slovenian Basin and the Dinarides

4.1.1 Relationships of the Recsk succession

4.1.1.1 Mónosbél succession (Bükk Mts.) Close relationship between the Recsk succession (Rs) and the Mónosbél succession (Ms) of the neighbouring Bükk Mts. was pointed out on the basis of lithological and age similarities (Haas et al., 2013, 2024). However, the Ms is truncated from the bottom at the Bajocian stratigraphic level, thus has no preserved Triassic part, and in contrast with the Rs, the well defined separation of the limestone-rich and shale + sandstone-rich part of the succession has not been detected (Fig. 7); the two main lithologies alternate within the whole Ms complex. The Ms olistostromes contain more variable clast composition than in the Rs, e.g., Triassic acidic to neutral igneous rocks (Csontos, 1988; Kövér et al., 2018), and low-grade metamorphic clasts (Pelikán et al., 2005). Despite the lithological similarities, temporarily we keep these two successions separate; a potential future unification is not excluded but needs further studies.

4.1.1.2 Bánkút succession The Bánkút succession (Bs, Bükk Mt.) is characterised by a long period of non-deposition/submarine erosion from the uppermost Triassic till the Bajocian (Haas et al., 2013) or the Callovian (Csontos et al., 1991, Dosztály, 1994) (Fig. 7). This very reduced succession may refer to the elevated position (submarine high/horst) of the whole Bs area (Fig. 7). Incomplete or very condensed Jurassic successions are known in different Dinaric units with gaps of variable length. In eastern Slovenia, the so-called "transitional unit" between the Inner and Outer Dinarides shows a complete gap from the Upper Triassic to the Tithonian Biancone Fm. (Placer, 2008; Scherman et al., 2023). Similarly to the shallow-marine regions within the Bs, in the Julian Alps carbonatic shallow marine condition was present in the Rhaetian, which was prolonged in the Early Jurassic. Platform drowning happened before the Toarcian, which led to deposition of condensed pelagic Ammonitico Rosso limestone sequences (Buser, 1986; Jurkovšek et al., 1990; Šmuc, 2005; Goričan et al., 2012) and Biancone-type limestone in the late Tithonian and Berriasian. Despite the similarities, there is a significant difference between the Julian Platform and the Bs in the Middle–Late Jurassic evolution. While the condensed carbonate sedimentation continued during the whole period in the Julian Platform, several hundred metres of dark shale with siliciclastic sandstone turbidites deposited in extensional half-grabens in the Bs (Fig. 7; Balla et al., 1987, Csontos, 1999, Pelikán et al., 2005).

4.1.1.3 Slovenian Basin The Upper Triassic to Middle Jurassic Rs is dominated by grey cherty carbonate rocks deposited in pelagic basins, although pelagic shale and radiolarite beds also occur usually in the upper part of the successions. Similar pelagic lithofacies characterise the coeval sequences in the Slovenian Basin (Bled Basin, Tolmin Basin). This basin existed from the Middle Triassic between the Adriatic Carbonate Platform to the south (also known as Dinaric or Adriatic–Dinaric Carbonate Platform—see discussion in Vlahović et al., 2005 and references therein) and the Julian Carbonate Platform to the north (Buser, 1989; Rožič et al., 2009). In the western part of this basin grey cherty limestone was deposited first (Buser et al., 2008), which is overlain by a succession of alternating fine siliciclastic and limestone beds containing late Carnian to early Norian conodonts (Kolar-Jurkovšek, 1991; Ramovš, 1998). During the Norian to Rhaetian deep-sea conditions became prevailing all over the basin

(See figure on next page.)

Fig. 7 Simplified lithostratigraphic columns of the Recsk succession (Rs), Mónosbél succession (Ms.), Bánkút succession (Bs) and selected areas of the Slovenian Basin from the uppermost Triassic to the upper Tithonian. While there is a remarkable thickness variation of the Middle Jurassic formations within the Rs, Ms and Bs, the detected maximum thicknesses are drawn for these formations. Note the thickness differences of the Middle Jurassic formations between the different areas. Data of the Ms is modified after Haas et al. (2024), those of Bs is after Balla et al. (1987), Csontos (2000), those of the Slovenian Basin are after Rožič and Popit (2006), Goričan et al. (2012), Rožič et al. (2014, 2019, 2022), Scherman et al. (2023). *Radi*. Radiolarite, *Dol*. Dolomite, *Fm*. Formation

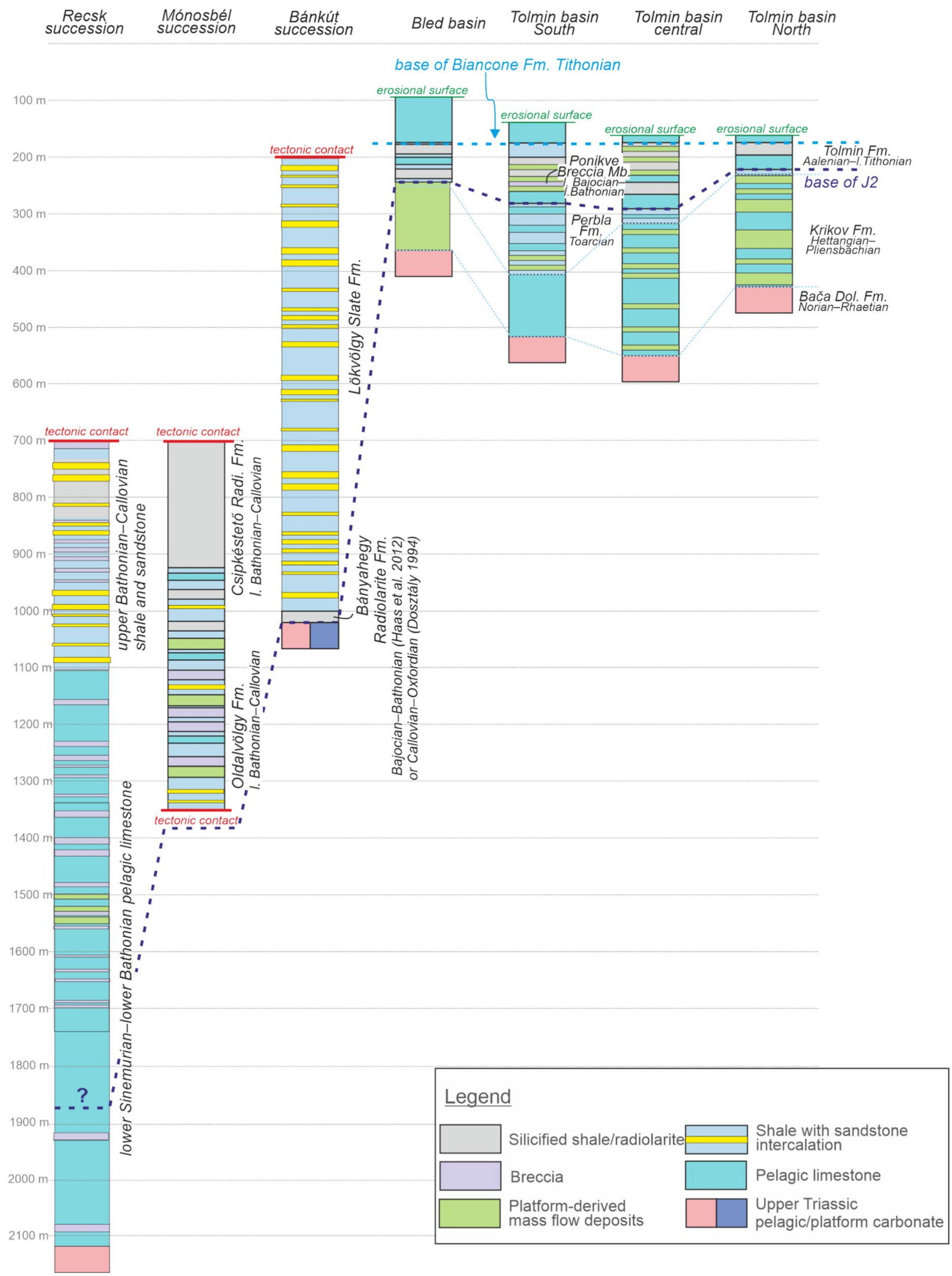

Fig. 7 (See legend on previous page.)

where cherty limestones were deposited (Ogorelec & Dozet, 1997; Rožič et al., 2009; Kolar-Jurkovšek, 2011), which shows a great similarity to the Felsőtárkány Fm. of the Bs and the coeval part of the Rs. The upper part of the cherty limestone was usually subject to pervasive dolomitization subsequently (Bača Dolomite). This dolomite can be correlated with the cherty dolomite of well Rm-58 of the Rs (Fig. 4). In contrast, the northern part of the Slovenian Basin (SB) cherty limestone with redeposited calcarenite and limestone conglomerate interbeds is present (Rožič et al., 2009, 2014). In the whole Slovenian Basin, the deposition of the pelagic to hemipelagic carbonates continued during the Lower Jurassic (Krikov Fm.) with a significant amount of Julian Platform-derived intercalations in the northern basin parts (Fig. 7). The southern areas of the Tolmin Basin, similarly to the Rs lacks these shallow-marine-originated mass deposits. In contrast to the Lower Jurassic, in the Middle Jurassic thick limestone breccias (debris-flow deposits; Ponikve Breccia Member of the Tolmin Formation) and graded oolite beds were deposited in the southern areas during the early Bajocian to early Bathonian (Rožič & Popit, 2006; Rožič et al., 2019; Scherman et al., 2023), which seems to be a wide-spread event being present also in the Rs and Ms (Fig. 7). Extensional down-faulting of the platform margin induced the formation of gravity mass flow deposits in the form of limestone breccias, and resulted in the exposure of all platform units down to the Upper Triassic (Rožič et al., 2019, 2022). Thus differential subsidence and normal fault activity were present in the southern areas of the SB during the early Middle Jurassic, which may indicate a link between the Middle Jurassic structural evolution of the Rs and this area.

In the Slovenian Basin the upper Bathonian to lower Tithonian comprises shale with intercalation of cherty limestone and radiolarite layers (Tolmin Fm.; Ogorelec & Dozet, 1997). Despite the similarities between the Middle Jurassic part of the Rs, Ms and southern SB, there are two major differences. The first is the thickness of the formations: while the maximal thickness of the whole Middle Jurassic to lower Tithonian sequence is around 100–120 m in the SB, only the Bajocian to Callovian succession can reach more than 1000 m in the Rs and 500 m in the Ms. This striking difference is may be caused by faster subsidence and more pronounced normal fault activity in the Rs and Ms. The other important difference is the upper Bathonian–Callovian deposits. It is condensed and very-fine grained in the SB (radiolarite, chert, shale, pelagic limestone beds) showing limited clastic input or a more distal sediment source or, alternatively, an elevated block position. In contrast, the Rs containing talus breccias and siliciclastic sandstone intercalations refer to half-graben position (Figs. 3, 4, 7). This is this clastic lithology where both the Rs and Ms are truncated so further comparision is hampered. In the SB this radiolarite and shale-dominated lithology is overlain by cherty calpionella limestone (biancone facies) of upper Tithonian to Berriasian age (Haas et al., 2011; Scherman et al., 2023; Rožič & Reháková, 2024).

The Aalenian(?)—Bajocian shallow marine carbonate succession found in core Rm-109 may have formed in the marginal belt of the Adriatic Carbonate Platform which faced the deep-water SB (Fig. 8). The same extensional faulting that created the mid-Jurassic breccias in the SB, Bs, Ms, Rs, could cause the drowning and the related abrupt significant facies change in the late Bathonian.

4.1.1.4 Mt. Ivanščica Existing correlations and palinspastic reconstructions along the Mid-Hungarian Fault Zone suggest that the closest relatives to the Recsk–Darnó–Bükk area may be found in the Medvednica and Ivanščica Mts. (Haas & Kovács, 2001; Csontos & Vörös, 2004, Ustaszewski et al., 2008, Tomljenović et al., 2008). Both areas are built up by Greater Adriatic margin successions, which are juxtaposed by the sub-ophiolitic mélange nappe. However, only the successions of Mt. Ivanščica contains Jurassic strata below this contact zone. Here, the subsidence of the Upper Triassic platform happened either at the Triassic/Jurassic boundary or in the Pliensbachian marked by the deposition of Lower Jurassic pelagic limestones, shales and marls or by formation of neptunian dykes (Vukovski et al., 2023). Radiolarian cherts and shales are the most characteristic deposits for the late Middle to Late Jurassic time (late Bathonian to early Tithonian). The detected successions are thin, finer-grained and condensed compared to the Rs.

4.1.2 Darnóhegy Mélange

This mélange shows great similarities towards the sub-ophiolitic mélange nappes of the Dinarides both in clast composition (predominantly basalt, gabbro, radiolarite, pelagic mudstone and grey siliceous shale) and its Callovian–Oxfordian age. The connection towards the ophiolites of the Dinarides and Hellenides was suggested by several authors in the last decades (Balla et al., 1980; Harangi et al., 1996; Józsa, 1999; Csontos, 1999; Dimitrijević et al., 2003; Kiss et al., 2011, 2012), but its sub-ophiolitic mélange nature was recognise only by Kovács et al., (2008, 2011a). However, the concept and definition for mélange nappes and the overriding ophiolite nappe have had a long evolution both in the Dinarides and in the Bükk-Darnó area (Dimitrijević et al., 2003, Karamata et al., 2005, Gawlick et al., 2009, 2017, 2018; Gawlick & Missoni, 2019; Schmid et al., 2008, 2020; Djerić et al., 2024). In the following, in line with the concept of Schmid et al. (2008, 2020), we

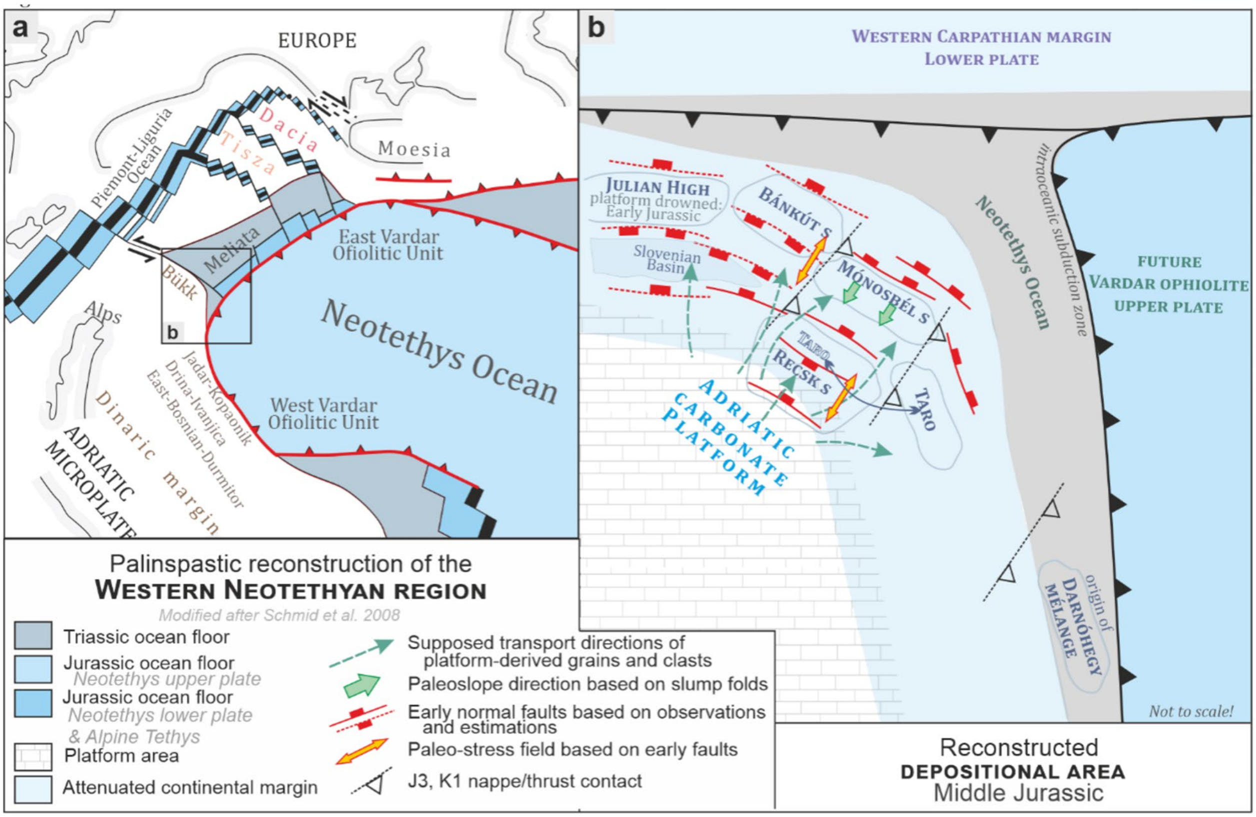

Fig. 8 **a** Palinspastic reconstruction of the northwestern termination of the Neotethys Ocean during the Middle Jurassic. Paleogeographic positions of the mentioned Cretacous Dinaric thrust sheets are indicated. (modified after Schmid et al., 2008). **b** Suggested paleogeographic positions of the discussed successions during the Middle Jurassic. Possible alternative positions of the future Taro during the Late Jurassic are included

use the name Western Vardar Ophiolite nappe to all the ophiolite thrust sheets obducted onto the Greater Adriatic continental margin in the Late Jurassic. We classify those block-in-matrix style complexes as real sub-ophiolitic mélange, which contain blocks/tectonic slices both from the lower plate (Middle to Upper Triassic basalts and their cover, slices of the distal passive margin) and from the upper plate ophiolite nappe (Middle to Upper Jurassic gabbro, basalt, and its sedimentary cover) and is mostly of Callovian–Oxfordian age (except for the younger Fruška Gora Mélange, Stojadinović et al., 2022).

In our view, the following complexes shows great similarities in age, block composition and tectonic position to the Darnóhegy Mélange: sub-ophiolitic mélanges of the Western Vardar Ophiolite nappe (Diabase-Radiolarite Formation of former Yugoslavia), including the Repno Complex of the Medvednica Mt. (Halamić et al., 1998, 1999; Babić et al., 2002; Slovenec & Pamić, 2002), in the Ivanščica Mt. (Babić et al., 2002) and Kalnik Mt. (Halamić & Goričan, 1995; Pamić, 1997) and the Fruška Gora Mélange (Stojadinović et al., 2022). (see Fig. 1 for the present geographic locations of the units). The similarities include the similar clast composition deriving from both the upper and lower plate, their similar matrix/youngest clasts ages (Callovian–Oxfordian), and their tectonic position over continental margin units.

4.1.3 *Analogy for the Tarna olistostrome*

In contrast with the uniform age of the sub-ophiolitic mélange, the youngest sedimentary age within the underthrust continental margin successions show a clear trend within the different thrust sheets of the Dinarides. In those thrust sheets, which derives from the more distal parts of the Greater Adriatic margin [Jadar–Kopaonik (JK) and Drina–Ivanjica Thrust Sheets (DI)] (Fig. 8), continental margin sedimentation terminated within the Middle Jurassic, usually in the Callovian (Vishnevskaya et al., 2009; Gawlick et al., 2017, Gawlick & Missoni, 2019). However, in the more proximal East-Bosnian-Durmitor Thrust sheet Tithonian or even Berriasian–Valanginian continental margin deposits are present (Djerić & Vishnevskaya, 2006; Gawlick et al., 2017, 2018, 2020; Stojadinović et al., 2022; Djerić et al., 2012, 2024). These Tithonian ages for the youngest sedimentary rocks under the sub-ophiolitc mélange show a possible connection towards the described Tarna olistostrome. The best studied locality among these Late Jurassic continental margin successions is the Krš Gradac locality and its neighbourhood (East-Bosnian–Durmitor Thrust Sheet). Here, directly underlying the sub-ophiolitic mélange and the Western Vardar Ophiolite nappes the uppermost part of the continental margin succession contains Bathonian to Tithonian radiolarite-rich formation (Gonje Fm.) which contains mass transport deposits and turbidites in the upper part (Gawlick et al., 2017, 2020, Djerić & Vuletić, 2023). In the upper(?) Kimmeridgian–upper(?) Tithonian part polymict carbonate breccias/olistostromes are present with Upper Jurassic shallow-water carbonates, Upper Triassic pelagic limestones, Norian reef limestones and radiolarite clasts derived partly from the platform, partly from slices detached from the top of the continental margin units and/or the mélange nappe (Gawlick et al., 2020). Highest part of the section lacks any limestone clasts and contains more and more fine-grained sandstone layers, which consist of quartz grains, heavy minerals and ophiolitic detritus. The Cr-spinells in the heavy mineral assemblage are derived clearly from the approaching ophiolite nappe. The whole Jurassic is condensed, only ~30 m thick, and can be interpreted as a part of a foreland basin on top of the passive margin succession. However, the small clast-size of the redeposited beds along with the condensed nature of the succession indicate that the obducted ophiolite nappe was still far away.

Despite the similarities in the age and style of sedimentation with the Tarna olistostrome, the two successions show differences. Regarding the distance from the advancing upper plate during the Late Jurassic, the Taro could have been in a similar paleogeographical position as the easternmost part of the East-Bosnian–Durmitor Thrust sheet (Fig. 8). However, the whole succession has significantly greater thickness (few tens of metres vs. several hundred metres) and coarser-grained components (Fig. 4; Haas et al., 2024), indicating closer position to the source.

However, the source area and the kinematics of the basins are still debated. Clast composition would rather refer to lower plate source, thus exhumation of the deeper part of the crust within the lower plate is needed. A basin system with a bit older formation age, but equally debated formation mechanism is present in the Outer Dinarides: the Lemeš and the Gorski Kotar Basins (Vitzhum et al., 2022). The specialities of these late Oxfordian to Kimmeridgian basins are their formation within the AdCP, the lack of coarse-grain gravitation mass flow deposits and the relationship of their fauna towards the Alpine–Atlantic Ocean.

4.2 Tectonic implication of Middle Jurassic extension

4.2.1 Orientation of the Bajocian–early Callovian normal faults

The supposed WSW–ENE orientation is in good agreement with the measured syn-sedimentary faults, silica dykes and slump folds in the Middle Jurassic carbonate turbidite beds of the Ms in the south-western Bükk Mts. (Oravecz et al., 2020). The original strike of the Middle Jurassic normal faults is difficult to decipher. Oravecz et al. (2020) used 80° clockwise (CW) back-rotation, compensating the well documented Miocene counter-clockwise (CCW) rotation of the entire Bükk–Recsk–Darnó area (Márton & Márton, 1996; Márton et al., 2007). However, only a few Cretaceous(?) paleomagnetic directions are known from remagnetised samples (Márton, 2004, and unpublished data), and no original Jurassic or Triassic magnetisation has been documented, so far. The closest well-characterised units, the Transdanubian Range and Rudabánya Hills all show net post-Triassic and/or post-Jurassic rotation of 45–80°CCW (Márton et al., 2025 and references therein). The other unit which can be related to the Bükk–Recsk nappe piles (Schmid et al., 2008), the Medvednica Mt. in Croatia behaved differently, and is marked by net CW rotation (Tomljenović et al., 2008). On the other hand, van Hinsbergen et al. (2020) used CW rotations to restore the position of the Bükk Mts.

All these data are not sufficient to draw a firm conclusion of the original orientation of Jurassic grabens and bounding normal faults. We used the most generally accepted Miocene 80° CW back-rotation, and postulate NW–SE orientations (Fig. 8), which would correspond to the paleogeography of the Greater Adriatic margin of the Neotethys Ocean and that of the Slovenian Basin, having been oriented ~N–S and ~E–W, respectively (Maffione et al., 2015; Goričan et al., 2018).

4.2.2 Bajocian–early Callovian extension in other Neotethyan marginal units of Greater Adria

The small-scale extensional features in the Ms, the reconstructed depositional environment, the cross sections and the stratigraphic and tectonic similarities to the SB suggest that the Middle Jurassic Rs and the Ms were formed in an extensional basin. This interpretation would modify earlier assumptions, which considered the Ms as part of the accretionary units. The geodynamic background for this extension can be the result of two reinforcing effects: (1) changing from rifting to spreading in the Alpine Atlantic Ocean (Handy et al., 2010, Le Breton et al., 2021), and the transfer of this deformation to the Neotethyan margin (Frasca et al., 2024), (2) downbending-related extension of the upper crustal region in the lower plate (Bradley & Kidd, 1991). In the first case, three times speed-up of the rifting-spreading velocities in the Alpine Atlantic region is estimated at 165 Ma (Le Breton et al., 2021). This accelerated extension could be transferred to the Neotethyan domain via transfer faults suggested by a number of maps (Schmid et al., 2008; Handy et al., 2010; van Hinsbergen et al., 2020; Le Breton et al., 2021; Frasca et al., 2024). In such a scenario the SB would have separated two platforms (Adriatic and Julian) and opened along a transform fault, while the Rs and the Ms were located at its transition to the Neotethys (Fig. 8). In the second scenario, an extension on the down-bending plate was described from the Transdanubian Range, which was situated on the more proximal part of the Greater Adriatic margin (Fig. 1b). This deformation is a bit younger, late Oxfordian–Kimmeridgian there (Fodor & Főzy, 2013). Late Jurassic normal faulting appeared in the Adriatic Carbonate platform (Bucković et al., 2004, Vitzhum et al., 2022) may have a similar explanation. These latter two cases may indicate the propagation of extensional deformation into the more proximal shelf area within the down-bending lower plate due to the forelandward movement of the ophiolite nappe.

4.2.3 Changing from extension to shortening

The change from extensional to contractional plate tectonic setting is a key question in the Neotethyan geodynamics. Several lines of arguments can be raised for the onset of contraction from theoretical plate tectonic inferences to the age of the metamorphic sole, which is related to intra-oceanic subduction, the age of mélange formation, obduction and continental margin imbrication, or the age of the overstep sequences. There are two main competing models concerning the way of obduction and lower plate imbrication. The first one suggests, that the Western Vardar Ophiolite nappe juxtaposed the Greater Adriatic margin during the Late Jurassic to earliest Cretaceous (Berriasian) with WNW- to NW-vergency, which predates the SW-ward nappe-stacking of the Greater Adriatic crust (Schmid et al., 2008, 2020; Djerić et al., 2012; Schefer et al., 2010; Porkoláb et al., 2019).

The second model suggests synchronous ophiolite obduction and continental margin imbrication in the Bajocian–Bathonian interval, then propagation of the deformation both in the upper plate (internal thrusting within the ophiolite nappe), and in the lower plate during the late Bathonian–Oxfordian (Gawlick & Missoni, 2019 and references therein). During the first step the nappe-stacking deformation penetrates the continental margin till the edge of the Upper Triassic platform areas (Drina-Ivanica unit), then propagates further towards the western foreland (East-Bosnian–Durmitor unit). The obduction of the ophiolite nappe is out-of-sequence, post-dating the imbrication of the continental margin. The very early imbrication of the continental margin comes from the age data of the basins with redeposited clasts, which are thought to be foreland basins, although no direct structural proof on their contractional origin is provided (Gawlick et al., 2017, 2018, 2020).

Our observations and age data from the Rs, the Taro and the Darnóhegy Mélange provide additional information in this question. The Middle Jurassic deposition occurred in extensional settings from the Bajocian to early Callovian. This model can be extended to the Bs and Ms in the Bükk Mts. on the basis of small–scale structures (Oravecz et al., 2020) and detailed cross-sections (Balla et al., 1987). The lack of contractional structures or ophiolite-derived material in the gravity mass flow deposits of the Ms and Rs exclude their attribution to any mélange units related directly or indirectly to the Neotethyan subduction front. It cannot be excluded that the upper Tithonian Taro (Haas et al., 2024) already indicates a compressional setting. The obtained stratigraphic age gives constraints on the earliest possible time for the overthrusting of the ophiolite nappe, which is late Tithonian in this sector of the continental margin. This suggests that the change from extension to shortening occurred between Callovian and Tithonian in the Taro, Ms and probably in the Rs, too.

On the other hand, the Callovian–Oxfordian DM (Haas et al., 2024), as a true sub-ophiolitic mélange could have formed in the front of the advancing ophiolite nappe in the early stage of subduction, incorporating material only from the upper plate and very distal lower plate. This means that the transition from extension to compression was gradual across the Neotethyan margin, as expressed by the model of Djerić et al. (2024).

4.2.4 Proposed paleogeographic position of the investigated units

The following paleogeographic position can be suggested for the described units during the Middle–Late Jurassic (Fig. 8).

The deposition areas of the Bánkút succession and the Mónosbél succession (Ms) of the Bükk Mts, the Recsk succession (Rs) and the Tarna olistostrome (Taro) were most probably located at the north-western termination of the Neotethys Ocean. The Rs and the Ms most probably deposited in a separate sub-basin close to the eastern continuation of the Slovenian Basin. The Bánkút succession (Bs) may have formed the eastern continuation of the elevated Julian High.

The DM formed during the earlier phase of the ophiolite obduction, during the Callovian–Oxfordian far to the SE from the SB and its surroundings, but in the vicinity of the advancing and overriding Western Vardar ophiolitic nappe (Fig. 8). Later, this unit approached the continental margin successions, namely the Taro, Ms, Rs then Bs. However, the lack of ophiolite-derived clasts in the Taro (Haas et al., 2024) indicate a certain distance from the overriding ophiolite nappe. The Taro reflects a sort of foreland basin, which could have an imbricate stack on its oceanward side. The Taro (already carrying the DM and the WV ophiolite nappe) thrust upon the Rs and Ms during the latest Tithonian–earliest Berriasian. This could be the timing when the Ms was sheared off its pre-Bajocian formations and thrust onto the Bs. Because the Rs still has its Triassic part, this unit could avoid such displacement or the basal detachment is deeper. The SB, located farther to the west of the nappe stack avoided contractional deformation during the Mesozoic, and is characterised by a continuous succession until the Maastrichtian. In such very proximal margin parts, the Neotethyan nappe stacking is indirectly reflected by ophiolite-derived detritus, deposited in foreland basin successions (Goričan et al., 2018).

The nappe packages suffered anchizonal metamorphism and folding during the Early Cretaceous, most probably due to the overburden of the ophiolite nappe (Árkai, 1983; Árkai et al., 1995; Csontos, 1988, 1999). After the nappe emplacement the units underwent further reorganisations, partly along the paleo-Darnó fault. The present-day configuration was achieved by the latest Cretaceous and Cenozoic thrusting and strike-slip faulting (Csontos, 1988, Csontos and Nagymarosy, 1998, Oravecz et al., 2024).

5 Conclusion

The examined core material from a displaced segment of the Greater Adriatic margin resulted in the following conclusions. The pre-Cenozoic basement of the area is characterised by three juxtaposed units: the lowermost Recsk succession (Rs), the Tarna olistostrome (Taro) and the topmost Darnóhegy Mélange nappe (DM). The Bajocian–early Callovian part of the Rs was deposited in an extensional graben-half-graben system. The subbasins were bounded by WNW–ESE oriented horsts, and they get coarser-grained sedimentary supply from two sources: from the footwall of the normal faults and from a coeval carbonate platform, which was located towards the SSW. The platform was active until the late Bathonian, when it drowned and a pelagic dark shale covered it. This drowning was most probably connected to the propagation of the normal fault activity towards the platform area. Among the coeval successions of the Dinarides, the Rs shows some similarities with the Upper Triassic to Middle Jurassic sedimentary succession of the southern areas of the Slovenian Basin (SB). The major differences are the thickness of the Middle Jurassic formations (Rs can be even ten times thicker) and the presence of sandstone turbidites, which are characteristic for the upper Bathonian–Callovian part of the Rs, but completely missing from the SB.

The Rs is juxtaposed by the upper Tithonian Taro, with clasts derived from the Upper Permian–Lower Jurassic succession of a distal Greater Adriatic margin. It shows some similarities with coeval pelagic successions from the East-Bosnian–Durmitor Thrust sheet, once being also part of the Greater Adriatic margin. The main differences are the thickness of the succession (the Taro is even ten times thicker) and the size of the clasts within the gravitation mass flows (mm to cm vs. blocks up to 100 m in Taro).

The uppermost unit, the DM is a typical sub-ophiolitic mélange nappe which can be correlated with the sub-ophiolite nappes under the Western Vardar Ophiolite in the Internal Dinarides.

The following tectonic contributions can be drawn up regarding the Middle to Late Jurassic evolution of the northern part of the Greater Adriatic margin:

1. During the Bajocian–early Callovian the investigated Greater Adriatic margin segment was the subject of extensional basin formation and pelagic sedimentation with mass-flow deposits deriving from the coeval platform and from the older passive margin formations, exposed in the footwall of basin-bounding normal faults. The extension may have been triggered by the opening in the Alpine-Atlantic realm and the down-bending of the Greater Adriatic plate due to the initial stage of the intra-oceanic subduction further in the east, near the axial part of the Neotethys Ocean.
2. As the obduction started and the Western Vardar Ophiolite nappe reached the attenuated distal continental margin of Greater Adria during the Callovian–Oxfordian, the sub-ophiolitic mélange (DM) was formed in its basal thrust zone far to the SE of the studied area. The obduction reached the area of the later Jadar–Kopaonik and Drina–Ivanjica thrust sheets in the Oxfordian, while continental margin sedimentation continued on the more proximal parts of the margin, like in the later East-Bosnian–Durmitor Thrust Sheet, in the Fruška Gora, in the Slovenian Basin and the depositional area of the Taro. These areas received fine- to coarse-grained material from the approaching ophiolite nappe and its underlying sub-ophiolitic mélange.
3. The eastern part of the East-Bosnian–Durmitor Thrust Sheet, the Fruška Gora and the Taro is reached by the obducting ophiolite nappe and its

underlying sub-ophiolitic mélange nappe not earlier than the latest Tithonian. Foreland basin type sedimentation continued until the Valanginian on the more proximal parts of the Greater Adriatic margin, like in the western part of later EBD. In the Valanginian, the overthrusting ophiolite juxtaposed this area, too. The emplacement of the Taro over the Recsk succession could happen in the earliest Cretaceous.

Acknowledgements

The Bükk National Park (UNESCO Geopark from 2024), and particularly S. Holló facilitated the field work and assisted at discussions. Field works of M. Fialowski and B. Scherman during their MSc works contributed to the knowledge on the Mónosbél succession. The authors thank P. Gál for the usage of his unpublished uncovered geological map of the Sirok area. B. Beke and A. Petrik assisted at field work around the Darnó Fault Zone. The very detailed reviews of Igor Vlahović and Špela Goričan along with the suggestions of SJG editor Wilfried Winkler have highly improved the quality of the manuscript.

Author contributions

SK performed microtectonic investigations, constructed cross-sections, prepared the figures, conceptualised the depositional and structural model and the tectonic implications. JH characterised the depositional environments and identified the source of gravitation mass flow deposits. ND, OP, SO contributed to the stratigraphical interpretations and comparison with other units. FL reviewed and refined the structural model, the basin model and the tectonic implications. All authors reviewed and approved the final manuscript.

Funding

Open access funding provided by Eötvös Loránd University. The research was supported by the National Research, Development and Innovation Office of Hungary, project 134873 (LF). N. Djerić acknowledges the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract no. 451-03-65/2024-03/200126) and Science Fund of the Republic of Serbia (Grant no. TF C1389-YF/Project no. 7461).

Data availability

The dataset supporting the conclusions of this article is included within the article.

Declarations

Competing interests

The authors declare no competing interests.

Received: 20 July 2024 Accepted: 29 November 2024
Published online: 03 February 2025

References

Arató, R., Zelenka, T., Less, Gy., & Fodor, L. (2024). Recsk Andesite Complex. In E. Babinszki, O. Piros, G. Csillag, L. Fodor, L. Gyalog, Zs. Kercsmár, Gy. Less, R. Lukács, K. Sebe, I. Selmeczi, J. Szepesi, & O. Sztanó (Eds.), *Lithostratigraphic units of Hungary II* (p. 34). Supervisory Authority for Regulatory Affairs (SARA).

Árkai, P. (1983). Very low- and low-grade Alpine regional metamorphism of the Paleozoic and Mesosoic formations of the Bükkium, NE Hungary. *Acta Geologica Hungarica, 26*(1–2), 83–101.

Árkai, P., Balogh, K., & Dunkl, I. (1995). Timing of the low-temperature metamorphism and cooling of the Paleozoic and Mesozoic formations of the Bükkium, innermost West Carpathians, Hungary. *Geologische Rundschau, 84*, 334–344.

Babič, L. J., Hochuli, P. A., & Zupanič, J. (2002). The Jurassic ophiolitic mélange in the NE Dinarides: Dating, internal structure and geotectonic implications. *Eclogae Geologicae Helvetiae, 95*, 263–275.

Balla, Z., Baksa, Cs., Földessy, J., Havas, L., & Szabó, I. (1980). The tectonic settings of the ophiolites in the Bükk Mountains (North Hungary). *Geologica Carpathica, 31*(4), 465–493.

Balla, Z., Csontos, L., Havas, L., & Horváth, Á. (1987). The Lök-Valley syncline in N Hungary. *Annual Report of the Geological Institute of Hungary from 1985.* p. 195–207 **(in Hungarian with English abstract)**

Bortolotti, V., Chiari, M., Marroni, M., Pandolfi, L., Principi, G., & Saccani, E. (2013). Geodynamic evolution of ophiolites from Albania and Greece (Dinaric-Hellenic belt): One, two, or more oceanic basins? *International Journal of Earth Sciences, 102*, 783–811.

Bradley, D. C., & Kidd, W. S. F. (1991). Flexural extension of the upper continental crust in collisional foredeeps. *Geological Society of America Bulletin, 103*, 1416–1438.

Bucković, D., Cvetko Tesović, B., & Gušić, I. (2004). Late Jurassic paleoenvironmental evolution of the Western Dinaries (Croatia). *Geologica Carpathica, 55*(1), 3–18.

Buser, S. (1986). *Basic geological map of Yugoslavia 1:100.000, Sheet Tolmin and Udine. Explanatory text,* 103 p. Belgrade.

Buser, S. (1989). Development of the Dinaric and Julian Carbonate Platforms and of the intermediate Slovenian Basin (NW Yugoslavia). *Memorie Societá Geologica Italiana, 40*, 313–320.

Buser, S., Kolar-Jurkovšek, T., & Jurkovšek, B. (2008). The Slovenian Basin during the Triassic in the light of the conodont data. *Bollettino della Società Geologica Italiana, 127*, 257–263.

Csontos, L. (1988). *Étude géologique d'une portion des Carpathes internes: le massif du Bükk (Nord-est de la Hongrie).* PhD Thesis, Université Lille Flandres-Artois, n° 250, 327 p. Lille, France.

Csontos, L. (1999). Structural outline of the Bükk Mts. (N. Hungary). *Földtani Közlöny, 129*(4), 611–651.

Csontos, L. (2000). A Bükk hegység mezozoos rétegtani újraértékelése. Stratigraphic reevaluation of the Bükk Mts.(N. Hungary). *Földtani Közlöny*, *130*, (1) 95–131. (in Hungarian with English abstract).

Csontos, L., Dosztály, L., & Pelikán, P. (1991). Radiolarians from the Bükk Mts. *Annual Report of the Geological Institute of Hungary from 1985*, 357–409.

Csontos, L., & Nagymarosy, A. (1998). The Mid-Hungarian line: A zone of repeated tectonic inversion. *Tectonophysics, 297*, 51–72.

Csontos, L., & Vörös, A. (2004). Mesozoic plate tectonic reconstruction of the Carpathian region. *Palaeogeography, Paleoclimatology, Palaeoecology, 210*, 1–56.

De Wever, P. (1984). Triassic radiolarians from the Darnó area (Hungary). *Acta Geologica Hungarica, 27*(3–4), 295–306.

Dimitrijević, M. N., Dimitrijević, M. D., Karamata, S., Sudar, M., Gerzina, N., Kovács, S., Dosztály, L., Gulácsi, Z., Less, Gy., & Pelikán, P. (2003). Olistostrome/mélanges—an overview of the problematics and preliminary comparison of such formations in Yugoslavia and NE Hungary. *Slovak Geological Magazine, 9*(1), 3–21.

Djerić, N., Gawlick, H.-J., & Sudar, M. (2024). The Jurassic ophiolitic mélanges in Serbia – a review and new insights. In A. Festa, Y. Dilek, & E. Barbero (Eds.), *Significance of ophiolites, mélanges and blueschist assemblages in probing the crustal anatomy and geodynamic evolution of orogenic belts* (2nd ed., Vol. 181). Geological Society, Special Publications. https://doi.org/10.1144/jgs2023-165

Djerić, N., Schmid, M. S., & Gerzina, N. (2012). Middle Jurassic radiolarian assemblages from the sedimentary cover of the Adriatic margin (Zlatar Mountain, SW Serbia). *Bulletin De La Société Géologique De France, 183*(4), 359–368.

Djerić, N., & Vishnevskaya, V. (2006). Some Jurassic and Cretaceous radiolarians of Serbia. In: Proceedings Mesozoic ophiolites of northern part of the Balkan Peninsula. *International Symposium Ophiolites* 2006.

Djerić, N., & Vuletić, M. (2023). Radiolarian assemblage from radiolarites of the Krš Gradac section (SW Serbia): On the way to a better reconstruction of the Middle-Late Jurassic geodynamic history of the Inner Dinarides. *Geološki Anali Balkanskoga Poluostrva, 84*(2), 107–116.

Dosztály, L. (1994). Mesozoic radiolarian investigations in Northern Hungary. Unpublished PhD Thesis 108 p. **(in Hungarian)**.

Dosztály, L., Gulácsi, Z., & Kovács, S. (1998). Lithostratigraphy of the Jurassic formations of North Hungary. In I. Bérczi & Á. Jámbor (Eds.), *Stratigraphy* *of the geological formations in Hungary* (pp. 309–318). MOL Ltd.—Geological Institute of Hungary. in Hungarian.

Dosztály, L., & Józsa, S. (1992). Geochronological evaluation of Mesozoic formations of Darnó Hill at Recsk on the basis of radiolarians and K-Ar age data. *Acta Geologica Hungarica, 35*(4), 371–393.

Einsele, G. (1992). *Sedimentary basins—evolution, facies, and sediment budget*. Springer.

Fodor, L., & Főzy, I. (2013). The place of the Gerecse Mountains in Alpine-Carpathian framework—a geological setting. In I. Főzy (Ed.), *Late Jurassic-Early Cretaceous fauna, biostratigraphy, facies and deformation history of the carbonate formations in the Gerecse and Pilis Mountains (Transdanubian Range, Hungary)* (pp. 15–20). GeoLitera Publishing House.

Fodor, L., Jelen, B., Márton, E., Skaberne, D., Čar, J., & Vrabec, M. (1998). Miocene-Pliocene tectonic evolution of the Slovenian Periadriatic Line and surrounding area—implication for Alpine-Carpathian extrusion models. *Tectonics, 17*, 690–709.

Frasca, G., Manatschal, G., & Chenin, P. (2024). Kinematic reconstruction of the Alpine Tethys and surrounding Mesozoic rifted margins. *International Journal of Earth Sciences, 113*, 1053–1065.

Gaina, C., Torsvik, T. H., van Hinsbergen, D. J. J., Medvedev, S., Werner, S. C., & Labails, C. (2013). The African Plate: A history of oceanic crust accretion and subduction since the Jurassic. *Tectonophysics, 604*, 4–25.

Gál P., Pecsmány P., Petrik A., Lukács R., Fodor L., Kövér Sz., & Harangi Sz. (2021): A Sirok környéki miocén rétegsor földtani és geomorfológiai reambulálása. In: J. Füri, & E. Király, (Eds.), *Átalakulások, 11. Kőzettani és Geokémiai Vándorgyűlés, Sopron, 2021*. szeptember 02–04. (p. 32). Budapest, Geological Society of Hungary, ISBN: 978-963-8221-83-4.

Gale, L. (2010). Microfacies analysis of the Upper Triassic (Norian) "Bača Dolomite": Early evolution of the western Slovenian Basin (eastern Southern Alps, western Slovenia). *Geologica Carpathica, 61*(4), 293–308.

Gawlick, H. J., Goričan, Š, Missoni, S., & Lein, R. (2012). Late Anisian platform drowning and radiolarite deposition as a consequence of the opening of the Neotethys ocean (High Karst nappe, Montenegro). *Bulletin de la Société Géologique de France, 183*(4), 349–358.

Gawlick, H.-J., & Missoni, S. (2019). Middle-Late Jurassic sedimentary mélange formation related to ophiolite obduction in the Alpine-Carpathian-Dinaridic Mountain Range. *Gondwana Research, 74*, 144–172.

Gawlick, H.-J., Missoni, S., Sudar, M. N., Suzuki, H., Méres, Š., Lein, R., & Jovanović, D. (2018). The Jurassic Hallstatt Mélange of the Inner Dinarides (SW Serbia): Implications for Triassic-Jurassic geodynamic and palaeogeographic reconstructions of the Western Tethyan realm. *Neues Jahrbuch Geologie Paläontologie Abhandlungen, 288*, 1–47.

Gawlick, H.-J., Sudar, M., Missoni, S., Aubrecht, R., Schlagintweit, F., Jovanović, D., & Mikuš, T. (2020). Formation of a Late Jurassic carbonate platform on top of the obducted Dinaridic ophiolites deduced from the analysis of carbonate pebbles and ophiolitic detritus in southwestern Serbia. *International Journal of Earth Sciences, 109*, 2023–2048.

Gawlick, H.-J., Sudar, M. N., Missoni, S., Suzuki, H., Lein, R., & Jovanović, D. (2017). Triassic Jurassic geodynamic history of the Dinaridic Ophiolite Belt (Inner Dinarides, SW Serbia). Field Trip Guide, 13th Workshop on Alpine Geological Studies (Zlatibor, Serbia 2017). *Journal of Alpine Geology, 55*, 1–167.

Gawlick, H.-J., Sudar, M., Suzuki, H., Djerić, N., Missoni, S., Lein, R., & Jovanović, D. (2009). Upper Triassic and Jurassic radiolarians from the ophiolitic mélange of the Dinaridic Ophiolite Belt, SW Serbia. *Neues Jahrbuch Für Geologie und Paläontologie Abhandlungen, 253*, 293–311.

Goričan, Š., Košir, A., Rožič, B., Šmuc, A., Gale, L., Kukoč, D., Celarc, B., Crne, A.E., Kolar-Jurkovšek, T., Placer, L., & Skaberne, D. (2012). *Mesozoic deep-water basins of the eastern Southern Alps (NW Slovenia)*. Field Trip Guide 29th IAS Meeting of Sedimentology Schladming, Austria. *Journal of Alpine Geology, 55*, ISSN(s) 1563–0846.

Goričan, Š, Žibret, L., Košir, A., Kukoč, D., & Horvat, A. (2018). Stratigraphic correlation and structural position of Lower Cretaceous flysch-type deposits in the eastern Southern Alps (NW Slovenia). *International Journal of Earth Sciences, 107*, 2933–2953.

Gyalog, L., & Síkhegyi, F. (2005). *Geological map of Hungary, 1:100 000*. Geological Institute of Hungary.

Haas, J., Fodor, L., Djerić, N., Szives, O., Ozsvárt, P., Fialowski, M., & Kövér, S. (2024). Middle to Late Jurassic pelagites and gravity mass flow deposits of a displaced Neotethyan margin: Microfacies and biostratigraphical studies in Northeast Hungary. *Geološki Anali Balkanskoga Poluostrva, 85*(2), 17–64. https://doi.org/10.2298/GABP241010014H

Haas, J., Görög, Á., Kovács, S., Ozsvárt, P., Matyók, I., & Pelikán, P. (2006). Displaced Jurassic foreslope and basin deposits of Dinaridic origin in Northeast Hungary. *Acta Geologica Hungarica, 49*(2–3), 345–362.

Haas, J., & Kovács, S. (2001). The Dinaridic-Alpine connection—as seen from Hungary. *Acta Geologica Hungarica, 44*(2–3), 345–362.

Haas, J., Kovács, S., Gawlick, H. J., Grădinaru, E., Karamata, S., Sudar, M., Péró, Cs., Mello, J., Polak, M., Ogorelec, B., & Buser, S. (2011). Jurassic evolution of the tectonostratigraphic units in the Circum-Pannonian region. *Jahrbuch der geologischen Bundesanstalt, 151*(2), 125–163.

Haas, J., Pelikán, P., Görög, Á., Józsa, S., & Ozsvárt, P. (2013). Stratigraphy, facies and geodynamic settings of Jurasic formations in the Bükk Mountains, North Hungary: Its relations with the other areas of the Neotethyan realm. *Geological Magazine, 150(1)*, 18–49. https://doi.org/10.1017/S0016756812000246.

Halamić, J., & Goričan, S. (1995). Triassic radiolarites from Mts. Kalnik and Medvednica (Northwestern Croatia). *Geologica Croatica, 48*(2), 129–146.

Halamić, J., Goričan, S., Slovenec, D., & Kolar-Jurkovšek, T. (1998). Triassic pelagic limestones in the Orešje quarry near Gornja Bistra, Medvednica Mt. (NW Croatia). *Geologica Croatica, 51(3)*, 33–45.

Halamić, J., Goričan, S., Slovenec, D., & Kolar-Jurkovšek, T. (1999). A Middle Jurassic radiolarite-clastic succession from the Medvednica Mt. (NW Croatia). *Geologica Croatica, 52*(1), 29–57.

Handy, M. R., Schmid, S. M., Bousquet, R., Kissling, E., & Bernoulli, D. (2010). Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps. *Earth-Science Reviews, 102*(3–4), 121–158.

Harangi, Sz., Szabó, Cs., Józsa, S., Szoldán, Zs., Árváné Sós, E., Balla, M., & Kubovics, I. (1996). Mesozoic igneous suits in Hungary: Implications for genesis and tectonic setting in the northwestern Tethys. *International Geological Revue, 38*, 336–360.

Józsa, S. (1999). *Petrography and geochemistry of ocean floor magmatic rocks of Darnó Hill, HE Hungary.* PhD thesis. Eötvös Loránd University, Budapest (p 137)

Józsa, S., Balogh-Kiss, G., & Fodor, L. (2024). Darnóhegy Mélange Complex. In E. Babinszki, O. Piros, T. Budai, L. Gyalog, A. Halász, E. Király, B. Koroknai, R. Lukács, & T. M.Tóth (Eds.), *Lithostratigraphic units of Hungary I. Pre-Cenozoic formations* (p. 213). Supervisory Authority for Regulatory Affairs SARA.

Józsa, S., Dosztály, L., Gulácsi, Z., & Kovács, S. (1996). *Ophiolites of Szarvaskő, Darnó Hill and Bódva Valley. Excursion guide IGCP-369*. Workshop of rift magmatism, (p 16) Budapest.

Jurkovšek, B., Šribar, L., Ogorelec, B., & Kolar-Jurkovšek, T. (1990). Pelagic Jurassic and Cretaceous beds in the western part of the Julian Alps. *Geologija, 31–32*, 285–328.

Karamata, S., Sladić-Trifunović, M., Cvetković, V., Milovanović, D., Šarić, K., Olujić, J., & Vujnović,. (2005). The western belt of the Vardar Zone, with special emphasis to the ophiolites of Podkozarje – the youngest ophiolitic rocks of the Balkan Peninsula. Bulletin T., 130, Serbian Acad. Sci. Arts. Cl., Sci. Math. Nat. *Sci. Nat., 43*, 85–96.

Kiss, G., Molnár, F., Koller, F., & Péntek, A. (2011). Triassic advanced rifting related and Jurassic ophiolite-like magmatic rocks in the Bükk Unit, NE-Hungary—an overview. *Mitteilungen der Österreichischen Mineralogischen Gesellschaft, 157*, 43–69.

Kiss, G., Molnár, F., Pálinkás, L., Kovács, S., & Horvatović, H. (2012). Correlation of Triassic advanced rifting-related Neotethyan submarine basaltic volcanism of the Darnó Unit (NE-Hungary) with some Dinaridic and Hellenidic occurrences on the basis of volcanological, fluid–rock interaction, and geochemical characteristics. *International Journal of Earth Sciences, 101*, 1503–1521.

Kolar-Jurkovšek, T. (1991). Microfauna of Middle and Upper Triassic in Slovenia and its biostratigraphic significance. *Geologija, 33*, 21–170.

Kolar-Jurkovšek, T. (2011). Latest Triassic conodonts of the Slovenian Basin and some regards on their evolution. *Geologija, 54*(1), 83–92.

Kovács, S., Gecse, Zs., Pelikán, P., Zelenka, T., Szebényi, G., & Szabó, I. (2013). Upper Triassic conodonts from deep boreholes of the Recsk—Darnó area: new data on the geology of its pre-Cenozoic basement. *Földtani Közlöny, 141*(1), 29–46.

Kovács, S., Haas, J., Ozsvárt, P., Palinkaš, L. A., Kiss, G., Molnár, F., Józsa, S., & Kövér, Sz. (2011b). Re-evaluation of the Mesozoic complexes of Darnó Hill (NE

Hungary) and comparisons with Neotethyan accretionary complexes of the Dinarides and Hellenides—preliminary data. *Central European Geology, 53*(2–3), 205–231.

Kovács, S., Haas, J., Szebényi, G., Gulácsi, Z., Józsa, S., Pelikán, P., Bagoly-Árgyelán, G., Görög, Á., Ozsvárt, P., Gecse, Zs, & Szabó, I. (2008). Permo-Mesozoic formations of the Recsk-Darnó Hill area: Stratigraphy, and structure of the Pre-Tertiary basement of the Paleogene Recsk Ore Field. *Publications of the University of Miskolc Series A-Mining, 73*, 33–56.

Kovács, S., Sudar, M., Grădinaru, E., Karamata, S., Gawlick, H. J., Haas, J., Péró, Cs., Gaetani, M., Mello, J., Polák, M., Aljinićić, D., Ogorelec, B., Kollar-Jurkovšek, T., Jurkovšek, B., & Buser, S. (2011a). Triassic evolution of the tectonostratigraphic units in the Circum-Pannonian region. *Jahrbuch der geologischen Bundesanstalt, 151*(3–4), 199–280.

Kövér, S., Fodor, L., Kovács, Z., Klötzli, U., Haas, J., Zajzon, N., & Szabó, Cs. (2018). Late Triassic acidic volcanic clasts in different Neotethyan sedimentary mélanges: Paleogeographic and geodynamic implications. *International Journal of Earth Sciences, 107*(8), 2975–2998.

Kozur, H. (1991). The evolution of the Meliata-Hallstatt ocean and its significance for the early evolution of the Eastern Alps and Western Carpathians. *Palaeography, Palaeoclimatology Palaeoecology, 87*, 109–135.

Kozur, H., & Krahl, J. (1984). Erster Nachweiss triassischer Radiolaria in der Phyllit-Gruppe auf der Insel Kreta. *Neues Jahrbuch Geologie Paläontologie Abhandlungen, 77*, 400–404.

Le Breton, E., Brune, S., Ustaszewski, K., Zahirovic, S., Seton, M., & Müller, D. R. (2021). Kinematics and extent of the Piemont-Liguria Basin—implications for subduction processes in the Alps. *Solid Earth, 12*, 885–913. https://doi.org/10.5194/se-12-885-2021

Less, Gy., & Mello, J. (Eds.). (2004). *Geological map of the Gemer-Bükk area, 1:100.000*. Geological Institute of Hungary, Budapest, and Geologicky Ústav Dionyza Stúra, Bratislava.

Maffione, M., van Thieulot, C., Hinsbergen, D. J. J., Morris, A., Plümper, O., & Spakman, W. (2015). Dynamics of intraoceanic subduction initiation: 1. Oceanic detachment fault inversion and the formation of supra-subduction zone ophiolites. *Geochemistry Geophysics Geosystems*. https://doi.org/10.1002/2015GC005746

Márton, E. (2004). Paleomagnetism of Permian-Triassic sections, Bükk Mts. *Hungary. Acta Geologica Hungarica, 47*(4), 341–347.

Márton, E., Haas, J., Imre, G., Velki, M., & Fodor, L. (2025). New Mesozoic APWP for Adria aided by data from the Transdanubian Range Unit—Tectonic interpretation in the Europe–Africa geodynamic system. *Gondwana Research, 137*, 274–298.

Márton, E., & Márton, P. (1996). Large scale rotation in North Hungary during the Neogene as indicated by palaeomagnetic data. In A. Morris & D. H. Tarling (Eds.), *Paleomagnetism and Tectonics of the Peri-Mediterranean Region* (Vol. 105, pp. 153–173). Geological Society Special Publications.

Márton, E., Zelenka, T., & Márton, P. (2007). Paleomagnetic correlation of Miocene pyroclastics of the Bükk Mts. and their forelands. *Central European Geology, 50*(1), 47–57.

Ogorelec, B., & Dozet, S. (1997). Upper Triassic, Jurassic and Lower Cretaceous beds in Eastern Sava Folds—Section Laze at Boštanj (Slovenia). *Rudarsko-Metalurški Zbornik, 44*, 223–235.

Oravecz, É., Benkó, Zs., Arató, R., Dunkl, I., Héja, G., Kövér, Sz., Németh, T., & Fodor, L. (2024). Age, kinematic and thermal constraints of syn-orogenic low-temperature deformation events: insights from thermochronology and structural data of the Nekézseny Thrust (Alpine-Carpathian-Dinaric area). *Tectonics, TECT22010*. https://doi.org/10.1029/2023TC008189

Oravecz, É., Kövér, Sz., Héja, G., & Fodor, L. (2020). Syn-sedimentary and early deformation structures as indications for Jurassic pre-orogenic deformation in the SW Bükk Mts. *Geologica Carpathica, 71*(4), 328–342.

Pamić, J. (1997). The northwesternmost outcrops of the Dinaridic ophiolites: case study of Mt. Kalnic (North Croatia). *Acta Geologica Hungarica, 40*(1), 37–56.

Pelikán, P. (2024). Oldalvölgy Formation. In E. Babinszki, O. Piros, T. Budai, L. Gyalog, A. Halász, E. Király, B. Koroknai, R. Lukács, & T. M.Tóth (Eds.), *Lithostratigraphic units of Hungary I Pre-Cenozoic formations* (p. 209). Supervisory Authority for Regulatory Affairs SARA.

Pelikán, P., Less, G. Y., Kovács, S., Pentelényi, L., & Sásdi, L. (2005). *Geology of the Bükk Mountains. Explanatory Book to the Geological Map of the Bükk Mountains, 1:50.000* (p. 284). Geological Institute of Hungary.

Placer, L. (2008). Principles of the tectonic subdivision of Slovenia. *Geologija, 51*(2), 205–217.

Porkoláb, K., Kövér, Sz., Benkó, Zs., Héja, G. H., Fialowski, M., Soós, B., Gerzina-Spajić, N., Đerić, N., & Fodor, L. (2019). Structural and geochronological constraints from Western Serbia: Implications for the Alpine evolution of the Internal Dinarides. *Swiss Journal of Geosciences, 112*(1), 217–234. https://doi.org/10.1007/s00015-018-0327-2

Ramovš, A. (1998). Conodonten-Stratigraphie der Obertrias von Slowenien: Ergebnisse eigener Untersuchungen. *Geologija, 40*, 223–232.

Robertson, A. H. F. (2012). Late Palaeozoic-Cenozoic tectonic development of Greece and Albania in the context of alternative reconstructions of Tethys in the Eastern Mediterranean region. *International Geology Review, 54*, 373–454.

Rožič, B., Gale, L., Oprčkal, P., Švara, A., Popit, T., Kunst, L., Turnšek, D., Kolar-Jurkovšek, T., Šmuc, A., Ivekovič, A., Udovč, J., & Gerčar, D. (2022). A glimpse of the lost Upper Triassic to Middle Jurassic architecture of the Dinaric Carbonate Platform margin and slope. *Geologija, 65*(2), 177–216. https://doi.org/10.5474/geologija.2022.011

Rožič, B., Gerčar, D., Oprčkal, P., Švara, A., Turnšek, D., Kolar-Jurkovšek, T., Udovč, J., Kunst, L., Fabjan, T., Popit, T., & Gale, L. (2019). Middle Jurassic limestone megabreccia from the southern margin of the Slovenian Basin. *Swiss Journal of Geosciences, 112*(1), 163–180. https://doi.org/10.1007/s00015-018-0320-9

Rožič, B., Goričan, Š, Švara, A., & Šmuc, A. (2014). The Middle Jurassic to Lower Cretaceous succession of the Ponikve Klippe: The southernmost outcrops of the Slovenian Basin in western Slovenia. *Rivista Italiana di Paleontologia e Stratigrafia, 120*(1), 83–102. https://doi.org/10.13130/2039-4942/6051

Rožič, B., Kollar-Jurkovšek, T., & Šmuk, A. (2009). Late Triassic sedimentary evolution of the Slovenian Basin (eastern Southern Alps): Description and correlation of Slatnik Formation. *Facies, 55*(1), 137–155.

Rozič, B., & Popit, T. (2006). Redeposited limestones in the Middle and Upper Jurassic successions of Slovenian basin. *Geologija, 49*(2), 219–234.

Rožič, B., & Reháková, D. (2024). Sedimentology and biostratigraphy of the Biancone Limestone Formation of the Tolmin Basin (Southern Alps, NW Slovenia). *Cretaceous Research*. https://doi.org/10.1016/j.cretres.2024.105958

Saccani, E., Beccaluva, L., Coltorti, M., & Siena F. (2004). Petrogenesis and tectono-magmatic significance of theAlbanide-Hellenide subpelagonian ophiolites. — Ofioliti, *29*(1), 75–93

Schefer, S., Egli, D., Missoni, S., Bernoulli, D., Gawlick, H.-J., Jovanović, D., Krystyn, L., Lein, R., Schmid, S., & Sudar, M. N. (2010). Triassic metasedimentary rocks in the Internal Dinarides (Kopaonik area, southern Serbia): stratigraphy, paleogeographic and tectonic significance. *Geologica Carpathica, 61*, 89–109.

Scherman, B., Rožič, B., Görög, Á., Kövér, Sz., & Fodor, L. (2023). Upper Triassic–to Lower Cretaceous Slovenian Basin successions in the northern margin of the Sava Folds. *Geologija, 66*(2), 205–228. https://doi.org/10.5474/geologija.2023.009

Scherreiks, R., Meléndez, G., Boudagher-Fadel, M., Fermeli, G., & Bosence, D. (2014). Stratigraphy and tectonics of a time-transgressive ophiolite obduction onto the eastern margin of the Pelagonian platform from Late Bathonian until Valanginian time, exemplified in northern Evvoia, Greece. *International Journal of Earth Sciences, 103*, 2191–2216.

Schmid, S. M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., Tischler, M., & Ustaszewski, K. (2008). The alpine-carpathian-dinaridic orogenic system: Correlation and evolution of tectonic units. *Swiss Journal of Geosciences, 101*(1), 139–183.

Schmid, S. M., Fügenschuh, B., Kounov, A., Maţenco, L., Nievergelt, P., Oberhänsli, R., Pleuger, J., Schefer, S., Schuster, R., Tomljenović, B., Ustaszewski, K., & van Hinsbergen, D. J. J. (2020). Tectonic units of the Alpine collision zone between Eastern Alps and western Turkey. *Gondwana Research, 78*, 308–374.

Slovenec, D., & Pamić, J. (2002). Geology of the Vardar Zone ophiolites of the Medvednica mountain area located along the Zagreb-Zemplin Line (NW Croatia). *Geologica Carpathica, 53*(1), 53–59.

Šmuc, A. (2005). *Jurassic and Cretaceous stratigraphy and sedimentary evolution of the Julian Alps* (p. 98). Ljubljana: ZRC Publishing, ZRC SAZU.

Stojadinović, U., Djerić, N., Radivojević, D., Krstekanić, N., Radonjić, M., & Džinić, B. (2022). Upper Jurassic radiolarites in the sub-ophiolitic mélange of the Fruška Gora (NW Serbia) and their significance for the evolution of the Internal Dinarides. *Ofioliti, 47*(2), 103–112.

Tari, G. (1994). Alpine Tectonics of the Pannonian basin. PhD. Thesis, Rice University, Texas, USA. 501 pp.

Tomljenović, B., Csontos, L., Márton, E., & Márton, P. (2008). Tectonic evolution of the northwestern Internal Dinarides as constrained by structures and rotation of Medvednica Mountains, North Croatia. In S. Siegesmund, B. Fügenschuh, & N. Froitzheim (Eds.), *Tectonic Aspects of the Alpine-Dinaride-Carpathian System* (Vol. 298, pp. 145–167). Geological Society, Special Publication.

Tremblay, A., Meshi, A., Deschamps, T., Goulet, F., & Goulet, N. (2015). The Vardar zone as a suture for the Mirdita ophiolites, Albania: Constraints from the structural analysis of the Korabi-Pelagonia zone. *Tectonics, 34*, 352–375. https://doi.org/10.1002/2014TC003807

Ustaszewski, K., Kounov, A., Schmid, S. M., Schaltegger, U., Krenn, E., Frank, W., & Fügenschuh, B. (2010). Evolution of the Adria-Europe plate boundary in the northern Dinarides: From continent-continent collision to back-arc extension. *Tectonics, 29*(TC6017), 1–34. https://doi.org/10.1029/2010TC002668

Ustaszewski, K., Schmid, S.M., Fügenschuh, B., Tischler, M., Kissling, E., Spakman, W. (2008). A map-view restoration of the Alpine-Carpathian-Dinaridic system for the Early Miocene. In: N. Froitzheim, S.M. Schmid, (Eds.) *Orogenic processes in the Alpine collision zone*. *Swiss Journal of Geosciences 101*, 273–294. https://doi.org/10.1007/s00015-008-1288-7.

Ustaszewski, K., Schmid, S. M., Lugović, B., Schuster, R., Schaltegger, U., Bernoulli, D., Hottinger, L., Kounov, A., Fügenschuh, B., & Schefer, S. (2009). Late Cretaceous intra-oceanic magmatism in the internal Dinarides (northern Bosnia and Herzegovina): Implications for the collision of the Adriatic and European plates. *Lithos, 108*, 106–125. https://doi.org/10.1016/j.lithos.2008.09.010

van Hinsbergen, D. J. J., Torsvik, T. H., Schmid, S. M., & Maţenco, L.C., Maffione, M., Gürer, D., Vissers, R.L.M. (2020). Orogenic architecture of the Mediterranean region and kinematic reconstruction of its tectonic evolution since the Triassic. *Gondwana Research, 81*, 79–229.

Vishnevskaya, V. S., Djerić, N., & Zakariadze, G. S. (2009). New data on Mesozoic Radiolaria of Serbia and Bosnia, and implications for the age and evolution of oceanic volcanic rocks in the Central and Northern Balkans. *Lithos, 108*, 72–105.

Vitzthum, M. A. J., Gawlick, H. J., Sachsenhofer, R. F., & Neumeister, S. (2022). Changing depositional environments in the semi-restricted Late Jurassic Lemeš Basin (Outer Dinarides; Croatia). *Facies, 68*(1), Artikel 2. https://doi.org/10.1007/s10347-021-00640-1

Vlahović, I., Tišljar, J., Velić, I., & Matičec, D. (2005). Evolution of the Adriatic Carbonate Platform: Palaeogeography, main events and depositional dynamics. *Palaeogeography, Palaeoclimatology, Palaeoecology, 220*, 333–360.

Vukovski, M., Kukoč, D., Grgasović, D., Fuček, L., & Slovenec, D. (2023). Evolution of eastern passive margin of Adria recorded in shallow- to deepwater successions of the transition zone between the Alps and the Dinarides. *Facies*. https://doi.org/10.1007/s10347-023-00674-7

Publisher's Note