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Discussion Note
Дискусија

Remarks on the Oligo-Miocene extensional episode(s) in Inner Dinarides: Towards the tectonic constraints of the origin of intra-montagne basins

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Abstract. The ongoing interest in the complex geology of the Dinaric orogen, in particular, its immediate, post-orogenic evolution (post-Lutetian), has produced a number of the tectonic solutions, proposing either extensional stage followed by the subsidence, extensional stage with immense lithospheric thinning resulting in the regional uplift, or even pure uplift episode(s). The unclear Late Oligocene–Miocene tectonic forces are often interpreted as interchange of the crustal-scale driven extensional uplift episodes, presumably affecting the formation of a number of the lacustrine mini-basins, often referred to as the „intra-montagne basins".A limited number of the available field-based structural interpretations tend to explain the Miocene crustal-rooted extensional episode(s). Despite lacking of the important subsurface data, such as wells-derived thickness and other data, commonly used for the reconstruction of the eventual subsidence stages, the available interpretations provide several deep crustal-scale models of the extensional setting. In order to better understand the timing and mechanism behind the onset of the Oligo-Miocene Dinaride "intra-montagne" extensional episode(s), this study uses the available information of the precursory oblique convergent margins, further proposing the use of a combination of the crustal and the basin modeling tools that could extract more information of the barely available subsurface data (subsidence rate, source-to-sink patterns, etc). The assessment of the recently published surface constraints, allowed the following discussion evaluating a set of the recently proposed crustal-scale "intra-montagne" tectonic models.

Key words:
Late Oligocene, "intra-montagne", Neogene, strike-slip, basin modeling.

Апстракт. Интересовање за комплексну геолошку грађу Динарида, нарочито за пост-орогену фазу или пост-лутетску геодинамичку еволуцију, произвело је неколико типова тектонских модела: екстензија која је резултирала субсиденцијом, екстензија литосферих размера која је довела до ексхумације самих Динарида, као и чисто издизање или „аплифт" Динарида као целине. Најчешће интерпретације засноване на горњоолигоценско-миоценској екстензији су довеле до стварања великог броја мини-басена који се у литератури могу наћи као „интра-плански". Релативно мали број регионално-теренских студија се труди да укаже и интепретира на могуће тектонске моделе литосферних размера. Иако су за интепретацију литосферних размера потребни различити потповршински подаци, као што су бушотине, моделовање и верифи-

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ковање типова и фаза субсиденције, публиковани радови указују на литосферна кретања и моделе, махом засноване на екстензији, док има и оних који указују на издизање самих Динарида. Да би се обезбедило боље разумевање самог почетка олиго-миоценске фазе настанка тих „интра-планинских“ басена, у овом раду се указује на значај наслеђених кинематских услова диктираних ранијим границама литосферних плоча. У раду се указује потреба за бољим разумевањем фаза субсиденције, као и механизмом спуштања, које на жалост нису доступне, или не постоје, а могу послужити истраживањима ових олиго-миоценских басена (нпр., брзина субсиденције, провенанца седимената, итд). С тога, у раду се дискутују постојећи модели и њихове интепретације ових олиго-миоценских „интра-планинских“ басена.

Кључне речи:
горњи олигоцен, „интра-планински“, неоген, транскуренција, басенско моделовање.

Introduction

Deciphering a mechanism behind intra-mountain basins is an essential element for any reconstruction of the post-collisional geodynamic evolution of a mountain belt. Dinaric highlands (*e.g.*, Dimitrijević, 1997; Picha, 2002; Ilić & Neubauer, 2005 and references therein; Korbar, 2009; Fig. 1a, b, c), in particular, its NE segment represents an ophiolite-decorated continental cross-lithospheric footwall (Maffione & van Hinsbergen, 2018) of the formerly subducting Adria microplate and its accretionary margin (hereinafter the Adria–Dinaria, Fig. 2). The composite Adria–Dinaria plate of the Mesozoic age (Spahić & Gaudenyi, 2020) was a segment of the foregoing oceanic subduction, descending in the oblique mode (Sava Suture Zone; subsurface lineaments from Vukašinović, 1973; Spahić & Gaudenyi, 2022) underneath the European microplates that were in a foreland position (Tisza- and the Serbo-Macedonian Unit; Karamata, 2006; Schmid et al., 2020; van Hinsbergen et al., 2020). Namely, the northwestern-positioned Southern Alps, as a "retro-wedge" (van Hinsbergen et al., 2020), gradually transfer its kinematics to the dominantly dextral shearing displacement of the Peri-Adriatic lineament representing the boundary between the Pannonian Basin and the Adria–Dinaria (Fig. 2). The Alpine Dinaride bilateral orogen (Doglioni et al., 2007), *i.e.* the Vardar Ocean underwent a terminal closure during Jurassic with the formation of the narrow strike slip corridor separating Adria from European affinities (Spahić & Gaudenyi, 2022). An earlier set of reports favor the prolongation of the Neotethys as a "relic ocean", having the final collision and related compressional events that occurred during the Late Cretaceous–Paleogene (Pamić & Jurković, 2002; Schmid et al., 2008; Tomljenović et al., 2008; Ustaszewski et al., 2009; Toljić et al., 2018; Márto et al., 2022; Spahić & Gaudenyi, 2022).

Fig. 1. ***a.*** *Position of the active and former subducting plates around Dinarides.* ***b.*** *Relief map of the former Yugoslavia and successor countries highlighting the position of Dinarides.* ***c.*** *Dinarides and Vardar Zone, the position of the External and Inner Dinarides within intra-montagne highlands, including the opposite Serbo-Macedonian Unit.*

After the compressional amalgamation of the intervening oceanic and continental crust, the suggested process of the orogenic relaxation allowed a

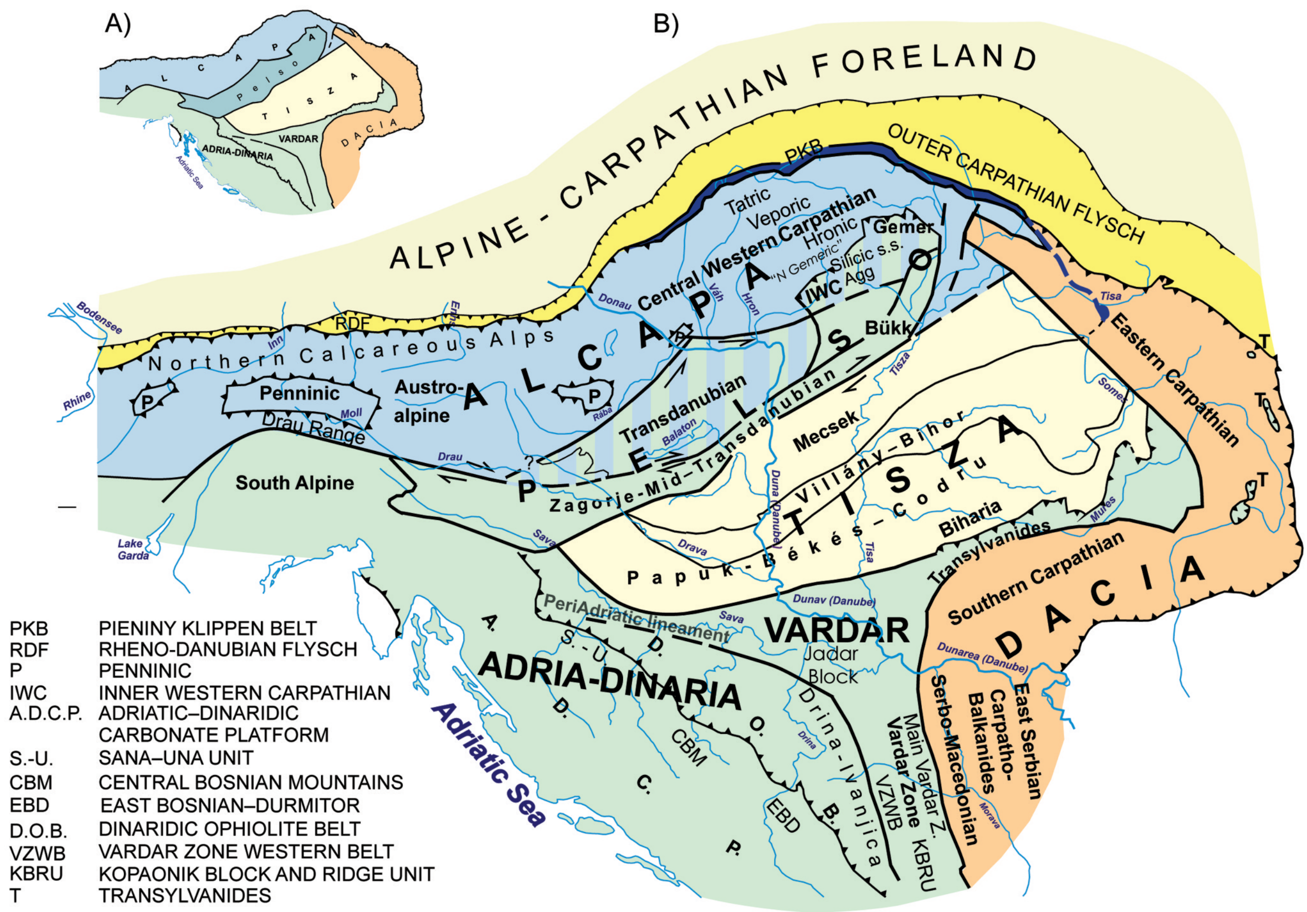

Fig. 2. *Structural mega units in the Circum-Pannonian region (inset from Kovács et al., 2011a, page 202, slightly modified). Per Adriatic lineament after Grubić (2002), Spahić & Gaudenyi (2022).*

tectonic decoupling of the Adria-Dinaria, and from the European affinities, the Tisza- and the Serbo-Macedonian Units. These newly formed differentiated basement units and its sedimentary cover underwent Miocene rotation (e.g., Inner Dinarides, whereas the External Dinarides were exposed to no Miocene rotation) (Fodor et al., 1999; De Leeuw et al., 2012; Mandić et al., 2019). However, the onset of the crustal extension along this previously elevated Adria-Dinaria Tethyan footwall segment has been barerly constrained, in particular accounting the Oligo-Miocene extensional episodes (De Leeuw et al., 2012 and references therein; Fig. 3). To make matters more difficult, a recent study proposes the regional uplift of the External Dinarides area (Baling et al., 2021). This area, in turn, carries a lagest number of the Dinaride intra-montagne mini-basins referred to as the Dinaride Lake System (e.g., De Leeuw et al., 2012).

The goal of following disussion is to provide a better overview of the post-collisional or post-Rupelian (Schettino & Turco, 2010) Oligo-Miocene extensional phases, recorded within the Adria-Dinaria highlands (De Leeuw et al., 2012). The focal point of this discussion are the reports providing the explanation for the extensional crustal-scale mechanisms. The most recent reports are discussing the earlier proposed retreating Apulia/Adria lithospheric-scale motions, which may have produced Miocene extensional stage. Nevertheless, the main reason for the precursory late Oligocene mini-basins formation – whether is it extensional stage, and which mechisms lie underneath of Late Oligocene mini-subsidence stage (Fig. 3), have had just recently been under focus (e.g., Andrić et al., 2018; de Leeuw et al., 2012). However, this mini-basin formation stage is considerably well-recorded across the

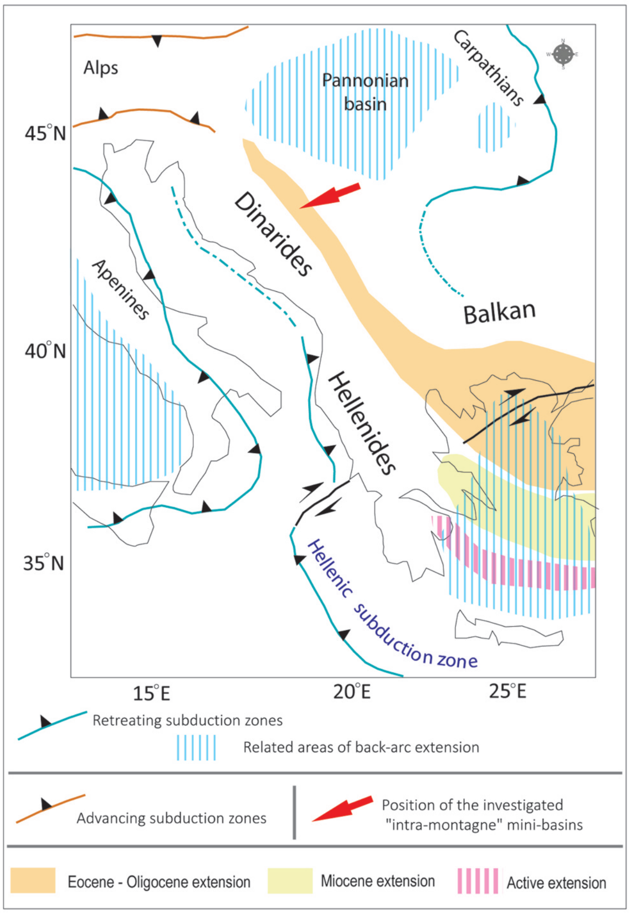

Fig. 3. *Simplified tectonic map of Dinaric-Hellenic region showing the migrating extension accounting for the retreating subduction zones (modified after* Burchfiel *et al., 2008). The map outlines the retreating subduction zones (blue) and related areas of back arc extension (vertical blue lines), including the advancing subduction zones (red).The position of the presumed volcanic arcs of Eocene-Oligocene age (Eo-Olig: red), Miocene (yellow), and Pliocene to Recent (red) are shown.*

several localities distributed within the Inner Dinarides, including the stratigraphically well-constrained coal-bearing Ugljevik location (Bosnia & Herzegovina; e.g., Vrabac et al., 1992; de Leeuw et al., 2011).

Overview of the intra-montagne basin formation models Late Oligocene mini-basins

During the Late Eocene - Priabonian–Beloglinian, Europe was an archipelago, whereas the western limb of the relic Tethys Ocean connected the Indo-Pacific and the Atlantic Ocean (Rögl, 1999). Only in early Oligocene - Early Kiscellian – Pshekian the new intracontinental sea rose, engulfing the central Adria-Dinaria land area (Fig. 2 of Rögl, 1999). In the immediate vicinity of the Inner Dinarides, or the border/former (paleo) northern shore of Adria/Dinarian land or the "Dinaride-Anatolian land" (de Leeuw et al., 2011), the documented deepwater Miocene sequences (*e.g.*, Avanić et al., 2021) indicate a continuity of an early Oligocene "Carpathian basin" (Sachsenhofer et al., 2018, and references cited therein) and its longevity throughout the Miocene development of Central Paratethys. Despite some earlier studies indicating a "Pyrenean stage", and the onset of the Late Oligocene extension in the nearby southern Serbian Inner Dinarides, including the Vardar Zone (*e.g.*, Anđelković et al., 1988), the origin of the Late Oligocene intra-montagne mini-basins formation remains unknown. Nevertheless, some recent models prefer a retreating of Adria plate slab, and/or delaminating crustal lithosphere (Andrić et al., 2018), extensional exhumation and the footwall uplift (van Unen et al., 2019). In the external realm of Adria-Dinaria, or towards the ophiolite-bearing Vardar Zone, there are several locations with documented record of the Late Oligocene, valleys-graben and half-graben structures (Obradović et al., 1997). Despite some of these mini-features cannot be sorted to belong to the "intra-montagne" mini-basins type, these mini-basins are characterized by a dominant lacustrine deposition as well (Fig. 4): Pranjani (western Serbia, Inner Dinarides; Lazarević et al., 2019; Andrić-Tomašević et al., 2021; Fig. 4#1), Ugljevik, Lopare, Tuzla of Inner Dinarides (Bosnia & Herzegovina; de Leeuw et al., 2011; Mandić et al., 2019; Fig. 4#2). These near-marginal extensional features extent to the south to include a pre-Miocene Lece massif at the contact between Vardar Zone and Serbo-Macedonian Unit (southern Serbia, to the east of the Kopaonik block; Tančić et al., 2021; Fig. 4#3). Of similar opinion are van Unen et al. (2019) indicating that the Late Oligocene-Miocene extension has affected the internal part of Dinarides and their contact with "Carpathians" or hinterland. Internally, within the central and southern Adria-Dinaria, there are several prominent basins, *e.g.*, the

Sarajevo-Zenica basin, Jablanica basin, and many others (Fig. 4#7, Fig. 5). In addition, there are several postdating principal Neogene basins, distributed in the northern and southern part of the Inner Dinarides (some with unconfirmed Oligocene successions; Fig. 4#4,5,6), including several locations with the magmatic intrusions with no record of accompanied extension-related subsidence, Fig. 4#8,9).

One of the more prominent sites in Inner Dinarides having the exposure of the oldest Late Oligocene mini-basin deposition is the Ugljevik coal-bearing site, in the vicinity of Bogutovo Selo (Vrabac et al., 1995; de Leeuw et al., 2011; Pežel j et al., 2013). The Ugljevik Late Oligocene sequence is positioned near the Sava River at the southern margin of the Pannonian Basin on top of the Jadar and West Vardar ophiolites or along the “Zvornik suture” (for the “Zvornik suture” see the map of Gerzina, 2010; Fig. 4). The collisional growth of northern Adria-Dinaria is reflected by Oligocene terrestrial and alluvial clays, sandstones, and conglomerates (Mandić et al., 2019). In the late Oligocene, rare lacustrine basins were mainly distributed along the northern Inner Dinardes, and are often with a coal succession having small and large mammal remains. This coal-bearing succession is followed by perennial lacustrine marl, with numerous ostracods (Hrvatović, 2006; de Leeuw et al., 2012). At the Ugljevik locality, the continental basin infill ends with the late Oligocene coal-bearing series, separated from the overlying middle Miocene marine Central Paratethys sediments by an angular unconformity (Pežel jet al., 2013).The detailed stratigraphic correlation pinpoints that the main lacustrine phase of the Banovići basin started shortly after 24 Ma, lasted up to ~23 Ma, with

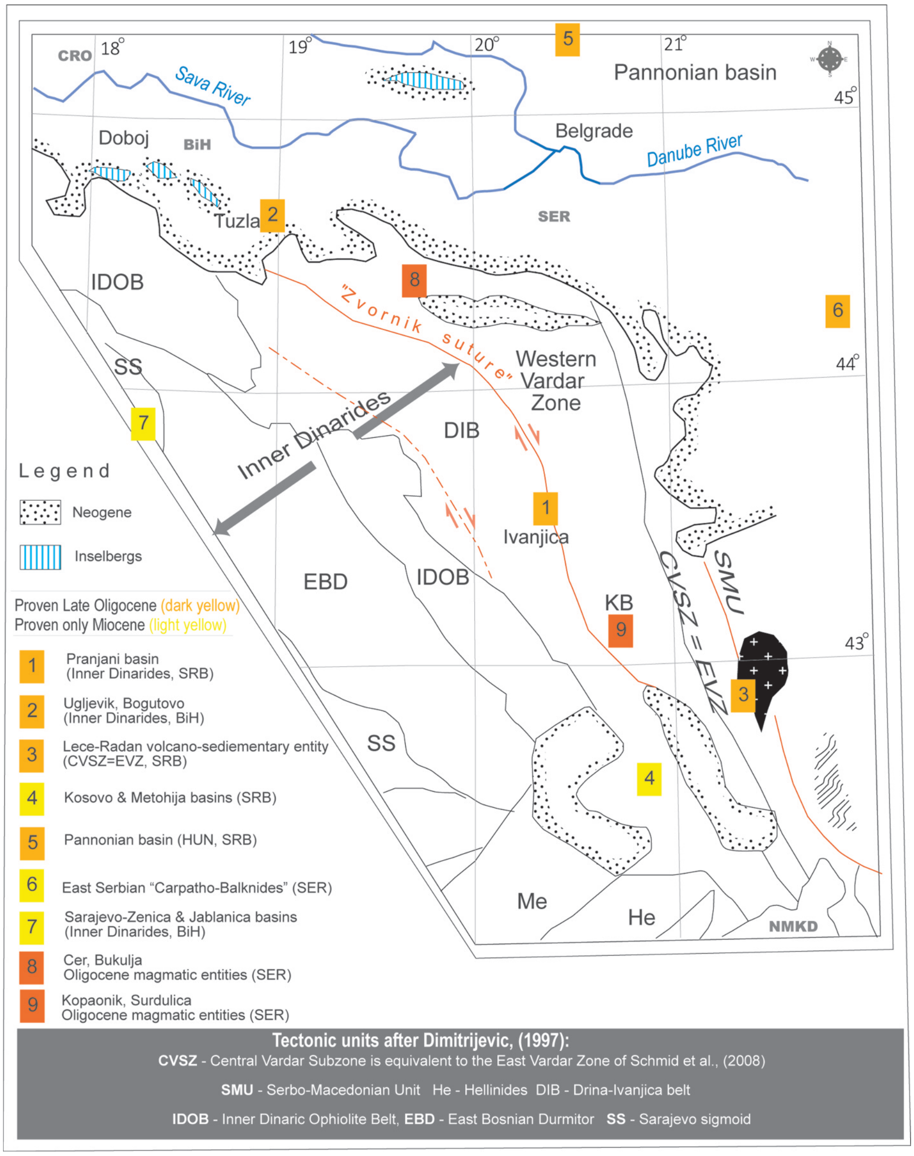

Fig. 4. *Sketch map of the ophiolite belts, and the overlapping Neogene basins (inset from Dimitrijević et al., 2003, slightly modified). The approximate postion of the major strike-slip faults taken from Ilić & Neubauer, (2005), including the dashed Lim fault, that is most likely extension of the Busovača fault (see Fig. 5); “Zvornik suture” taken from Spahić & Gaudenyi, (2022), and references therein. The basement tectonic units are according Dimitrijević (1997). Orange numbers designate some, not all locations with the proven or suspected Late Oligocene sequences, whereas yellow color designate locations with the proven Miocene, and not proven Oligocene successions. Red number #8 represents solemnly the magmatic intrusions of the Oligocene age. Some of the Neogene features are not represented on the sketch, e.g., #1. Pranjani basin.*

a deposition rate of 0.2 m/kyr (de Leeuw et al., 2011).

In the western Serbian Inner Dinarides, the localized Pranjani Miocene basin contains little evidence of the Late Oligocene fossilized paleoflora (Lazarević et al., 2019). To the south, the Lece massif exhibits the initial Late Oligocene volcanic activity, occurring with the deposition of conglomerates, sandstone, and marlstone (Malešević et al., 1974). The initial volcanism was succeeded by the emplacement of the Miocene calc-alkaline volcanic complex (also in Tančić et al., 2021). Interestingly, these occurrences are on top of the former Late Mesozoic convergence front, or near the Sava Suture Zone (see Spahić & Gaudenyi, 2022). The extensional migration toward the central part of the Adria-Dinaria (Andrić-Tomašević et al., 2021 and references therein), was accompanied by a voluminous Miocene extension, recorded across both domains of the post-Neotethyan overriding and descending plates (Adria-Dinaria, Serbo-Macedonian Unit, Tisza; see Blagojević et al., 2019, for an overview). This represents another source of extension induced by the Hellenic slab, which has been in the active ongoing extension recorded across northern Greece, North Macedonia (Dumurdžanov et al., 2005), and is associated with the Aegean Hellenic arc (Fig. 3).

Miocene extension *vs.* uplift, a few recent models of the Adria-Dinaria “intra-montagne” stage

In their reconstruction, Facenna et al. (2014) argue that after 30–35 Ma tectonic regime changed in all back-arc regions (relative to the Tethyan closure), and the extension took over the dominance. The Tethyan trenches (Fig. 3) started to retreat at rates of a few cm/yr, with the increased spreading velocity throughout the Miocene. This extensional setting led to the collapse of the previously thickened orogenic wedges and the exhumation of high-temperature metamorphic domes underneath the shallow-dipping extensional shear zones. A few most recent reports indicate that the Oligo-Miocenecrustal-scale extensional events were affected by the several mechanism related to the post-collisional events that occurred during Miocene: (i) trench retreat or retreating plate boundaries (Royden, 1993; Wortel & Spakman, 2000; Facenna et al., 2014; Spahić & Gaudenyi, 2020), (ii) Adria-Dinaria and Carpathian slab rollback initiating at ca. 20 Ma ago (Matenco & Radivojević, 2012; Andrić et al., 2018; van Unen et al., 2019), and/or (iii) post collisional mantle delamination beneath the Adria-Dinaria allowing, in turn, the uplift of the entire Adria-Dinaria (Baling et al., 2021). With regards to the most recent concept of Baling et al. (2021), prior to the first phase of the Adria-Dinaria intra-montagne basin development, the underlying crustal plate underwent tectonic thinning, *i.e.*, crustal delamination, following the early Oligocene slab detachment. The Early Oligocene slab break-off below Dinarides led to the Moho- and surface uplift (Baling et al., 2021). In the costal region of the External Dinarides, marine terraces were uplifted in the Late Oligocene to Early Miocene, while other regional studies (e.g. van Unen et al., 2019) are suggesting thrusting followed by extension in that parts during the same period. In the Internal Dinarides, according to Baling et al.(2021) mantle delamination affected an Oligocene-Miocene post-collisional magmatism. In other words, the post-collisional mantle delamination underneath the Adria-Dinaria began at 28 Ma and terminated 22 Ma ago uniformly lifting upwards the entire Adria-Dinaria Miocene land (Fig. 5).

Another report, in turn, proposes a polyphase footwall Adria-Dinaria slab extension driven by the slab rollback, explaining the footwall uplift as the consequence of the principal extensional geodynamic driver (van Unen et al., 2019). A bit earlier study proposes a depositional-kinematic interplay that was controlled by the formation of the principal extensional detachments or normal fault systems, associated with a significant exhumation of the Adria-Dinaria footwalls (Andrić et al., 2018). Modeling study of Andrić et al. (2018) showed that progressive slab retreat can control change from Eocene contraction to Oligocene-Miocene eduction and extension. In that sense, it is plausible model of extension in the Internal Dinarides and the former Sava Zone. Ustaszewski et al. (2009) use the $^{40}Ar/^{39}Ar$ sericite and zircon and apatite fission-track ages from the footwall rocks, pinpointing the extensional unroofing between 25

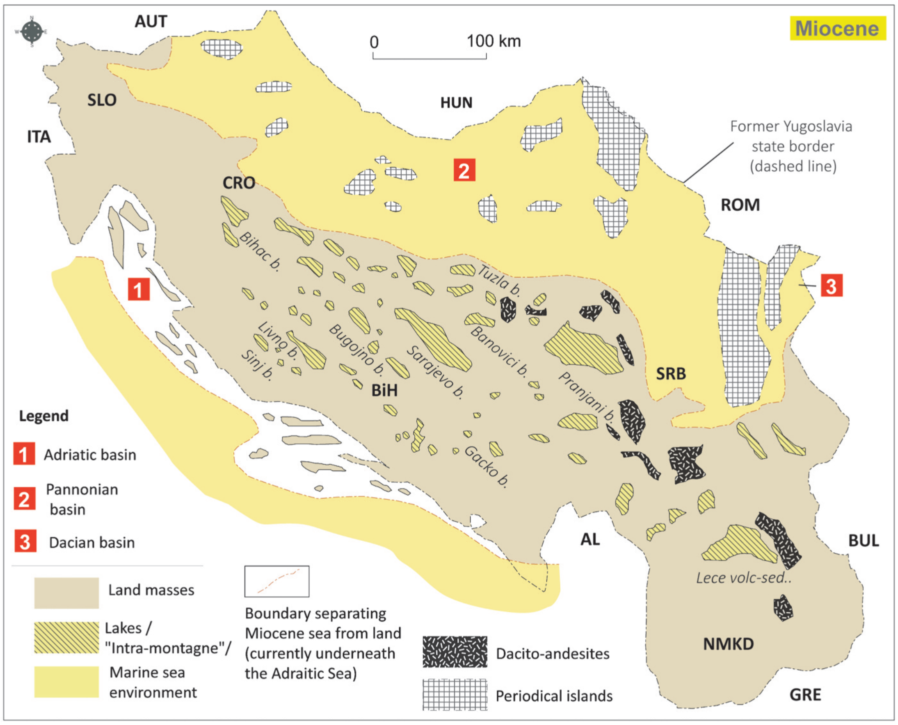

Fig. 5. *Paleogeographic map of Miocene of the Adria-Dinaria and surroundings (inset from* GRUBIĆ, *1980, modified).*

and 14 Ma. This extensional event is linked to the Miocene rift related subsidence in the Pannonian Basin, which represents a back arc basin, formed due to subduction rollback in the Carpathians (USTASZEWSKI et al., 2009). The terminal stage of the Pannonian basin development is also referred to as the "Lake Pannon" (e.g., ANĐELKOVIĆ & RADIVOJEVIĆ, 2021).

With regards to the recent surface observations, VAN UNEN et al. (2019) reported a cluster of the Miocene deformations across the majority of Adria-Dinaria highlands, in particular, within the thin-skinned successions belonging to the External Dinarides (Fig. 1c). The principal deformations accommodating the extension are described as those developed on top of the inherited rheological "weakzones". The model proposes that the Miocene extension of the Adria-Dinaria highlands was interrupted by a continuous shortening, showing a lower plate crustal accretion mechanism that was spatially and temporally correlated with a gradual slab retreat. However, by using analogy from the precursory Late Cretaceous – Paleogene core-complex exhumation event, it appears that retreating motions affected solemnly the Tethyan hinterland or Balkans, not Adria-Dinaria (see later in the text). Later on, a number of dacite-andesite magmatic occurrences of the Neogene age, were distributed in the vicinity of the Vardar Zone (*e.g.*, CVETKOVIĆ et al., 2004; GRUBIĆ, 1980; STOJADINOVIĆ et al., 2017; see also in BALING et al., 2021; Fig. 5). Accordingly, the Sava Neogene depression was formed as the result of this back-arc extension of the Pannonian Basin that was active since ~18 Ma (the date provided by MANDIĆ et al., 2012), including the principal geodynamic driver, propelled by the Carapathian lithospheric rollback behavior (FODOR et al., 1999). In the External Dinarides, VAN UNEN et al. (2019) reported normal fault activity that yielded a principal direction of the Miocene extension, the dominant NNE-SSW extension. The observed large offset normal faults tend to define a NE–SW oriented extension, whereas the smaller offset of the normal faults defines a NW-SE oriented. The study emphasizes two successive episodes of the Miocene extension which is obscured by the presence of strike-slip geometry (late Miocene inversion). In turn, across the Tethyan hinterland, a number of Neogene depositional systems, in particular, within the "Carpatho-Balkanides" underwent intensive horizontal mobility, characterized by a differential clockwise rotation (*e.g.*, MAROVIĆ et al., 2001), including the presence of large-scale transcurrent motions (e.g., KRSTEKANIĆ et al., 2020).

Discussion: Lithospheric-scale Adria-Dinaria footwall extension – comparison with the Aegean

The "retreating plate boundaries" associated with the pronounced Oligo-Miocene roll-back at the expense of the slab tear or "retreating collision" were proposed earlier than the gradual rollback and associated footwall uplift (Royden, 1993; Wortel & Spakman, 2000; Spahić & Gaudenyi, 2019). By comparing the widespread Miocene extension with the Aegean system, the Apulia/Adria was in the descending position or in the footwall domain. This means that the main extensional basins in the Aegean were formed on top of the hanging wall, or across the overriding plate (e.g., Jolivet & Brun, 2008; Jolivet et al., 2013; Menant et al., 2016). Thus, the Aegean overriding plate underwent the same Miocene core-complex production episode, accounting for the substantial syn-orogenic extensional deformation. Retreating plate boundaries coupled with the main phases of a pronounced roll-back (Wortel & Spakman, 2000) in a low convergence rate situation, commonly induce delamination and regional extension within an overriding plate, affecting the formation of the core complexes, likewise, those widely recorded across the Balkan Peninsula (e.g., Menant et al., 2016). Nowadays, the retreating African slab is coupled with the overriding plate, affecting the upper plate apart as it retreats, breaking the latter into numerous small plates with frequent earthquakes along their boundaries (Mengl et al., 2021). The African plate is subducting northwards beneath Eurasia induced by the gravitational forces. Thus the plate is causing the southwards-directed retreat (Mengl et al., 2021). There, the slab remains attached to the former Mesozoic – Paleogene Vardar oceanic subduction, being confirmed by the several 2D visualization tomographic models. The models interpreted a crustal connection of the Hellenic slab,(East) Vardar- and deeper most Triassic- and Jurassic Kure, Izmir-Ankara slabs (Hosseinpour et al., 2016). Based on the deformation recorded in Hellenic basement units (ductile stretching lineations), the three distinct stages of post-orgenic extensional stages are recognized in the Aegean region (Walcott & White, 1998). Initially, extension of the almost entire Aegean region started in the Late Oligocene–Early Miocene (ca. 36–25 Ma ago).This stage was followed by the division of the Aegean crust into the West Aegean Block (a coupled assemblage of small blocks), reaching the Scutari–Pec Line and Mid-Cycladic Lineament (fracture zones). The rotation continued at 25 Ma and ca. 3 Ma, moving the West Aegean Block that underwent ca. 30º clockwise rotation, where, in turn, the eastern Aegean underwent, ca. 19º anticlockwise rotation.

The late Eocene to Neogene tectonic evolution of the Adria-Dinaria was under control of the dominant shortening and orogen-parallel wrenching (Ilić & Neubauer, 2005). Such a structural kinematic framework contributed to developing principal dextral SE-trending strike-slip faults, which followed the boundaries of the major tectonic units (dextral orogen-parallel wrenching of the whole Central Adria-Dinaria; Ilić & Neubauer, 2005). According to this model, the strike-slip mode was also active during the Neogene indentation of the Apulian microplate, and its amalgamation into the Alps, followed by the back-arc type extension of the Pannonian Basin. Nevertheless, the intermittent extension of the Late Cretaceous age appears to have occurred within a regional convergent tectonic setting (pull-apart; Spahić & Gaudenyi, 2022). Following an oblique diachronous complete closure alongside the Vardar suture zone (lasting from the middle Eocene to late Oligocene), the transition from a regionally convergent, towards a regionally extensional tectonic setting occurred accounting aforementioned mechanisms. The early extensional subsidence was associated with the abundant magmatism and formation of the localized sedimentary basins, likewise the Ugljevik and other Dinaride-related mini-basins (Fig. 4, 5). The area with the most prominent Eocene-Oligocene extension is recorded in the Balkans (overriding plate), or on top of the Hellenic slab, and its hinterland (Dumurdžanov et al., 2005; Fig. 3, light-red area). Otherwise, considering that the mini-basins occur along a rather narrow Adria-Dinaria extensional corridor (Fig. 3, thin red-colored area crossing northern Dinarides), this study speculates that these Late Oligocene, mainly coal-bearing mini-basins, are the result of the localized inversion of the precursory oblique margin (as suggested by Dumurdžanov et al., 2005; Ilić & Neubauer, 2005). The localized extensional inversion or transtension, induced the onset of the localized pull-apart releasing band systems, a successor phenomenon inherited from the precursory Upper Cretaceous to Paleogene plate boundaries (Ilić & Neubauer, 2005; Spahić & Gau-

DENYI, 2022). This is in line with the regional-scale Neogene observations recorded in the Central Alps (RING & GERDES, 2016), including the famous pull-apart Vienna Basin (FODOR, 1995; SPAHIĆ et al., 2013), further documented southwards in the Aegean-western Anatolia region (*e.g.*, DUMURDŽANOV et al., 2005; SÖZBILIR et al., 2011). The palaeostress analysis in the easternmost Alps and the westernmost Carpathians revealed the existence of the Middle and Late Miocene combination of extensional and strike-slip faulting (FODOR, 1995).

To summarize, there are several principal mechanisms of the Neogene extension, and one of these often proposed is extension that created large-scale detachments with listric normal faults geometry along the entire length of the Sava Suture Zone and other Dinarides nappe contacts, indicating even remote foreland as the Sarajevo-Zenica Basin (*e.g.*, VAN UNEN et al., 2019, and references therein). This model introduces a process of Oligocene-Early Miocene foreland flexural deposition over the Bosnian Flysch in the footwall of the East Bosnian-Durmitor thrusting (Figure 3a) and was affected by a large-scale asymmetric extension. The formation of this asymmetric fault system caused rheological weakness of the NE dipping Bosnian Flysch turbidites (VAN UNEN et al., 2019; Fig. 1c, 3). This invoked, according to VAN UNEN et al. (2019), the Miocene isostatic rebound, or the event that was associated with the upward-directed elevation of the Adria-Dinaria (mainly External Dinarides as a footwall). In this manner, the Inner Dinarides and the main portion of External Dinarides should elevate/lift upwards relative to the majority of the Inner Dinarides (representing the foreland area of the former descending plate). The footwall uplift presumably occurred by the reactivation of the "rheologically weak" Lower Cretaceous 'Bosnian flysch'. However, the occurrence of several contemporaneous mini-Neogene systems to the south of Banovići and Bugojno basins (DE LEEUW et al., 2012; ANDRIĆ et al., 2017) or the south of the strike-slip Lim fault (ILIĆ & NEUBAUER, 2005): Sarajevo-Zenica basin, Jablanica basin, Livno basin, Sinj basin, Lake Gacko (GRUBIĆ, 1980; MANDIĆ et al., 2011; Fig.5) are not in line with the suggested massive crustal-scale footwall uplift. The basement faults have mainly a listric shape (PICHA, 2002), which could be in accordance with the earlier proposed strike-slip wrenching pattern and related flower structures (ILIĆ & NEUBAUER, 2005; KORBAR, 2009).

Another option is that the crustal extensional reactivation of the principal faults (former thrusts, likewise the Late Cretaceous East Bosnian-Durmitor thrust) was guided by a slab-tear direction (WORTEL & SPAKMAN, 2000). With regards to the proposed process of syn-orogenic exhumation (VAN UNEN et al., 2019), this phenomenon is commonly formed at the expense of the retreat of subducting margins, thus accommodating the regional extension, but dominantly within the hanging wall of overriding plate (ROYDEN, 1993). The crustal-scale isostatic rebound of the descending plate or footwall plate and its uplift is often accompanied by the extracted metamorphic core complexes. The metamorphic core complexes formation has been occurring at the expense of the tectonic denudation of the crystalline cores, and the activity along detachment faults that bound them (for details see the model of WDOWINSKI & AXEN, 1992, and references cited therein). Thus, opposite to the Apulia/Adria, the accretionary complex of the Vardar Zone (Bukulja Mt of the debatable Bukulja-Venčac affinity), and the Serbo-Macedonian Unit (Jastrebac Mt.) as a distant overriding hinterland, have experienced a significant extension-related crustal delamination, allowing the emplacement of several regionally distributed core complexes (MAROVIĆ et al., 2007; ERAK et al., 2016, STOJADINOVIĆ et al., 2017; SPAHIĆ & GAUDENYI, 2019).

Concluding remarks

Following the analysis of the recently published ideas, there are three scenarios, that probably led to the Late Oligocene mini-basins, and limited Miocene "intra-montagne" extension-related basin formation: (i) the mechanism of the Adria-Dinaria lower plate retreat,(ii) the tectonic thinning and the early Oligocene slab detachment followed by the uplift of the entire Adria-Dinaria (BALINGet al., 2021), and (iii) here underlined, the earlier proposed strike-slip inheritance (ILIĆ & NEUBAUER, 2005; KORBAR, 2009). The new review-based constraints are that the strike-slip transtensional reactivation model may explain the Late Oligocene "intra-montagne" pull-apart mini-basin formation (similar to the Santonian episode of the collisional Sava Vardar Zone; Spahić & Gaudenyi, 2022). It fits with the assymetrical opening of intra-montagne basins suggested by Obradović et al. (1997), van Unen et al. (2019).

In addition to the earlier opinion that slab tear in the central part of Adria-Dinaria could be a source of the crustal extension (Wortel&Spakman, 2000) pronounced rollback during Miocene is expected in a similar low convergence rate situation. Nevertheless, having a large-size orogenic accretion with the paroxysm occurred during Eocene, there is a high likelihood of the crustal-scale flexural isostatic lithosphere downwrapping (accounting for the magnitude of its load, along with a temporal lithospheric polarity inversion; see the point #3 and #4 below). The tectonic thinning and the early Oligocene slab detachment, causing a widespread uplift (Baling et al., 2021) provide tentively the explanation for the unconformity, recorded after the deposition of the Ugljevik coal-bearing sequence (see Vrabac et al., 1995, for details). According to Baling et al. (2021), Adria-Dinaria was during the late Oligocene partially under the marine environment and partially a landmass of the European archipelago (*e.g.*, Rögl, 1999; Sachsenhofer et al., 2018). The Neogene basins underwent vertical uplift, without any significant deformation. However, the uplift does not provide the explanation of the formation of the Adria-Dinaria intra-montagne basins lacustrine systems (as per Andrić et al., 2017, 2021). Thus, the tectonic origin of the subsidence and formation of a number of Late Oligocene and Adria-Dinaria Miocene lakes remains not fully understood (Fig. 5).

The discussion incorporates further remarks on the methodology largely used for the subsurface subsidence *vs*. tectonic constraints and proposes a quantification of the several tentative lithospheric-scale scenarios/processes inducing the Miocene extension. The Miocene extension is just superficially outlined within the Adria-Dinaria, in particular the occurrence of the Late Oligocene mini-basins. Thus, this discussion imposes the set of methodology-based remarks that could be of use for future study of intra-montagne extension:

In the case of the lower plate retreat during Miocene, what was the behavior of Apulian tensor (Adriatic foreland)? It is to note that Apulian plate started with the retreat in the early Miocene (for example in Greece; Jolivet et al., 2013). See also discussion in Le Breton et al. (2017);

· Is there a possibility for the forward modeling and creation of subsidence (mini) basin models (well data piercing the Oligo-Miocene i.e. Neogen base)? The results (subsidence curves) would largely facilitate the eventual thick-skinned involvement. A successful model must predict not only differences between a footwall/foredeep fill v*s.* foreland stratigraphy, it must also include the exhumation, topography, and crustal thickness (Toth et al., 1996; for crustal thickness see Milivojević, 1993);

Because even subsidence models do not account for flexural-isostatic responses of the lithosphere, it does not exclude this possibility for the Late Oligocene extension of Adria-Dinaria. As this Late Oligocene event has mild character, having a deposition rate of 0.2 m/kyr, thus it also could be explained by a short crustal dowlifting of previously thickened crust. In either case, this topic requires further study. This issue is rather important because the pre-Miocene shortening result in a significant sheet emplacement and crustal thickening;

· What are the differences/similarities with the reconstructions of the Aegean early Miocene slab retreat and associated back-arc extension model (e.g., Jolivet & Brun, 2008; there is no (former) lower plate extension, likewise suggested for Adria-Dinaria (van Unen et al., 2020))?

Finally, review and discussion provide a hint, that both, the central Adriatic transform zone as a complex active transform microplate boundary (Korbar, 2009; Subašić et al., 2017), including the external or Inner Dinaride/Vardar Zone former oblique boundary, could have been reactivated (transtension) during a very limited period of the Upper Oligocene or Miocene times. In that manner, a short episode (de Leeuw et al., 2011) of a localized coal-bearing, dominantly lacustrine paleoenvironment could be explained.To this hypothesis, contributes the fact that the investigated basins are mainly formed by sedimentation in hangingwall dipslope setting, which was localized in the form of half-grabens (Obradović et al., 1997). Moreover, by overlapping the two features, the Upper Oligocene–Miocene "intra-montagne" mini-basins were developed mainly on top of the former plate boundaries.

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Резиме

Напомене о олиго-миоценским екстензионим епизодама у унутрашњим Динаридима: тектонска ограничења настанка интра-планинских басена

У последњих неколико година расте интересовање за пост-компресиону фазу развоја Динарида која отпочиње током олигоцена, и карактерише се формирањем тзв. „интра-планинских“ басена. Седименти горњег олигоцена су пронађени на више локација широм Динарида: Угљевик, Лопаре, Тузла мини-басени, Сарајево–Зеница, као и бројни мини-басени у спољашњим Динаридима. Уз сам обод унутрашњих Динарида, према Вардарској зони, такође су развијени олигоценски депонати, али у вулкано-седиментној фази, нпр. Леце (Tančić et al., 2021), али се они не могу третирати као „интра-планински". Значај реконструкције формирања ових „интра-планинских" басена лежи у бољем разумевању саме пост-колизионе историје, тј. геодинамичке еволуције новонасталих планинских венаца као што су Динариди.

Динариди или Динарски ороген (нпр., Dimitrijević, 1997; Picha, 2002; Ilić & Neubauer, као и поједине цитиране референце; Korbar, 2009; Fig. 1a,b,c), а нарочито његов СИ сегмент, који је носилац офиолита јурске старости (унутрашњи динарски појас), чини континентални сегмент литосферних размера, некад субдуковане Адријске микроплоче и њене акреционе маргіне/призме (Karamata, 2006; Maffione & van Hinsbergen, 2018; Schmid et al., 2020; van Hinsbergen et al., 2020). У тексту се узима подела са слике 2, која ову литосферну амалгамацију назива „Adria-Dinaria" или „Адрија-Динарија". Ова композитна микроплоча се некад подвачила у транскурентном кинематском моду, испод ободних Европских ентитета, као што су Тиса плоча, и Српско-македонска јединица. Као непосредан доказ конвергенције ових ентита остала је тзв. Сава сутурна зона (Spahić & Gaudenyi, 2022). Ова сутура је видљива и у потповршинским условима (Vukašinović, 1973). Међутим, Алпски билатерани динарски ороген (Doglioni et al., 2007), пре свега Вардарски океан, се затворио током јуре, где је након јуре преостали „коридор" углавном имао транскурентни карактер (Spahić & Gaudenyi, 2022). Поједине публикације и даље фаворизују кредно затварање Вардарског океана, објашњавајући да је то „реликт океан" Неотетис, које се затворио током горње креде и палеогена (Pamić & Jurković, 2002; Schmid et al., 2008; Tomljenović et al., 2008; Ustaszewski et al., 2009; Toljić et al., 2018; Márto et al., 2022).

Након завршетка конвергентних односа и стварања високог планиског ланца, тј самих Динарида, долази до екстензије и стварања олиго-миоценских мини-басена. Међутим, екстензионе епизоде или једна епизода, које су довеле до стварања поменутих басена, тек недавно добијају заслужену пажњу (нпр., De Leeuw et al., 2012; van Unen et al., 2019; Fig. 3). Да ствари буду још компликованије, једна од последњих студија указује на континуирано издизање спољашњих Динарида (Baling et al., 2021).

Од последњих тектонских модела који објашњавају настанак интра-планинских" басена су: (i) екстензија која је резултат деламинације литосферне плоче (Andrić et al., 2018), (ii) екстензија литосферих размера која је довела до ексхумације самих Динарида (van Unen et al., 2019), као и (iii) униформно издизање или „аплифт" Динарида као целине, пре свега спољашњих Динарида (Baling et al., 2021). Иако су за интерпретацију покрета литосферних размера потребни различити потповршински подаци, као што су бушотине и дебљине слојева/стратиграфских хоризоната, или верификовање порекла фаза субсиденције, публиковани радови указују на литосферна кретања и моделе, махом засноване на екстензији, док има и оних који указују на издизање самих Динарида. Да би се обезбедило боље разумевање самог почетка олиго-миоценске фазе настанка тих „интра-планинских" басена, у овом раду се указује на значај наслеђених кинематских услова диктираних ранијим границама литосферних плоча.

Осврт на тектонске моделе који указују на настанак „интра-планинских" мини-басена

а) Горњоолигоценска екстензија

Током касног еоцена, приабонијског или белоглинијског ката, Европа је била архипелаг у коме је западно крило Неотетиса било у конекцији са Индо-пацификом и Атланским океаном. Тек у раном олигоцену – кисцелисјком или пшекијском кату, дошло је до новог подизања интраконтиненталног мора које је окруживало тадашње Адрија-Динарија острво (Fig. 2 of Rögl, 1999). Ранији радови указују на „пиринејску фазу" „отварања" горњоолигоценских басена (нпр., Anđelković et al., 1988). Те структуре су представљене махом „полу-ров" структурама („half-graben") и тектонским палео-удолинама („half-valley") (Obradović et al., 1997). Једна од истраженијих локација је Угљевик, мини-басен у коме је присутан угаљ горњоолигоценске старости (Vrabac et al., 1995; de Leeuw et al., 2011; Peželj et al., 2013).

б) Миоценска екстензија или ипак „чисто“ издизање „интра-планинских“ мини-басена?

Што се миоценске екстензије тиче, објашњена је од стране неколико аутора на различите начине. У палеотектонској реконструкцији, Facenna et al. (2014) су мишљења да је пре око 30–35 Ма дошло до промене у тектонском режиму Динарида, када долази до доминације екстензионих покрета. Тетиске некадашње сутуре се „повлаче“ неколико cm/годишње, са повећаном брзином током самог миоцена. Доминантна екстензија у регионалним оквирима, доводи до колапса орогеног тела (са карактеристичним задебљањем саме литосфере), што доводи до ексхумације високо-температурних метаморфних дома, које се утискују кроз зоне ширинга или зоне истезања тзв. „shear zones“. Између осталих модела, предложена су следећа решења која указују на механизам настанка „интра-планинских“ басена:

„Trench retreat“ или „повлачење“ самог субдукционог система (Royden, 1993; Wortel & Spakman, 2000; Facenna et al., 2014; Spahić & Gaudenyi, 2020),

Адријско-Динарски или Карпатски „rollback“ који је отпочео пре отприлике са. 20 Ма (Matenco & R adivojević, 2012; Andrić et al., 2018; van Unen et al., 2019),

Као и пост-колизиона деламинација мантла испод саме Адријско-Динарске плоче која сопственим истањивањем омогућава издизање комплетних Динарида (Baling et al., 2021).

Што се тиче површинских опсервација на миоценским депонатима, van Unen et al . (2019), указали су на постојање целог кластера деформација, а нарочито у спољашњим Динаридима. Главни механизам екстензије је објашњен преко реактивације реолошки „слабих зона“ тј. зона које су биле активне у ранијем периоду, као што је „Босански флиш“. Овај модел се заснива на екстензији која је прекинута указујућу на механизам акреције доње плоче, која је како просторно, тако и временски корелативна са постепеним „повлачењем“ исте („slab retreat“). У склопу спољашњих Динарида, van Unen et al. (2019), указују на главне правце миоценске екстензије ССИ–ЈЈЗ. Опсервирани регионални раседи имају пружање СЗ–ЈИ, где се наглашавају две фазе миоценске екстензије које су оверпринтоване присуством транскурентних раседа насталих током касномиоценске инверзије ових простора. У моделу који истиче рано олигоценско цепање саме литосферне плоче („slab break-off“) испод самих Динарида, указује се на последично издизање самог Мохо дискунтинутета, и издизање целе површине Динарида (Baling et al., 2021).

При упоређивању екстензионих процеса у Хеленидима са онима који су се одвијали у Динаридима током миоцена, уочава се главна разлика која је представљена самом позицијом литосферних ентитета, или блокова, у односу на екстензионе деформације и саму архитектуру субдукционог рова. Наиме, у Хелинидима, тј. Егејском субдукционом систему, екстензија се махом развијала током еоцена и миоцена, са континуитетом (данашња активност) на повлатном блоку, или самим Хеленидима (случај „повлачења“ подинске океанске литосфере) (e.g., Jolivet & Brun, 2008; Jolivet et al., 2013; Menant et al., 2016). Доња литосферна плоча Хеленида је остала повезана са некадашњом мезозојко-(делом) палеогеном литосфером, давно затвореног јурског Вардарског океана. Оваква интепретација је заснована на потповршинским геофизичким подацима, тј. подацима визуализованим 2D томографским моделима, а који повезују доњу плочу Хеленида са Вардарском зоном, такође са развићем тријаса и јуре Кире океана, као и Измир и Анкара океанима, и њиховом доњом литосферном плочом (Hosseinpour et al., 2016). С тога, поређење ефеката миоценске екстензије са екстензионом етапом развијеном на Динарској микро-плочи или Адрија-Динарији, није целисходно, јер се ради о подинском, а не повлатном литосферном блоку. Даље, упоређивањем горњих литосферних ентитета (повлатних блокова) може се запазити појављивање истовремених „core-complex“ епизода, насталих током саме конвергенције („syn-orogenic extensional deformation“). Литосферне границе настале „повлачењем“ или „retreating plate boundaries“, нарочито када се јавља и изражен

„rollback" океанске литосфере, утичу на настанак екстензионог механизма, али у горњој или повлатној плочи (Wortel & Spakman, 2000). Велики број „core complex" система или појава забележен је на читавом Балканском полуоству (нпр., Menant et al., 2016), међутим нису забележени у Динаридима. Горњоеоценска до миоценска тектонска еволуција Динарида била је под утицајем транскурентних кретања која су била паралелена са самим орогеном (Ilić & Neubauer, 2005). Такав кинематски оквир је допринео развоју главних декстралних транкурентних раседа са трендом ка ЈИ. Исти су подударни са границама главних тектонских јединица. Према овом моделу, тракуренција је била активна и током неогеног утискивања тзв. „индентације" Апулијске микроплоче, и њене амалгамације са Алпима. Након тога, долази до екстензије „back-arc" типа, и равоја самог Панонског басена. Повремена екстензија која прати транскуренцију је уочена у доминантно конвергентном горњокредном систему (pull-apart; Spahić & Gaudenyi, 2022). Ако се узме у разматрање комплетно затварање Вардарског сутурног коридора или формирање Сава сутурне зоне, пост-орогени прелаз ка доминантном екстензионом у олигомиоцену је највероватније заснован на наведеном прекугсору.

Од тектонских концепата развијаних у скорије време, могуће је издвојити неколико сценарија развића горњоолигоценско-миоценске екстензије, а који су довели до стварања „интра-планинских" басена: „trench retreat" или „повлачење" самог субдукционог система (Royden, 1993; Wortel & Spakman, 2000; Facenna et al., 2014; Spahić & Gaudenyi, 2020), Адријско-Динарски или Карпатски „rollback" који је отпочео пре отприлике са. 20 Ma (Fodor et al., 1999; Matenco & Radivojević, 2012; Andrić et al., 2018; van Unen et al., 2019), као и пост-колизиона деламинација мантла испод саме Адријско-Динарске плоче (Baling et al., 2021). Такође, током анализе наведених модела, у овом раду указана је и могућност реактивације транскурентних кретања која су дефинисана нешто раније (Ilić & Neubauer, 2005; Korbar, 2009). Наиме, предложени модел трантензионе реактивације се садржи у томе, да на некадашњим "pull-apart" мини-басенима кредне старости (сантон; Spahić & Gaudenyi, 2022), пост-орогени или пост-компресиони литосферни покрети су могуће довели до њихове делимичне екстензионе реактивације. Предложени горњо-олигоценски модел екстензије се може усагласити са асиметричном екстензијом предложеном такође нешто раније Obradović et al. (1997). Но потребно је даље истраживање.

У овом прегледном раду се даље предлажу методе, као и правци који могу да укажу на тектонска решења, а која могу бити од велике помоћи за даље истраживање „интра-планинских" басена:

Утврдити како је дошло до екстензије подинског блока (Динариди) током миоцена, ако се узме у разматрање компресионо напонско стање самог Апулијског тензора? Треба имати у виду да је Апулијски тензор кренуо са „повлачењем" океанске литосфере тек у горњем миоцену (погледати модел од Jolivet et al., 2013; дискусију од Le Breton et al., 2017)?

У случају да постоји могућност тј. да се могу користити подаци из бушотина које пробијају горњоолигоценску подину, било би неопходно одрадити басенско моделовање, најпре сваког појединачног басена, а касније да се уради покушај 3D моделовања читаве целине, тј. целог горњоолигоценског архипелага, тј. тадашњих Динарида. Као резултат, могле би се интерпретирати субсиденционе криве које би увелико олакшале интпретацију, нарочито у случају екстензије саме литосфере („thick-skinned"). Комплексан басенски модел морао би укључивати не само разлике у кинематици подинског у односу на повлатни блок, принос у лакустричне мини-басене и њихову стартиграфију, већ би морао укључивати и фазе ексхумације, палеотопографију, и саму дебљину литосферних блокова (Toth et al., 1996; за дебљину коре видети Milivojević, 1993);

У моделима субсиденције треба водити рачуна о флексурно-изостатичким литосферним кретањима која су се могуће догодила током горњег олигоцена. Обзиром да је субсиденција била блага, са спуштањем око 0.2 m/kyr, такав сценарио може упућивати на краткотрајно вертикално спуштање саме литосфере, а под тежином нараслог горњокредно - олигоценског орогена;

На крају, кроз публиковане радове може се прелиминарно закључити да су постојале две главне трансформне/транскурентне зоне (Korbar, 2009; Subašić et al., 2017) које су повезане и са спољашњим и са унутрашњим Динаридима. Такође, у раду је указано на транспресионо затварање некадашња два главна ентитета, Динарида и јужноевропских маргиналних ентитета. Ако је такав сценарио јасно објашњен у претходним тектонским активностима, врло је могуће да је током горњег олигоцена дошло до краткотрајне транстензије (de Leeuw et al., 2011) и стварања већег броја малих, махом угљоносних мини-басена лакустричног типа.

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