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Orogenic evolution of the External Dinarides in the NE Adriatic region: a model constrained by tectonostratigraphy of Upper Cretaceous to Paleogene carbonates

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A R T I C L E I N F O

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A B S T R A C T

Mesozoic to Cenozoic evolution of the central part of the Adriatic plate (External Dinarides and Adriatic foreland) is still a matter of debate. This is expressed by opposing paleogeographic models: single carbonate platform (Adriatic or Adriatic–Dinaridic) versus two carbonate platforms (Adriatic and Dinaridic) separated by the inter-platform Budva–Cukali basin. Estimates of shortening during Adria NE subduction, that resulted in the development of the Dinaric Alps, differ substantially. The single-platform model involves minor shortening achieved by folding and faulting along steep reverse faults. The two-platform model involves significant shortening achieved mainly by thrust stacking, which resulted in almost complete underthrusting of the intervening basinal deposits.

Analysis of Upper Cretaceous to Paleogene stratigraphical data from both outcrops and boreholes allows regional correlation and the interpretation of major lithostratigraphic units. As a result, a few tectonostratigraphic units are recognized. The tectonostratigraphy is used as a basis for a new model on the late Mesozoic to Cenozoic evolution of the region.

Generally, Adriatic and Dinaridic segments acted as major regional crustal entities of Adria. The upper portions of the sedimentary cover were differentially affected by progressive, southwestward verging thin-skinned deformations during the Paleocene to Eocene (Miocene?). The Adriatic foreland stayed out of the deformations, and is characterized predominantly by wrench and salt tectonics. The regional tectonic map shows arcuate thrust fronts of the External Dinarides. They could be a consequence of both, differential propagation of early-orogenic thin-skinned deformations over crustal fragments separated by transversal faults, and/or differential (isostatic?) movements of the fragments. The collision zone of the Adriatic and Dinaridic segments is characterized by late-orogenic (Oligocene to Miocene) thick-skinned compressional uplift (exhumation), related gravity gliding, and still active escape tectonics (wrenching). These processes masked primary thin-skinned deformations. A significant amount of shortening within and between the thin-skinned sedimentary covers is proposed. Therefore, the question of the general paleogeography of the region and the original NW extent of the Budva–Cukali basin (NE Adriatic trough) remains open.

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1. Introduction

As pointed out by Cassinis (2006, and references herein), lithospheric-scale transition between “… the Adria plate and the Dinaric domain…” remains up to now the most problematic geotectonic issue in the NE Adriatic region (Fig. 1). One of the crucial facts is the absence of geological evidence of any oceanic crust between these two domains. Thus, if two lithospheric units exist, they would be separated by a transform plate boundary. However, both would belong to a unique unit — the Adriatic microplate or Adria (Channell et al., 1979), even if the plate may have been fragmented during the late Cenozoic (Oldow et al., 2002; Piromallo and Morelli, 2003; Marton, 2006).

The External Dinarides are fold-and-thrust belt, part of the Alpine orogenic system, characterized by generally SW verging structures, and can be considered as the detached, backthrust and highly deformed upper crust of the Adria during subduction to the NE. The belt, along with the related part of the Adriatic foreland (Fig. 1) is geographically situated within the Dinaric Karst region. Differing opinions about the geologic evolution of the system in the NE Adriatic region highlight its complexity (Aubouin et al., 1970; D'Argenio et al., 1971; Chorowicz, 1975a,b; Herak, 1987; Buser, 1989; Cati et al., 1989a; Jelaska et al., 1994; Lawrence et al., 1995; Grandić et al., 1997; Pamić et al., 1998; Grandić et al., 1999, 2001; Picha, 2002; Tari, 2002; Marton et al., 2003; Vlahović et al., 2005).

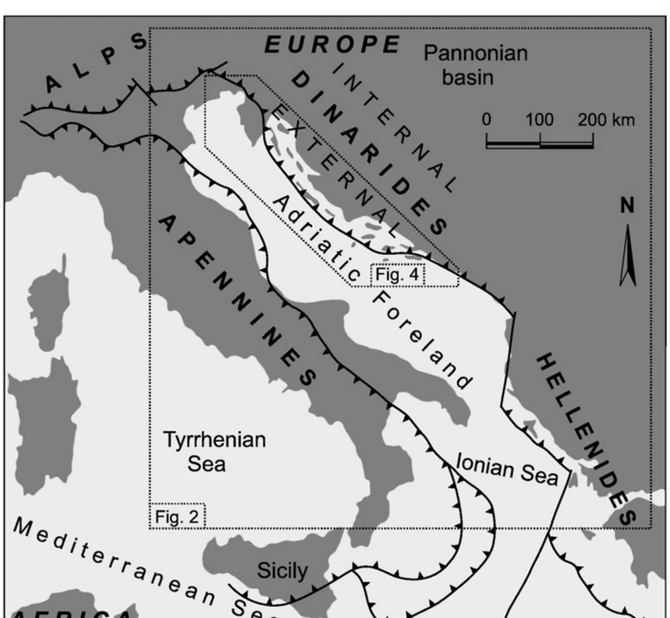

Fig. 1. Tectonic map of the Adriatic region showing the deformation fronts of the major Alpine orogenic belts.

In the middle of the 70's of the 20th century, teams from the Institute of Geology in Zagreb (today Croatian Geological Survey), along with colleagues from Slovenia, Bosnia and Herzegovina, and Montenegro, produced a comprehensive geological mapping of the region which resulted in 40 sheets of the official Basic Geological Map of the former Yugoslavia, scale 1:100,000 (available on www.hgi-cgs.hr). The region has also been comprehensively investigated by French geologists (so-called Aubouin's team) during the same period.

One of the earlier paleogeographic models of the region is based on a clear tripartite paleogeographic subdivision in its southeastern part (D'Argenio et al., 1971). The model comprises two carbonate platforms — Adriatic and Dinaric, and the intervening Budva–Cukali Basin (BCB). The idea was followed by Chorowicz (1975a), who suggested NW prolongation and termination of the BCB (NW end of the NEAT on Fig. 2).

The second early model considers the region as a more or less unique carbonate shelf of the External Dinarides (Grandić, 1974) characterized by maximal subsidence in the central zone and intrashelf troughs that developed during the Late Cretaceous.

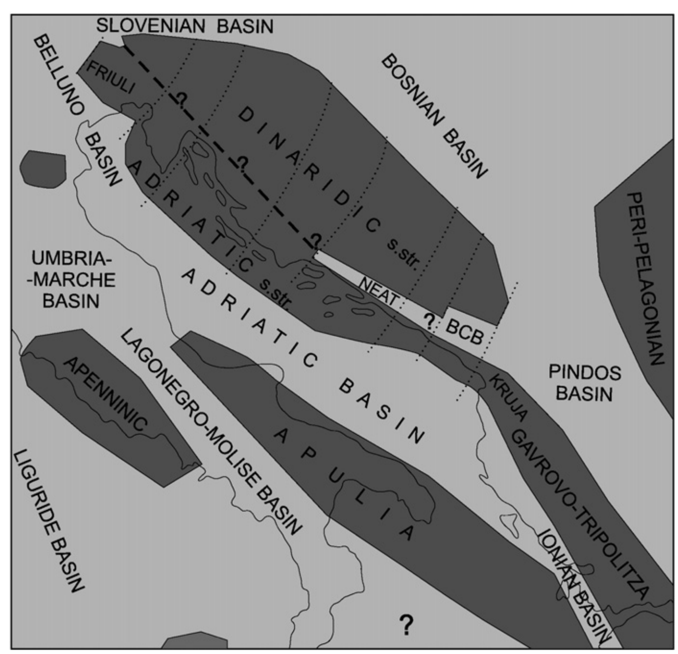

Fig. 2. Conservative paleogeographic map of the Adriatic region for the Late Cretaceous time (some present-day geographic lineaments are indicated, see Fig. 1; redrawn and simplified after Dercourt et al., 2000; Bosellini, 2002). The Adriatic–Dinaridic carbonate platform (s. lato) is split into the Dinaridic and Adriatic platforms (s. str.) by the supposed continuous NE Adriatic trough (NEAT, thick dashed lines). Hypothetical transform faults (thin dotted lines). Basins on the continental and oceanic crust — light grey. Carbonate platforms and shelves — dark grey. BCB — Budva–Cukali Basin.

Other interpretations can be generally referred to one of the above mentioned end-member models as follows:

- single carbonate platform: External Dinarides Carbonate Platform (Grandić et al., 1999), Adriatic–Dinaridic Carbonate Platform — ADCP (Gušić and Jelaska, 1993; Pamić et al., 1998), Adriatic Carbonate Platform — AdCP (Vlahović et al., 2005), and
- two carbonate platforms: Adriatic and Dinaridic/Dinaric, separated by deeper-water inter-platform belt called Epiadriaticum (Herak, 1986, 1987) or Budva–Cukali Basin (Tari, 2002; Schmid et al., 2008).

Estimates of shortening during the Tertiary compression, that resulted in the formation of the Dinaric chain, differ substantially. The single-platform model involves minor shortening achieved predominantly by folding and faulting along steep reverse faults. The two-platform model involves significant shortening achieved predominantly by thrust stacking, which resulted from more or less complete underthrusting of the inter-platform basinal unit.

However, neither low-quality seismic nor borehole data provide evidence for an underthrust inter-platform basinal unit which should be a NW extension of the BCB. Yet, lateral stratigraphic variations within the Upper Cretaceous to Paleogene shallow-water carbonate successions, and the presence of isolated outcrops of contemporaneous basinal carbonates, suggest different pre-compressional subsidence (see Section 5).

Upper Cretaceous to Paleogene stratigraphic data from papers published during last 40 years were studied for the purpose of regional

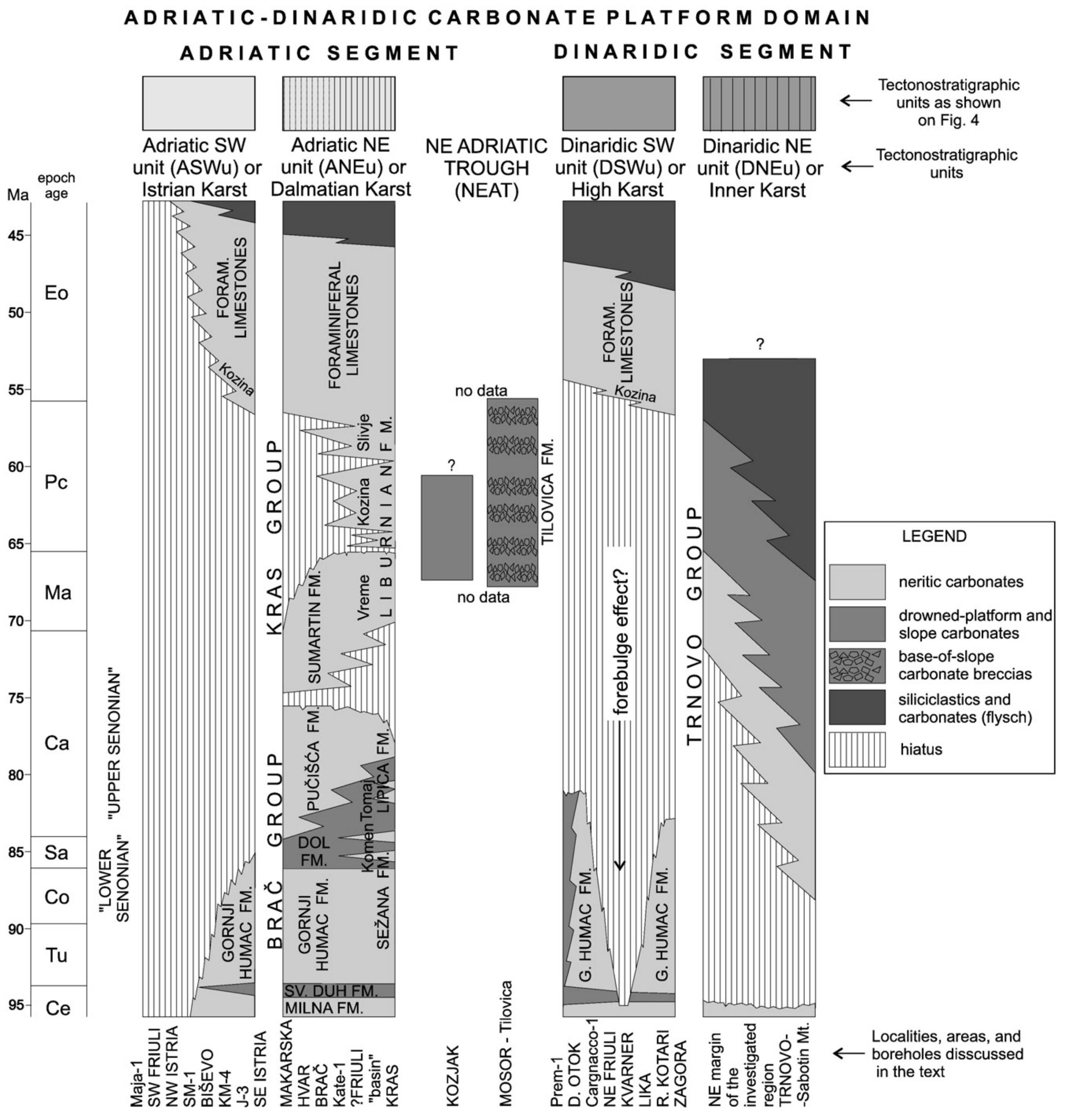

Fig. 3. Chronostratigraphic correlation of Upper Cretaceous to Paleogene carbonates of Adriatic–Dinaridic Carbonate Platform (ADCP) domain in the present-day NE Adriatic region.

tectonostratigraphic interpretation. The data were re-evaluated within the frame of a new lithostratigraphic scheme that evolved during the last two decades and are used as a base for a regional lithostratigraphic correlation (Fig. 3). Distribution map of recognized stratigraphical units (Fig. 4) is used as a base for regional tectonostratigraphic interpretation of the Upper Cretaceous to Paleogene carbonates. The tectonostratigraphy became a crucial argument for the interpretation of the orogenic evolution of the NE Adriatic region.

2. Geological setting

The present-day peri-Adriatic area belongs to the more or less deformed cover of a major regional lithospheric unit of African affinity, the Adriatic microplate or Adria (Channell et al., 1979; Wortmann et al., 2001; Bosellini, 2002; Rosenbaum and Lister, 2005), equivalent to the Apulia microcontinent (cf. Dercourt et al., 1986). During the Late Triassic to Early Jurassic, several extensive and long-lived carbonate platforms developed in the area (D'Argenio et al., 1971; Zappaterra, 1994; Dercourt et al., 2000; Ciarapica and Passeri, 2005; Fig. 2). The largest among them was the Adriatic–Dinaridic Carbonate Platform (cf. Jenkyns, 1991; Gušić and Jelaska, 1993; Jelaska et al., 1994; Pamić et al., 1998), also named External Dinarides Carbonate Platform (Grandić et al., 1999), or Adriatic Carbonate Platform (cf. Vlahović et al., 2005). The name Adriatic–Dinaridic Carbonate Platform (ADCP) is considered in this paper since it best fits the results presented here. Longlasting carbonate-platform-type deposition started in the latest Triassic and, punctuated by episodes of drowning or emersion, persisted into the Eocene (Jelaska, 2002).

The main Dinaridic thrust-related deformations took place during the Paleogene (Aubouin et al., 1970; Chorowicz, 1977; Cadet, 1978; Lawrence et al., 1995; Pamić et al., 1998; Tari, 2002; Schmid et al., 2008), or the Miocene (De Capoa et al., 1995; see Section 7.4), when

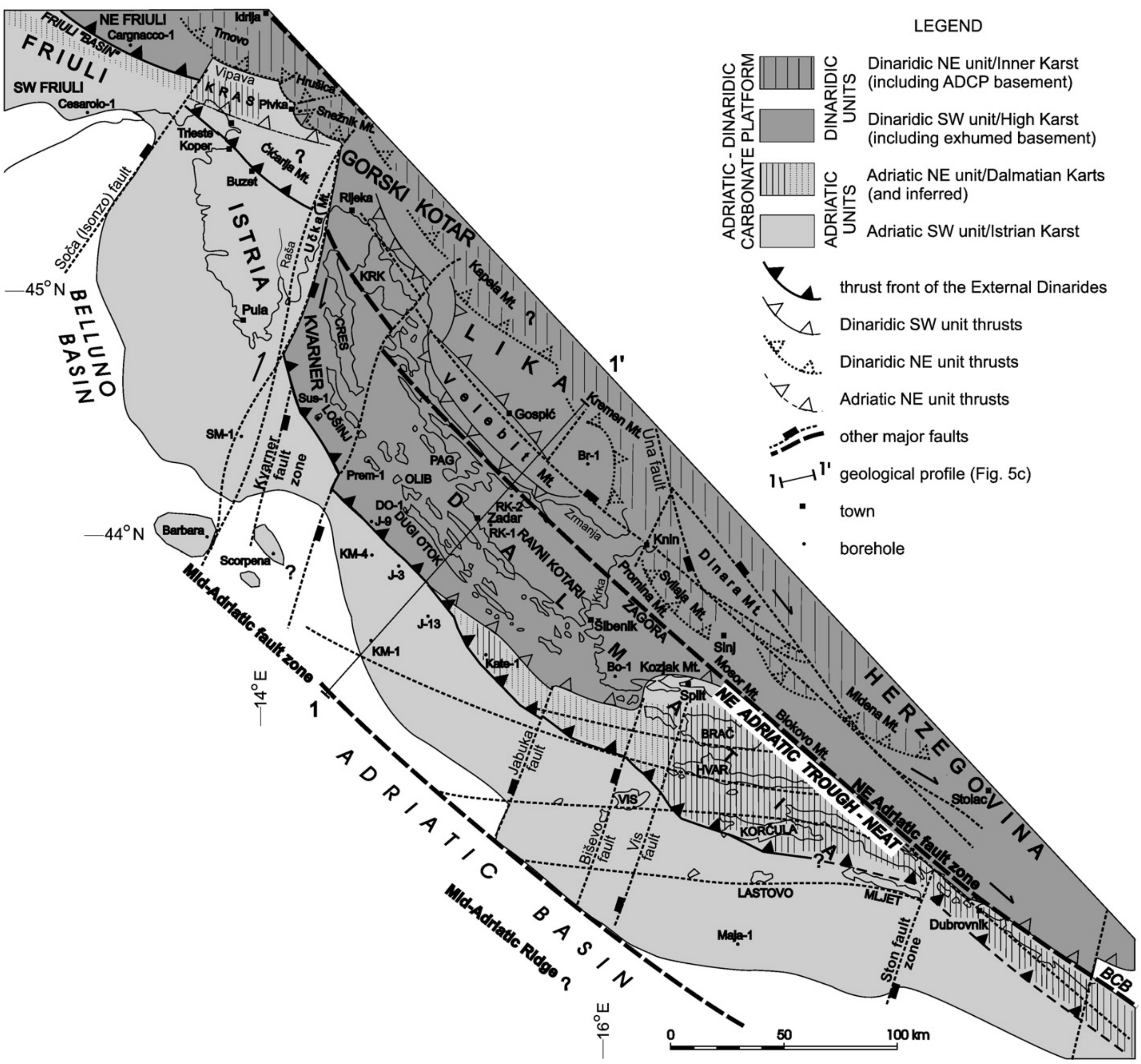

Fig. 4. Simplified tectonic map of the NE Adriatic region showing the present-day distribution of the recognized tectonostratigraphic units (see Fig. 1 for the location). BCB — Budva–Cukali Basin.

the complex tectonic structure of the region was formed. However, the present day geomorphology is rather an expression of wrench tectonics (Prelogović et al., 1995a) along a zone of steep faults, striking generally NW–SE. This zone probably marks a deep-rooted lineament that originated during the Triassic (Grandić et al., 2001), affected pre-orogenic sedimentation, and was reactivated during orogenic compression. Transport along the zone is still active during the present day escape tectonics (Picha, 2002). The most obvious geomorphological evidence of the tectonic activity along the NE Adriatic fault zone is a mountain range characterized by generally NW–SE (Dinaridic) trend (Fig. 4). Today more or less deformed successions of the ADCP carbonates outcrop in the NE Adriatic region (NE Italy, SW Slovenia, SW Croatia, SW Bosnia and Herzegovina, SW Montenegro and NW Albania, GKSFRJ, 1970; GKRH, 2009).

3. Mesozoic paleogeography of the northern-central Mediterranean

The NE Adriatic region is traditionally recognized on the paleogeographic maps of the central Mediterranean Tethys as a single carbonate-platform unit (Dercourt et al., 1986, 2000). However, two distinct Mesozoic carbonate-platform domains, Adriatic and Dinaridic, were clearly separated by Triassic to Eocene Budva–Cukali Basin (BCB, Fig. 2) in the bordering area of the SE Dinarides and NW Hellenides (i.e. Montenegro and NW Albania — Aubouin et al., 1970; D'Argenio et al., 1971; Cadet, 1978; Robertson and Shallo, 2000; Tari, 2002).

In spite of the still dubious NW extension of the BCB and timing of opening of the NE Adriatic trough (NEAT, Fig. 2), lithostratigraphic and tectonic relations speak in favour of the existence of two-platform domains in the region of central and southern Dalmatia during the Late Cretaceous and Early Paleogene (Chorowicz, 1975a). Concerning the differences in Upper Cretaceous to Paleogene stratigraphy described in the paper, I will refer these domains to the SW and NE one, i.e. to the Adriatic Carbonate Platform s.str. (ACP) and the Dinaridic Carbonate Platform s.str. (DCP), respectively (Fig. 2). Thus, it is a strong argument for the name of the carbonate-platform domain individualized during Late Triassic?–Early Jurassic in the peri-Adriatic region: Adriatic–Dinaridic Carbonate Platform s.lato (ADCP). Even in the case that the ADCP was not split by a basin into ACP and DCP on the northern Adriatic area (Friuli, Kras, Kvarner, northern Dalmatia; Fig. 4), it should be referred to as either DCP or ACP, to allow for easier distinction and to emphasize regional differences in stratigraphy.

Bosellini (2002) suggested that the Friuli–Istria–Dalmatia carbonate platform (Adriatic s. str., Fig. 2) was connected via the Gavrovo–Tripolitza platform to the Apulia platform, and possibly further to Africa during late Mesozoic (figs. 16 and 17 in Bosellini, 2002). In this, a deep embayment on the eastern part represents the BCB that separates Friuli–Istria–Dalmatia platform on the south (Adriatic platform s.str.) from an unnamed carbonate platform on the north (Dinaridic platform s. str., Fig. 2). Dinosaur footprints reported from the Upper Turonian to Lower Coniacian deposits of the Dalmatian part (ACP) of the ADCP (Mezga et al., 2006), support the hypothesis. The hypothesis is also supported by the latest review of paleomagnetic investigations in the region (Marton, 2006), suggesting a coherent movement of Adria and Africa until the Eocene. However, the question of NW extension of the BCB (NEAT on Fig. 2), which possibly completely separated the ACP from the DCP at least since the latest Cretaceous, still remains open.

A significant platform-retreat event took place during late Early Jurassic (Toarcian) when a large former platform area (present-day Umbria–Marche and the central Adriatic) became drowned, resulting in the formation of the Adriatic Basin (Grandić et al., 1999; Ciarapica and Passeri, 2005; Vlahović et al., 2005; Fig. 2). One of the most prominent seismic features situated generally along the axis of the central Adriatic is formed at that time — ADCP SW margin (East Adriatic Slope — EAS in Grandić et al., 1999, 2001). Open question is the connection of the former larger platform in the present-day area of Umbria–Marche and Apulia with the ADCP during the latest Triassic to earliest Jurassic, i.e. possible earliest initiation of the Adriatic Basin (Ciarapica and Passeri, 2005; Korbar et al., 2009). According to the published data, a drilled part of the lowermost Belluno basinal succession is of earliest Jurassic age and is underlain by the Upper Triassic Dolomia Principale (Bosellini, 1989; Cati et al., 1989a). That was certainly the earliest evidenced individualization of the ADCP in the northern Adriatic. However, extensional tectonic obviously affected the Adriatic region since Middle Triassic (Bosellini, 1989; Grandić et al., 2001). The small platform sectors (Barbara, Scorpena etc.), and deeply buried rift structures are recognized in the central part of the region, along the Mid-Adriatic fault zone (Fig. 4), and should be investigated in future (Del Ben, 2002). Besides, the thickest sediment successions between the Adriatic and Apulia platforms (Figs. 1, 2 and 4) in the central Adriatic Sea are recognized on seismic profiles, as well (Grandić et al., 1997, 1999, 2001). Thus, the Belluno basin could be connected with the evolving Adriatic Basin to the southeast since Late Triassic (A. Del Ben oral presentation, 2006). Platform retrogadation in the area during the Middle Triassic to Middle Jurassic allows the assumption that the earliest troughs are buried within the deepest depressions. These structures possibly represent initial rift phase and the earliest separation of the Adriatic from Apulia carbonate platform (Fig. 2). Considering the discussion above, the interpretation of the Late Triassic to earliest Jurassic paleogeography of the region is still open.

4. Upper Cretaceous to Paleogene stratigraphy of the ADCP domain

4.1. Stratigraphy of platform carbonates

Typical Upper Cretaceous succession (Fig. 3) has been described in detail from the island of Brač (Gušić and Jelaska, 1990; Cvetko Tešović et al., 2001) and has been subdivided into the following informal lithostratigraphical units: Milna formation (Cenomanian) — platform interior, Sveti Duh formation (uppermost Cenomanian to lower Turonian) — pelagic incursion over the platform, Gornji Humac formation (Turonian to Coniacian) — platform interior, Dol formation (Coniacian to Campanian) — intra-platform basin indicating a second Late Cretaceous pelagic episode, Pučišća formation (Santonian to Campanian) — rudist-bearing margin of intra-platform basin, back-margin and platform interior, and Sumartin formation (Upper Campanian to Maastrichtian) — platform interior, equivalent of the lower part of the Liburnian formation (Vreme beds) of the Kras area (Stache, 1889; Bignot, 1972; Jurkovšek et al., 1996 and references therein). The succession is referred to as the Brač group (Fig. 3). Early to Middle Eocene Foraminiferal limestone (Marjanac et al., 1998; Ćosović et al., 2004) unconformable overlay the Sumartin formation over a clearly expressed emergence surface (hiatus).

The Kras region (Carso in Italian, Fig. 4) is characterized by the most complete Upper Cretaceous to Paleogene succession in the studied region (Jurkovšek et al., 1996 and references herein; Fig. 3), including Maastrichtian to Paleocene restricted inner-platform carbonates. The later succession is referred to as the Liburnian formation (Stache, 1889), equivalent to the Monte Grisa member (Cucchi et al., 1989a). The deposits of the Liburnian formation disconformably overlay succession of Turonian to Campanian inner- to open-platform carbonates subdivided into two formations: the Sežana formation below and the Lipica formation above (Fig. 3). The Liburnian formation (s. lato) includes both, uppermost Cretaceous rudist-bearing carbonates referred to as the Vreme beds (equivalent to the Sumartin formation of Gušić and Jelaska, 1990), and the lowermost Paleogene (Paleocene) part of the Liburnian formation (Bignot, 1972; Drobne et al., 1989; Jurkovšek et al., 1996 and references therein). The Kozina beds/facies appear in the middle part of the Liburnian formation (Stache, 1889; Jurkovšek et al., 1996). However, the beds are commonly distributed within the entire NE Adriatic region (sheets of Basic Geological Map of the former Yugoslavia, scale 1:100,000), and are not exclusively related to the succession of the Liburnian formation (outcropping in the Kras region). The Kozina beds are characterized by up to 150 m thick succession of dark, bituminous limestones deposited in brackish waters, in places with coal beds. These beds deposited locally onto karstified Cretaceous carbonates during the very beginning of the Paleogene transgression. The Kozina beds have been usually named outside the Kras region as liburnian deposits. However, within the historical Liburnian region (an area from Raša river in eastern Istria to Zrmanja river in northern Dalmatia, once inhabited by the Illiric tribe Liburni) there are no outcrops of Maastrichtian to Lower Paleocene shallow-water carbonates, originally referred to the Liburnian formation (Stache, 1889; Jurkovšek et al., 1996). This geographical discrepancy certainly contributed to a confusion related to the use of the term Liburnian deposits/formation during the last decades (see discussion in Gušić and Jelaska, 1990).

Steuber et al. (2005) suggested that only the upper part (Paleocene) of that Cretaceous to Paleogene succession should be named the Liburnian formation, while the lower, rudist-bearing part (Upper Campanian to Maastrichtian) should be referred to as the Sumartin formation (Vreme beds in the Kras region of the NE Italy and the SW Slovenia, Fig. 4). Nevertheless, the key stratigraphic features for the reconstruction of regional palaeogeography are the Sumartin and/or Liburnian formations, two main members of the proposed Kras group (Fig. 3), which appears in distinct areas of the NE Adriatic region.

The Liburnian formation is overlain by neritic, inner to outer ramp limestones of Late Paleocene (Thanetian) to Eocene age (Bignot, 1972; Drobne, 1977; Ćosović et al., 2004). The limestones are rich in larger benthic foraminifers: mostly miliolids, alveolinids and orthophragminids, and referred to as alveolinid–nummulitid limestone (Gušić and Jelaska, 1990; Jurkovšek et al., 1996), or the Foraminiferal limestones (Dragičević et al., 1992; Marjanac et al., 1998; Ćosović et al., 2004). The formation either (dis)conformably overlay Paleocene restricted inner-platform carbonates (as in the Kras region) or unconformably various Upper Cretaceous lithostratigraphic units over a major hiatus related to a regional subaerial exposure (Fig. 3). However, the formation is not a common stratigraphic component within the NE Adriatic region (Fig. 3). Foraminiferal limestones are overlain by Middle to Upper Eocene (predominantly) clastics, which are referred to as flysch (GKSFRJ, 1970; Marinčić, 1981; GKRH, 2009).

4.2. Stratigraphy of basinal carbonates

Although platform carbonates predominantly crop out within the investigated region, isolated outcrops of deeper-water carbonates and carbonate clastics (breccias) are also reported from the ADCP domain. The breccias, along with other lithotypes of deeper-water carbonates, indicate synsedimentary tectonics and enhanced subsidence of an elongated area during the latest Cretaceous to the Early Paleogene (Chorowicz, 1975a; Jelaska et al., 2003, and references therein).

Maastrichtian to Paleocene basinal carbonates occur in a few kilometers-long outcrops along the NE Adriatic coast in central and southern Dalmatia (Fig. 4). From NW to SE these are as follows: Kozjak Mt. (Chorowicz, 1975a), Tilovica locality on Mosor Mt. (Jelaska et al., 2003; Ćosović et al., 2006), and Kotišina locality on Biokovo Mt. (Jelaska et al., 2003). As proposed by Chorowicz (1975a), basinal limestones in the area between Split and Dubrovnik were deposited within a trough, that palaeographically represented a NW embayment of the Budva–Cukali basin (Aubouin et al., 1970; D'Argenio et al., 1971; Robertson and Shallo, 2000), here referred to as the NE Adriatic trough (NEAT).

Another group of Maastrichtian to Paleocene basinal marly limestones occurs on the Trnovo, Hrušica and Snežnik thrust sheets (NW on Fig. 4; Postojna and Ilirska Bistrica sheets of the Basic Geological Map of the former Yugoslavia, scale 1:100,000). A stratigraphy of the outcrops was established by Cousin (1970) and improved by Pavšič (1994). The strata have been interpreted as the earliest distal foredeep deposits of the region investigated (Otoničar, 2007), deposited originally on today highly deformed and displaced tectonostratigraphic unit of the External Dinarides (Internal Karst and Pre-Karst cf. Chorowicz, 1975b, here referred to as the Dinaridic NE unit, see Section 5). The deposits are overlain by the synorogenic flysch deposited during Early Paleogene in the northernmost part of the NE Adriatic region (NE Friuli, Fig. 4, NW), i.e. to the Flysch del Grivò (Merlini et al., 2002).

In addition to Maastrichtian to Paleocene carbonates, Turonian to Santonian (?Lower Campanian) basinal carbonates occur close to the Dinaridic frontal thrust in outcrops and boreholes located NE of the thrust (Figs. 3 and 4). A few occurrences are reported from the islands of Susak and Lošinj (Đurasek et al., 1981; Korbar et al., 2001), and the islands of Premuda and Dugi Otok (Kapović and Bauer, 1971; Tončić-Gregl and Prpić, 1971; Fuček et al., 1991). The paleogeographical position of the carbonates will be discussed below (Sections 5.2 and 7.1).

5. Tectonostratigraphic units of the ADCP domain

The stratigraphic scheme of the ADCP domain (Fig. 3) is based on data published in numerous papers dealing with the stratigraphy of the Upper Cretaceous to Paleogene carbonates in the investigated area. I will highlight a few papers which report outcrop data: Bignot (1972), Drobne (1977), Gušić and Jelaska (1990) and Jurkovšek et al. (1996), and one which reveals borehole data (Tari-Kovačić et al., 1998).

Five units can be recognized according to their stratigraphic analysis (Figs. 3, 4 and 5), and are named according to their relative position within the Dinaridic (DCP) or Adriatic (ACP) domain (from NE to SW): Dinaridic NE unit (DNEu) or Inner Karst, Dinaridic SW unit (DSWu) or High Karst, NE Adriatic trough (NEAT), Adriatic NE unit (ANEu) or Dalmatian Karst, and Adriatic SW unit (ASWu) or Istrian Karst. Concerning their relation to synsedimentary tectonics (including subsidence), the domains are referred to as tectonostratigraphic units (Figs. 3, 4 and 5).

The above units are characterized as follows: a) the DNEu by the oldest (Maastrichtian to Paleocene) synorogenic platform drowning, siliciclastic input and flysch deposition; b) the DSWu by a long lasting emersion which resulted in a major hiatus between Upper Cretaceous and Paleogene deposits, due to possible forebulge effect in its central part (Fig. 3); c) the NEAT by Maastrichtian to Paleocene slope and base-of-slope carbonates; d) the ANEu by the most complete stratigraphic record of the Upper Cretaceous, and, in places, almost continuous sedimentation up to the Paleocene (e.g. the Kras region), and e) the ASWu by a longlasting emersion which resulted in a major hiatus between Upper Cretaceous and Paleogene deposits.

Localities, including outcrops and boreholes, along with their major characteristics are listed below and assigned to one of the proposed tectonostratigraphic units (Fig. 3). These units are tentatively compared to the tectonic zones of Chorowicz (1975a,b, 1977) in Table 1.

5.1. The Dinaridic NE unit (DNEu) or Inner Karst

The Upper Cretaceous to Palaeogene successions of the unit are characterized by an intra-Upper Cretaceous (uppermost Cenomanian to Santonian) hiatus marked by bauxitic deposits. The hiatus is probably related to the DNEu forebulge phase, that was followed by formation of the distal foredeep ramp during Santonian to Maastrichtian. The Maastrichtian to Paleocene basinal carbonates are characterized by increasing marly component upward the successions, and are overlain by Paleocene flysch (Cousin, 1970). The succession is here referred to as the Trnovo group (Fig. 3).

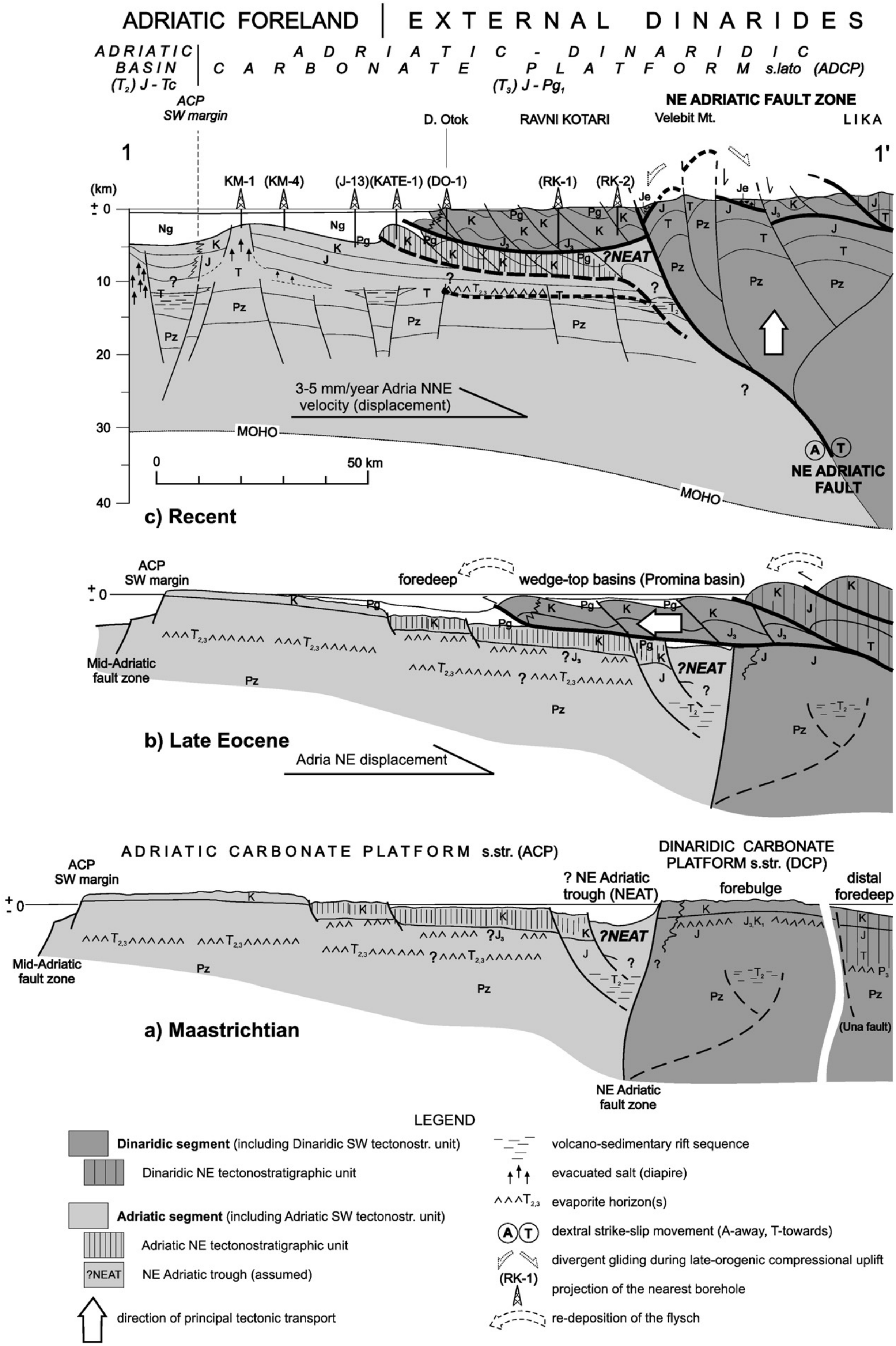
ADRIATIC FORELAND
EXTERNAL DINARIDES
ADRIATIC BASIN
(T2) J - Tc
ADRIATIC - DINARIDIC CARBONATE PLATFORM s.lato (ADCP)
(T3) J - Pg1
ACP SW margin
D. Otok
RAVNI KOTARI
NE ADRIATIC FAULT ZONE
Velebit Mt.
LIKA
1
1'
KM-1
(KM-4)
(J-13)
(KATE-1)
(DO-1)
(RK-1)
(RK-2)
(km)
± 0
10
20
30
40
Ng
Pg
K
J
T
Pz
Je
?NEAT
3-5 mm/year Adria NNE velocity (displacement)
MOHO
0
50 km
NE ADRIATIC FAULT
c) Recent
foredeep
wedge-top basins (Promina basin)
Mid-Adriatic fault zone
b) Late Eocene
Adria NE displacement
ADRIATIC CARBONATE PLATFORM s.str. (ACP)
DINARIDIC CARBONATE PLATFORM s.str. (DCP)
? NE Adriatic trough (NEAT)
forebulge
distal foredeep
(Una fault)
a) Maastrichtian
NE Adriatic fault zone
LEGEND
Dinaridic segment (including Dinaridic SW tectonostr. unit)
Dinaridic NE tectonostratigraphic unit
Adriatic segment (including Adriatic SW tectonostr. unit)
Adriatic NE tectonostratigraphic unit
NE Adriatic trough (assumed)
direction of principal tectonic transport
volcano-sedimentary rift sequence
evacuated salt (diapire)
evaporite horizon(s)
dextral strike-slip movement (A-away, T-towards)
divergent gliding during late-orogenic compressional uplift
projection of the nearest borehole
re-deposition of the flysch

Table 1
Tentative correlation of the tectonostratigraphic units and paleogeographic domains (this paper) and the tectonic zones of Chorowicz (1975a,b, 1977).

This paper		Chorowicz (1975a,b, 1977)
Tectonostratigraphic units	Paleogeogeographic domains	Tectonic zones
Dinaridic NE unit (DNEu) *or* Inner Karst	Dinaridic carbonate platform s.str (DCP)	Pre-Karst + Internal Karst zones
Dinaridic SW unit (DSWu) *or* High Karst		External + High Karst zones
NE Adriatic trough (NEAT)		Split sub-zone + Budva zone
Adriatic NE unit (ANEu) *or* Dalmatian Karst	Adriatic carbonate platform s.str (ACP)	Dalmatian zone
Adriatic SW unit (ASWu) *or* Istrian Karst		

The clear recognition of the DNEu is restricted to the NW part of the investigated area (Trnovo thrust, Sabotin Mt., Fig. 4), as recently reported by Venturini et al. (2008). The unit was previously referred to the central sub-zone of the Friuli zone, and was interpreted as High Karst zone by Cousin (1970). However, the High Karst zone (DSWu) is almost completely overthrust by the DNEu (Inner Karst), and only an isolated thrust sheet (Pivka) characterized by the DSWu affinities is recognized in the front of Snežnik thrust (Fig. 4).

Further to the SE (Gorski Kotar and northern Lika region; Fig. 4), the Upper Cretaceous to Paleogene successions are eroded, and the DNEu is inferred according to the stratigraphy of the thrust sheets from the hinterland (Črnomelj, Karlovac, Slunj, Bihač and Drvar sheets of the Basic Geological Map of the former Yugoslavia, scale 1:100,000; Jelaska et al., 1969). The thrust sheets characterized by the DNEu affinities were previously referred to as Pre-Karst and Internal Karst zones (Chorowicz, 1975b, 1977). Noteworthy, it seems that the Upper Jurassic intra-platform deeper-water successions referred to as Lemeš deposits (Vlahović et al., 2005 and references herein) mark the SW margin of the DNEu.

5.2. The Dinaridic SW unit (DSWu) or High Karst

The unit is characterized by the Santonian (Early Campanian) to Late Paleocene hiatus and possible forebulge effect in the central part (Fig. 3). The Upper Cretaceous strata underlying the hiatus generally show bio- and lihofacies characteristic of the Gornji Humac formation, originally described on the Island of Brač (Gušić and Jelaska, 1990). Thus, these strata enclose Turonian to "Lower Senonian" (Coniacian to Santonian) interval (Fig. 3). This stratigraphic unit has two synonyms in the Kras area: Borgo Grotta Gigante member (Cucchi et al., 1989a) and Sežana formation (Jurkovšek et al., 1996).

The most NW evidence of the unit is in the deep borehole Cargnacco-1, Friuli (Venturini, 2002; Fig. 4). A thrust fault is recognized within the borehole (Merlini et al., 2002). The Upper Cretaceous to Paleogene shallow-water carbonates in the hanging wall have DSWu affinity (DCP). Thus, the Friuli "basin" deposits recognized on seismic sections in front of the thrust (Cati et al., 1989b) is here referred to the underthrust NEAu, as mentioned below (Section 5.4).

In the front of Snežnik thrust sheet (Fig. 4, NW) there is a narrow belt of the overturned Upper Cretaceous to Paleogene succession of shallow-water carbonates (Pleničar, 1959) characterized by typical DSWu stratigraphy.

Many localities are characterized by Turonian to "Lower Senonian" shallow-water carbonates directly overlain by transgressive Foraminiferal limestones of Eocene age. In the Kvarner area (Fig. 4) this situation can be observed on the islands of Cres (Korbar and Husinec, 2003) and Olib (Moro and Jelaska, 1994), in the Lika region, Ravni Kotari and Zagora (unpublished report of Croatian Geological Survey), as well as in the Biokovo hinterland (Jelaska et al., 2000). The lowermost Paleogene horizons within the region are referred to the Lower Eocene (Drobne and Trutin, 1997).

The "Lower Senonian" open platform and slope carbonates occur in outcrops located close to the Dinaridic frontal thrust in the central part of the investigated region (Lošinj — Korbar et al., 2001 and Dugi Otok — Fuček et al., 1991; Fig. 4). The Turonian to Santonian (?Lower Campanian) open-platform pithonellid limestones are overlain by Eocene Foraminiferal limestones in the neighbouring borehole Prem-1 (Tončić-Gregl and Prpić, 1971). Similar stratigraphic relation is found also in the borehole J-9, situated close to the frontal thrust further to the SE (Tari-Kovačić, 1997).

In the southeasternmost part of the area investigated (Herzegovina, Fig. 4) "Senonian" rudist limestones are overlain by Eocene transgressive carbonates (Slišković, 1968; Cadet, 1978). However, according to descriptions of Slišković (1983), a narrow belt striking NW–SE in the area of central Herzegovina (NE of Stolac, Fig. 4) is characterized by up to 200 m thick succession of the Liburnian formation. The belt is situated in the marginal part of the studied region and its tectonostratigraphic meaning is not recognized in the model presented here. Further investigations on the stratigraphy are needed in that area.

5.3. The NE Adriatic trough (NEAT)

Maastrichtian to Paleocene slope to base-of-slope carbonates occur in a few kilometers-long outcrops along the NE Adriatic coast in central and southern Dalmatia (Fig. 4). From NW to SE they are, among others, as follows: Kozjak Mt. (Chorowicz, 1975a), Tilovica locality on Mosor Mt. (Jelaska et al., 2003; Ćosović et al., 2006), and Kotišina locality on Biokovo Mt. (Jelaska et al., 2003).

Massive to thick-bedded carbonate clastics (intra-, bio-, lithoclastic breccias), alternate with pelagic mudstones to wackestones containing planktonic foraminifers, along with skeletal to bioclastic packstones to rudstones containing benthic foraminifers. The successions are topped by thrust faults. As proposed by Chorowicz (1975a), basinal limestones in the area between Split and Dubrovnik were deposited within a trough, that palaeogeographically represents a NW embayment of the Budva–Cukali basin.

Today, these basinal carbonates are strongly compressed between two-platform domains: the ACP and the DCP (referred also to as the Dalmatian and the High Karst zones by Chorowicz, 1975a and Jelaska et al., 2000). Jelaska et al. (2003) proposed a name for this basinal domain — the Kotišina–Tilovica trough. Considering its wider distribution and possible extension to the NW (Figs. 2, 4 and 5), in this paper the domain is named NE Adriatic Trough (NEAT, Fig. 2).

5.4. The Adriatic NE unit (ANEu) or Dalmatian Karst

The unit is characterized by thicker and more complete Upper Cretaceous to Paleogene carbonate successions in respect to the other

Fig. 5. Orogenic evolution of the NE Adriatic region along SW–NE profile in the central part of the region. (a) Maastrichtian pre-orogenic extension related to the activity of the NE Adriatic fault. Hypothetical NW extent of the NE Adriatic trough (NEAT) separating the Adriatic and Dinaridic platforms. Note distal foredeep on DNEu in the NE part of the region (see Section 5 in the text for details). (b) Late Eocene early-orogenic thin-skinned thrusting of the detached sedimentary successions (see Section 7 in the text for details). (c) Geological profile showing recent structural arrangement of the units. Drawn after map, seismic and borehole data discussed in the text (see Section 6 in the text for details and Fig. 4 for location). Pz — Paleozoic, T — Triassic, J — Jurassic, K — Cretaceous, Pg — Paleogene, Ng — Neogene, Je — Jelar breccias, MOHO — Mohorovičić discontinuity.

units. The distribution of the Maastrichtian–Paleocene Liburnian and/or Sumartin formations (Kras group) is the key feature which defines the ANEu (Figs. 3 and 4).

The most NW outcrops of the ANEu carbonates are exposed in the Kras area (Cucchi et al., 1989a; Drobne et al., 1989; Pugliese et al., 1995; Jurkovšek et al., 1996; Fig. 4 NW), as described in Section 4.1. Further to the west the unit is recognized in the subsurface of the Friuli region in NE Italy. The Friuli platform carbonates are largely buried under younger, predominantly siliciclastic deposits (Cati et al., 1989a; Merlini et al., 2002). Friuli "basin" is recognized on seismic profiles, and is characterized by increased thickness of the Cretaceous to Paleogene succession, probably reflecting pronounced synsedimentary subsidence with respect to SW and NE Friuli platforms (Cati et al., 1989a). The deposits previously interpreted as Friuli "basin" were penetrated by the borehole Cargnacco-1 (Venturini, 2002; Fig. 4). These are shallow-water carbonates placed in the footwall of the Dinaridic frontal thrust (Merlini et al., 2002), here referred to the underthrust ANEu. That is why the complete Friuli "basin" is here interpreted as the ANEu of the ACP (Fig. 4).

In the central Adriatic area, approx. 20 km southeast of the island of Dugi Otok, the deposits referable to the DSW unit are reported from the Kate-1 borehole (Tari-Kovačić et al., 1998; Fig. 4).

Further to the SE, the ANEu deposits, characterized by the presence of the Sumartin formation within the successions, outcrop on the islands of central and southern Dalmatia. The deposits are reported from the island of Brač (Gušić and Jelaska, 1990; Korbar, 2003), the island of Hvar (Jerinić et al., 1994; Korbar, 2003), the Pelješac peninsula (Radoičić, 1970; unpublished reports of Croatian Geological Survey), and in an isolated outcrop along the coast on the mainland in the town of Makarska (Jelaska et al., 2000, 2003; Steuber et al., 2005). Although Cadet (1978) reported that "Lower Senonian" underlay ?Upper Paleocene/Lower Eocene "liburnian" lacustrine deposits at the Molunat–Sutorina section (SE of Dubrovnik), it is referred to the ANEu or Dalmatian zone, situated in the footwall of the Budva–Cukali zone thrust (Dubrovnik sheet of the Basic Geological Map of the former Yugoslavia, scale 1:100,000).

Interestingly, the Sumartin formation also recalls the Uppermost Cretaceous to Paleogene stratigraphy of the Gavrovo–Tripolitza platform (Fig. 2) in the External Hellenides (Fleury, 1980; Zambetakis-Lekkas et al., 1998).

5.5. The Adriatic SW unit (ASWu) or Istrian Karst

The unit is characterized by a major hiatus between Cretaceous and Paleogene carbonates, that generally increases from the NE to the SW (Fig. 3).

In the NW sector of the ACP, the Upper Cretaceous to Paleogene successions are very thin (the southern margin of the SW Friuli), since Lower Cenomanian platform carbonates are directly overlain by Lower Miocene clastics (Cesarolo-1 borehole, Fig. 4; Cati et al., 1989a).

Blašković (1969) reported a Turonian or "Lower Senonian" age for the topmost Cretaceous crystalline limestones, underlying the Paleogene shallow-water limestones from Ćićarija Mt. (Fig. 4). Drobne (1977) analyzed the Paleogene stratigraphy of Ćićarija Mt. in detail, and attributed it to the earliest Eocene (possibly latest Paleocene) transgression over the Cretaceous strata in the area. On the highest peaks of the Učka Mt. (Fig. 4) peritidal limestones of Coniacian–Santonian ("Lower Senonian") age has been recognized by Moro et al. (2002). However, the topmost Cretaceous horizons were not described. In the Istrian part of the ACP, the hiatus is even longer along the axis of a regional anticline striking NNE–SSW (Matičec et al., 1996). Lower Cretaceous shallow-water carbonates are directly overlain by the Foraminiferal limestones along the axis of the anticline. Upper Cenomanian limestones are overlain by the Foraminiferal limestones in NW Istria (Velić and Vlahović, 1994) as well as in the offshore borehole SM-1 (Tari-Kovačić, 1997; Fig. 4). In the southeastern Istria, the Paleogene overlies Santonian peritidal limestones (Moro et al., 2002). Lateral differences in Upper Cretaceous to Paleogene stratigraphy of the unit could be referred to the both, forebulge effect (Otoničar, 2007) and complex tectonic style in the area.

In the central SW part of the ACP, in the boreholes KM-4 and J-3, "Lower Senonian" platform carbonates are transgressively overlain by Lower Eocene Foraminiferal limestones (Tari-Kovačić, 1s997). This is in contrast with the stratigraphy of neighbouring Kate-1 borehole, which has clear ANEu affinities. Further to the SE, on Biševo island of the Vis archipelago, Lower Oligocene limestones unconformably overlay karstified "Lower Senonian" rudist limestones (unpublished data of Croatian Geological Survey; V. Ćosović pers. comm.

Furthermore, some boreholes located in the central Adriatic (e.g. Maja-1 borehole, Grandić et al., 1999; Fig. 4, SE) provide evidence that Lower Cretaceous shallow-water carbonates along the ACP southern margin are, at least in places, directly overlain by Miocene molasse-type clastics. The data allow the assumption that some parts of the ACP SW margin have emerged even since the Early Cretaceous. This is supported by interpretation of transversal seismic profiles showing a decrease in thickness of the Cretaceous to Paleogene shallow-water carbonates from the NE to the SW (Lawrence et al., 1995; Grandić et al., 1997).

6. Geological profile

Considering the relative completeness of published geological data in the central part of the area investigated, which include data from boreholes and seismic lines, a transversal geological profile is constructed here (Figs. 4 and 5c).

The Mohorovičić discontinuity (MOHO on Fig. 5c) is recognized at depth of approx. 30 km below the Adriatic foreland and is depressed down to 40–45 km below a zone striking NW–SE, along the NE Adriatic coast (Aljinović et al., 1987). The deepest base of sediments is situated along the zone (Aljinović, 1986). The zone is believed to represent Tertiary continental subduction predisposed by a pre-orogenic labile belt named Epiadriaticum which separated the two Mesozoic carbonate platforms, Adriatic and Dinaric, situated SW and NE of the belt, respectively (Herak, 1986, 1987).

The Adriatic foreland area (SW part of the profile) is characterized by normal faulting and salt tectonics, resulting in the formation of salt swells, diapire piercings and salt walls (Grandić et al., 2001, 2002). Below the external part of the Dinarides, a prominent seismic reflector, referred to as base of carbonates or E-horizon (Tari Kovačić and Mrinjek, 1994; Prelogović et al., 1995b; Grandić et al., 2002), is recognized at depth of approx. 10 km in the Dugi Otok area (Fig. 5c). This horizon is individuated further to the south as a major seismic reflector at depth of approx. 4 km in the front of the Kate-1 well (Grandić et al., 2002), representing the Dinaridic frontal thrust which dips to the NE. It has ramp geometry (Prelogović et al., 1995a; Grandić et al., 2002), and is here interpreted as the ANEu frontal thrust. Another major thrust-related reflector may be traced from the sea bottom in front of the island of Dugi Otok, dipping in the same direction slightly steeper than the frontal one (Prelogović et al., 1995a). The horizon is here interpreted as the DSWu frontal thrust. It is recognized on seismic profiles at depth of 7 km in the subsurface of the Ravni Kotari (Tari Kovačić and Mrinjek, 1994), and is referred to as a major detachment horizon activated during Tertiary compression within the Upper Jurassic–Lower Cretaceous succession (Fig. 5). The superimposed sedimentary units are characterized by thin-skinned tectonic deformations and tectonic thickening. Thus, a major shortening within the thin-skinned part of the upper crust is proposed. Sedimentary successions below the detachment are affected just by pre-orogenic extensional tectonics and are not involved into Tertiary shortening (Tari Kovačić and Mrinjek, 1994). Further to the NE, the base of carbonates is recognized at depth of approx. 11 km in the subsurface of the Ravni Kotari area (Tari Kovačić and Mrinjek, 1994).

All seismic reflectors dip to the NE where the basal reflector is flexured down to 17 km in the collision zone of the Adriatic and Dinaridic segments of the Adria (?upper) crust (Prelogović et al., 1995a). Further to the NE, below the easternmost extension of the Velebit Mt., a significant seismic reflector (probably representing the crystalline basement) is reversely upthrown (Prelogović et al., 1995a,b) and is interpreted here as a frontal compressional antiform of the Dinaridic segment formed during late-orogenic thick-skinned tectonic phase in the collision zone with the Adriatic one (Fig. 5c).

7. Cenozoic orogenic evolution

7.1. Tectonic overview

Beside the sheets of the Basic Geological Map of the former Yugoslavia, scale 1:100,000, the most systematic tectonic data are published by Aubouin et al. (1970, and references therein), Chorowicz (1977), Cadet (1978), and Lawrence et al. (1995). I will review the most relevant data on the tectonics of distinct areas proceeding from the NW to the SE of the NE Adriatic region.

Cati et al. (1989b) interpreted the Palmanova line as a frontal Dinaridic thrust in the NW part of the region (Friuli, Fig. 4 NW). The Upper Cretaceous to Paleogene stratigraphy in the hanging wall of the thrust (Venturini, 2002) shows clear DSWu affinities, while the stratigraphy of the deposits situated in the front of the line (interpreted as Friuli basin by Cati et al., 1989b) has inferred ANEu affinities, assumably similar to the Upper Cretaceous to Paleogene succession outcropping in the Kras area (Fig. 3). Recently, Merlini et al. (2002) recognized a lobate geometry of the frontal thrust system in the central Friuli, and distinguished between two flysch sequences, Paleocene–Eocene Flysch del Grivò and Eocene Flysch di Cormons, situated north and south of the Cividale tectonic lineament (NW extension of the Trnovo thrust), respectively.

The best documented nappe and low-angle thrust structures in the region are reported from the area of Trnovo, Hrušica and Snežnik Mt. (Pleničar, 1959; Cousin, 1970; Placer, 1981; Fig. 4 NW). The thrusts are here interpreted as highly deformed and displaced successions of the DNEu which almost completely overthrust the DSWu (as outlined in Fig. 4). The DNEu is characterized by Paleocene synorogenic clastics (Cousin, 1970), indicating that a foredeep is formed there prior than on the DSWu.

Further to the south, between the Kras region and Istria, almost perpendicular strikes of the Ćićarija and Učka Mts. depict the complexity of the contact between the External Dinarides and the Adriatic foreland (Blašković, 1969; Placer, 1981). Placer (1981) distinguished between Ćićarija imbricate structures and the Komen (Kras) thrust sheet. However, Cucchi et al. (1989b) reported on major differences between tectonic styles in the wider Trieste area, subdividing it into a northwestern Karst (Kras) unit and a southeastern Ćićarija unit. Ćićarija was referred to as the most southwestern edge of the Dinarides, since the frontal Dinaridic thrust is reported from the Buzet–Koper flysch zone (Placer et al., 2004). Thus, the Ćićarija structure can be interpreted as an internal imbricated system of the NE margin of the ASWu, while the NNE–SSW striking Učka structure was probably formed along the dextral Kvarner fault zone (Fig. 4). Alternatively, Ćićarija structures could be interpreted as highly displaced allochthon of the DSWu (question mark on Fig. 4). The central part of the Istrian foreland is characterized by gentle compressional late-orogenic deformations (Matičec, 1994), possibly reflecting CCW rotation (Marton et al., 2003) and/or Adriatic foreland transpression.

Another evident nappe structure on the surface is reported from the Gorski Kotar area (Fig. 4). The highly allochthonous unit of the NE Gorski Kotar is overthrust onto huge autochthonous antiform of the SW Gorski Kotar that is characterized by similar sedimentary succession (Herak et al., 1961; Herak, 1980). In the area of NW Lika (Kapela Mt., question mark on Fig. 4), the latest-orogenic (neotectonic) transpression zone (Matičec et al., 1997) probably dissected the DNEu thrust front. However, due to erosion of the Uppermost Cretaceous to Paleogene deposits, it is not possible to refer the zone ultimatively neither to DSWu nor to the DNEu.

A major seismic reflector in the transversal profile of the Kvarner region, interpreted as “base of carbonates”, is situated at 4 km depth in the SW and dips down to 6 km in the NE of the region (Prelogović et al., 1995b). However, it cannot be interpreted as “base of carbonates” since the Lower Cretaceous horizons are penetrated at approx. the same depth in the boreholes (Đurasek et al., 1981). There should be more than one-km-thick carbonate succession of underlying Triassic and Jurassic carbonates. The reflector is here interpreted rather as a base of the DSWu overthrust (cf. Fig. 5c).

Chorowicz (1974, 1975b) interpreted the stratigraphic and tectonic relationships in the central Dalmatia. Thrusts are reported from the Dalmatian hinterland which are characterized by the Internal Karst units thrust over the High Karst, i.e. the DNEu over the DSWu. A paleotransform fault Split–Karlovac (Chorowicz, 1975b) is characterized by a zone of Upper Permian evaporites outcropping along the Una fault zone (Bahun, 1985). Cadet (1978) reported on thrust-tectonic relations of the High Karst and Dalmatian units in southern Dalmatia (Dubrovnik area) and Herzegovina.

Along the Velebit, Mosor, and Biokovo Mts. along with the hinterland, the late stage in the mountain-building process (latest orogenic) is characterized by wrench and escape tectonics (Prelogović et al., 1995a; Dragičević et al., 1999; Picha, 2002; Tari, 2002). Dextral tectonic transport along predominantly reactivated reverse faults (Prelogović et al., 1995a; Dragičević et al., 1999; Picha, 2002) resulted by further structural re-arrangements along the NE Adriatic fault zone (e.g. flower, pop-up, pull-apart structures, Figs. 4 and 5). Lower to Middle Miocene lacustrine succession deposited within pull-apart setting of the Sinj basin (Mandić et al., 2009), indicates the onset of the deformations within the Dinaridic domain.

The NEAT (Figs. 2, 4 and 5c) is strongly compressed in the front of the Dinaridic segment (Jelaska et al., 2000). As interpreted in this paper, the trough could extend further to the NW but related deposits are not exposed at the surface (Fig. 5c).

The present-day fault geometry of the central- Dalmatian islands (Brač, Hvar, Fig. 4) has been recently referred to the strike–slip tectonics along sinistral faults conjugated to the NE Adriatic fault zone that is characterized by the dextral tectonic transport (Picha, 2002). However, differences in general orientation of older Dinaridic structures (NW–SE strike) and younger NE Adriatic structures (WNW–ESE strike, generally parallel to the longitudinal axes of the central Dalmatian islands) could be a consequence of the shifting regional tectonic stress during the Tertiary, generally from NE–SW to N–S (Ilić and Neubauer, 2005).

The wrench tectonics and related flower structures are recognized on seismic profiles offshore the NE Adriatic region (Grandić et al., 1997, 1999, 2001; Picha, 2002; Prtoljan et al., 2007), within both, the External Dinarides and the Adriatic foreland domains. Wrench tectonics of the central part of the foreland domain is topographically expressed along the Mid-Adriatic Ridge (Finetti et al., 1989; Fig. 4).

7.2. Orogen geometry

The position of the main tectonic lineaments combined with the distribution of recognized tectonostratigraphic units (Fig. 4) suggests the existence of orogen-parallel segments that were characterized by differences in pre-orogenic stratigraphy and tectonics (including subsidence; Fig. 5). The major crustal segments of the Adria are separated by the NE Adriatic fault (Figs. 2 and 4). The Dinaridic segment is situated at the NE while the Adriatic one is at the SW of the fault. The position of major seismic horizons suggests a further subdivision into fragments separated by transversal faults (Figs. 4

and 6). The NE Adriatic fault is dextrally displaced along the Kvarner fault zone approx. 50 km northward, where it probably corresponds to the Idrija fault (Placer, 1981; Fig. 4). Six fragments are inferred within the Adriatic segment: Friuli, Istria, Kvarner, Northern Dalmatia, Central Dalmatia, and Southern Adriatic (Figs. 4 and 6). Tectonic deformations within the fragments of the Dinaridic segment are more complicated, since the fragments were strongly affected by the latest-orogenic wrench tectonics. The deepest seismic reflectors on the fragments are today at different elevations (Aljinović and Blašković, 1981; Fig. 6), possibly as a consequence of isostatic rebound in response to diachronous along strike deformations and differential orogenic load. Namely, stratigraphic peculiarities of some fragments (Section 7.3) contributed in the differential along strike propagation of the Dinaridic thrust front, resulting in its present arcuate shape in the central part of the region investigated. On the NW, the front is displaced along the regionally important dextral Kvarner fault zone (Turk, 1971; Aljinović and Blašković, 1981; Prelogović et al., 1995b), which runs further to the NE, dissecting the once probably unique NE Adriatic fault zone (Figs. 4 and 6). The most SW propagation of the front is recognized on the Kvarner and the Northern Dalmatia fragments (Figs. 4 and 6). From the south, the front is displaced along the Jabuka, Biševo and Vis faults (Finetti et al., 1989; Fig. 4 and unpublished data of the Croatian Geological Survey). These transversal faults could be related to a deeply buried Triassic rift system (Grandić et al., 2001), and probably had a major role during the formation of the arcuate front geometry (Fig. 4). The NNE–SSW trending faults recognized on the island of Biševo could be a part of an active fault system in the central Adriatic Sea, since the topography is consistent with the orientation of the faults, while soft sediment deformations suggest rapid deposition during the latest Quaternary (Trincardi et al., 2004).

The SW margin of the ACP (the ASWu) is the most outstanding paleomorphological feature recognized on the undeformed part of the Adriatic foreland (Grandić et al., 1999). The recent position of the margin (Fig. 4) implies differential horizontal movements of crustal fragments or platform margin collapses. Thus, small carbonate-platform sectors (Barbara, Scorpena, etc.; Fig. 4) recognized on seismic profiles in the central Adriatic area (Del Ben, 2002) could represent remnants of once unique platform domain that was segmented due to extension in the central Adriatic area (Mid-Adriatic fault zone; Finetti et al., 1989; Fig. 4).

Generally, the thrust front of the External Dinarides (Fig. 4) strongly resembles the overall orogen geometry in the younger (Neogene) Northern and Central Apennines fold-and-thrust belt characterized by multiple décollements (Corrado et al., 1998; Massoli et al., 2006). A general Dinaridic kinematics could be figured particularly well by the model II2 of Corrado et al. (1998). Furthermore, the Northern Apennines front characterized by the northeastward convexity and vergence of an arc-shaped fold-and-thrust belt resembles the Dinaridic geometry in a wider Dugi Otok island area, but in the opposite direction (southwestward convexity and vergence, Grandić et al., 2002). For comparison, the arcuate thrust front in the External Hellenides is interpreted also as a result of lateral differences in stratigraphy of thrust successions, related to the pre-orogenic activity of transform faults which were reactivated during the orogenesis as transversal faults (Skourlis and Doutsos, 2003).

7.3. Role of evaporite horizons

Pre-compressional evaporite provinces were bordered by longitudinal and transversal faults which split segments into smaller fragments (Figs. 4 and 6). The investigated region of the External Dinaridies and the Adriatic foreland is characterized by at least three major evaporite horizons that are distributed within inferred evaporite provinces:

– Upper Permian evaporites of the central part of the Dinaridic segment (Grandić, 1974; Šušnjara et al., 1992), that occur in the thrust fronts of the central part of the DNEu, were distributed east of the Una fault (Fig. 4);
– Upper Jurassic–Lower Cretaceous evaporites of the Dinaridic segment, today reported from the Kvarner and Northern Dalmatia subsurface (Đurasek et al., 1981), presumably displaced from the Velebit fragment of the DSWu;
– Middle–Upper Triassic evaporites of the central part of the ASWu, possibly along with Upper Jurassic within the southern part of the ANEu (Grandić et al., 1999, 2001).

Stratigraphic differences among evaporites in the region are detected also by differences in their sulfur isotope composition (Šiftar, 1986). The composition of the Upper Permian evaporites which

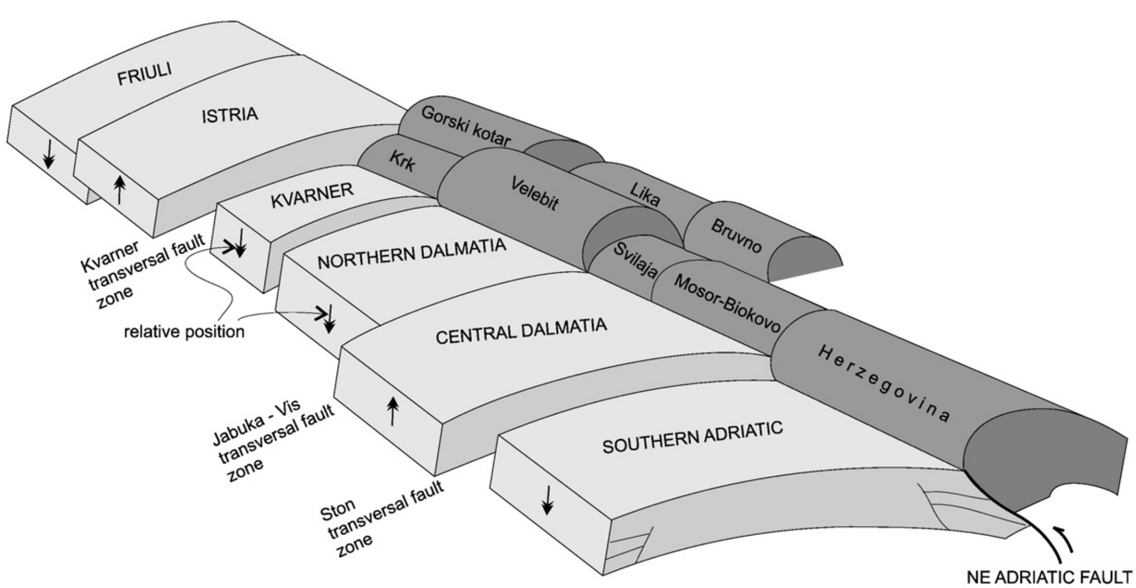

Fig. 6. Sketch of spatial relations of the crustal segments (Dinaridic — dark grey, Adriatic — light grey) and related fragments on different elevations (possible isostatic rebound) in the NE Adriatic region prior to the latest-orogenic wrench tectonic deformations. The superimposed thin-skinned sedimentary cover (early-orogenic) is not shown.

characterizes the Una zone within the Dinaridic segment (Chorowicz, 1977; Šušnjara et al., 1992; Fig. 4), is clearly distinct from Upper Jurassic–Lower Cretaceous evaporites (Đurasek et al., 1981) of the Kvarner and Northern Dalmatia (Šiftar, 1986).

The along strike differences in tectonic styles are mostly related to the pre-orogenic distribution and stratigraphical position of the weakest horizons, acting as detachments, within the laterally different sedimentary successions. For example, the sedimentary successions of the central part of the DNEu were detached during Paleocene within the Upper Permian evaporites and clastics, representing the beginning of the early-orogenic, thin-skinned tectonic deformations in the region. The supra-evaporite successions (including the basement of the DCP) were thrust onto the DSWu. The sedimentary successions of the central part of the DSWu were detached during Eocene within the Upper Jurassic to Lower Cretaceous evaporite horizons (Fig. 5b) and thrust further to the SW. The thrust front of the DSWu is here recognized offshore, SW of the Dugi Otok island.

Noteworthy, significant role of Mesozoic evaporite horizons is recognized also by Merlini et al. (2002) in the NW part of the NE Adriatic region (Friuli; Fig. 4).

7.4. Foredeep migration and flysch deposition

The SW verging Dinaridic orogen was progressively deformed from the NE to the SW (Lawrence et al., 1995; Tari, 2002). The orogenic deformations began earlier within the Internal Dinarides (Late Cretaceous), and affected the External Dinarides during the Paleogene. The Paleocene to Eocene clastic successions in the region are traditionally referred to as flysch (sheets of the Basic Geological Map of the former Yugoslavia, scale 1:100,000; Marinčić, 1981; GHRH, 2009) marks the onset of the early-orogenic deformations. As proposed by a few authors (Lawrence et al., 1995; Tari, 2002), uplift and re-working of ophiolitic and associated sedimentary masses from the Internal Dinarides provided sources of clastics during progressive deformations. SW migration of the Dinaridic foredeeps in front of the migrating Dinaridic wedge resulted in progressive re-deposition of siliciclastic detritus. Mikes et al. (2006) reported Internal Dinaridic provenance of minerals which are found in the Eocene flysch of the External Dinarides. Similar mechanisms are inferred from the heavy mineral composition of Paleogene flysch of the External Hellenides on Peloponnesus (Faupl et al., 2002).

The flysch succession is disconformably overlain by the Upper Eocene to Oligocene molasse-type Promina deposits in the area of Ravni Kotari (Babić and Zupanič, 1983; Tari Kovačić and Mrinjek, 1994). Elsewhere, the flysch successions are eroded or topped by SW verging thrusts and reverse faults. Thus, it is not clear what are the youngest flysch deposits within the External Dinarides.

The age of the flysch is still a matter of debate. The nanofossil biostratigraphy from a few sampling points situated within southern part of the External Dinarides flysch belt indicates Miocene age of the deposits (Radoičić et al., 1991; De Capoa et al., 1995; De Capoa and Radoičić, 2002). However, Early to Middle Miocene age of latest-orogenic (wrench tectonic phase) lacustrine succession of the Sinj basin is reported recently (Mandić et al., 2009; Fig. 4, the town of Sinj). There is a question on possible co-existence of Miocene lakes (e.g. Sinj lake) placed on deformed Dinaridic units, i.e. in the wedge-top position, and foredeeps on the Adriatic units (e.g. Split and Dugi Otok foredeep basins). The latest results based on the integrated biostratigraphy (nanofossil, planktonic and benthic foraminifera) in Istria (north of Raša area, Fig. 4), confirmed Middle Eocene age of the ASWu flysch (Babić et al., 2007). Nevertheless, the youngest flysch-like deposits (early Miocene) are reported from the southwesternmost Dinaridic foredeep — the Dugi Otok basin, penetrated by the offshore borehole J-13 (Fig. 4; Grandić et al., 2002). Concerning the debate, further detailed and integrated investigations on flysch successions are needed.

7.5. Upper Eocene to Oligocene (Miocene?) "molasse"

Intriguing late-orogenic tectonosedimentary features are two regionally important sedimentary units: the Promina formation and the Jelar breccias. The units are traditionally referred to as the Upper Eocene to Oligocene (Miocene?) "molasse" (Babić and Zupanič, 1983). In the area between Ravni Kotari and Velebit Mt., these two sedimentary units have previously been interpreted as contemporaneous thrust-front related clastics (Bahun, 1974; Tari Kovačić and Mrinjek, 1994; Tari, 2002). However, there are neither evidences that these two formations are related to the thrust front, nor that are contemporaneous.

Dragičević et al. (1992) argued for contemporaneous deposition of the Lower Eocene Promina-type clastics and the Foraminiferal limestones in the area of southwestern Herzegovina, based on the abundant calcareous nanoplankton from the transgressive shallow-water marls of the Promina-type clastics. However, laterally equivalent conglomerates contain pebbles of alveolina limestones — eroded and redeposited Foraminiferal limestones (personal observation). Thus, the nanoplankton could originate from the DNEu, i.e. from the Paleocene to Lower Eocene flysch, redeposited onto strongly deformed and eroded Cretaceous to Eocene successions of the DSWu, within a wedge-top basin.

Propagation of the Dinaridic wedge over the Kvarner and Northern Dalmatia fragments was followed by formation of the wedge-top (piggyback?) basin in the area of Ravni Kotari and Promina Mt. (Figs. 4 and 5b). The basin could be formed also as a result of shift from thin- to thick-skinned tectonic phase. The basin is filled up in the southern part firstly by reworked early-orogenic flysch and subsequently by prograding alluvial fans characterized by coarse grained carbonate conglomerates. In the northern part, predominantly coarse grained carbonate conglomerates unconformably overlay deformed Cretaceous and Paleogene carbonate successions. As a result, the more than 2000 m thick succession, referred to as the Promina formation, was deposited (Babić and Zupanič, 1983; Tari Kovačić and Mrinjek, 1994; Fig. 4).

The Jelar breccias are predominantly unsorted polymictic strongly cemented carbonate breccias consisting of Jurassic, Cretaceous and Paleogene lithoclasts, including also rare fragments of Promina formation sediments (Bahun, 1974). Jelar breccias mostly crop out on Velebit Mt., in the neighbouring Lika region and on some Kvarner islands (sheets of the Basic Geological Map of the former Yugoslavia, scale 1:100,000; Fig. 4).

The origin of the Jelar breccias seems to be among the most important issues for the interpretation of the orogenic evolution of the NE Adriatic region. I suggest that the detachments activated during the early-orogenic thin-skinned tectonics (Fig. 5b) were later reactivated as extensional features during the late exhumation phase of the orogen, when the megafeature of the Velebit Mt. anticline was formed. Probably narrow and deep extensional "troughs" (neo-autochthonous pull-apart basins cf. Pamić et al., 1998) were contemporaneously filled during extension with breccia deposits originated from collapsed successions above the detachments. Therefore, the thickness of the tectonosedimentary unit depends on the present-day position of the detachment surface. The thickness could be more than 1500 m, as evidenced from the Krk-1 borehole, situated in the central part of the island of Krk (Kvarner area — Đurasek et al., 1981; Fig. 4), within a narrow zone characterized by outcrops of the Jelar breccias.

Thus, the origin of the Jelar breccias must be related to a major mechanism which accommodated late-orogenic uplift of the very large Velebit Mt. anticline. I suggest that it was a large-scale divergent extension and gravity gliding of the thin-skinned uppermost Jurassic to Eocene successions of the DSWu on the limbs of the anticline. That is probably why the Jelar breccias on Velebit Mt. never cover older stratigraphic horizons than Upper Jurassic in the internal position of the periclinal breccia belt. In the external positions of the anticline the breccias cover younger stratigraphic horizons (Mamužić et al., 1969; Mamužić et al., 1970; Sokač et al., 1974; Velić et al., 1974; Fig. 5c). The original geometry of the exhumation process has been masked during the latest-orogenic wrench tectonics (Prelogović et al., 1995a; Picha, 2002).

In areas that are characterized by surface occurrences of low-angle thrusts (e.g. eastern Lika region, Chorowicz, 1975b, 1977), coarse carbonate breccias referred to as the Jelar formation (Bahun, 1985) are also characterized by very heterogeneous fragments (Lower Triassic to Cretaceous) and siliciclastic or calcitic matrix/cement. The breccias appear either in narrow belts encompassing low-angle tectonic contacts or along subvertical tectonic contacts striking generally N–S. Therefore, a final interpretation of the breccia genesis is probably similar to that of the Velebit Mt. Jelar breccias. However, the thin-skinned successions of the DNEu of eastern Lika are thicker than those of the DSWu on the Velebite Mt., since these were detached within Upper Permian to Lower Triassic clastics and evaporites. That is why the Jelar breccias in eastern Lika contain also Lower Triassic fragments, collapsed from the successions overlaying the detachments. The breccias along subvertical tectonic contacts could be related to neotectonic movements.

7.6. Shortening rate

Although faults along the External Dinarides are predominantly steep at the surface, low-angle thrust sheets are evident at some places (Trnovo, Snežnik Mt, Učka Mt., eastern Lika, etc., on related sheets of the Basic Geological Map of former Yugoslavia, scale 1:100,000). The differences in shortening rates within the thin-skinned sedimentary successions along strike of the External Dinarides are suggested by the map showing the distribution of the main tectonostratigraphic units (Fig. 4). A major shortening must be accommodated by thrusting within and between thin-skinned units during the first phase of the Dinaridic orogenic compression (i.e. NE–SW; Figs. 4 and 5b).

There is an inclination between WNW–ESE strike of the ANEu structures (central-southern Dalmatian islands), and general NW–SE strike of the typical Dinaridic structures (Fig. 4). Picha (2002) suggested that the central-southern Dalmatian islands (Brač, Hvar etc., Fig. 4) were formed along left-lateral strike–slip faults, conjugated to the major dextral NE Adriatic fault. However, surface data (sheets of the Basic Geological Map of Yugoslavia, scale 1:100,000) and the interpretation of the transverse seismic profiles show asymmetrical anticlines and reverse faults, both with southern vergence (Lawrence et al., 1995; Grandić et al., 1997). Although the structures could be related to both, thin-skinned and thick-skinned tectonics, a shortening within the ANEu must have taken place during the second phase of the Dinaridic orogenic compression (NNE–SSW; Fig. 5c), probably before the suggested strike–slip was activated.

A significant shortening below the here proposed detachments (Fig. 5) would be possible just in case of deeper crustal subduction of the Adriatic segment under the Dinaridic one (Herak, 1986; Tari, 2002; Schmid et al., 2008). However, in this paper shortening between the segments is considered to be of minor importance. Generally, Mesozoic stretching is compensated by the Cenozoic shortening within the basement of thin-skinned successions (Fig. 5). The basement is reversely upthrown in the collision zone of the segments, and is interpreted here as a frontal compressional antiform of the Dinaridic one (Fig. 5c).

Isolated and highly deformed pre-orogenic basinal and slope carbonates of the NE Adriatic trough (NEAT; Fig. 5) are compressed in the frontal collision zone of the segments, and thus the shortening must not be significant. SE of Split, the NEAT successions are probably transpressionally uplifted along the main zone of the NE Adriatic fault (Fig. 4).

Alternatively, the basinal carbonates can be considered as large blocks detached from their wider basinal domain underthrust during compression and incorporated in the frontal thrust zone. If so, the ACP and the NW extent of the Budva–Cukali Basin (the NEAT) are underthrust below Dinaridic thrusts (cf. Tari, 2002). However, the Bruvno well in the Lika area (Br-1 on Fig. 4) did not penetrate any basinal succession, although it reached Carboniferous clastics (Grandić et al., 1997). Thus, the only possible way to accommodate supposed underthrust basinal unit would be deeper crustal detachment placed within the base of sediments (below Paleozoic on Fig. 5c) or even deeper in the crust, as suggested by Schmid et al. (2008). In view of this, a significant shortening within the complete upper crust should be expected within the NE Adriatic region.

The amount of shortening could be numerically defined only by analysis of more precisely balanced geological sections across the External Dinarides. It is noteworthy that the highest estimate of the total shortening within the Southern Apennines is 300 km (Scrocca et al., 2005).

7.7. Late Neogene geodynamics

The NE Adriatic region is seismically active (Herak et al., 1996) as a result of wrench and escape tectonics (see the last paragraph of the Section 7.1). A few mm year^{-1} discrepancy between horizontal GPS velocities of the SE Adriatic segment in respect to the Dinaridic one (Bennett et al., 2008) could be accommodated rather by vertical tectonic transport along the NE Adriatic fault zone (transpression, Fig. 5c) than by active thrusting suggested by Bennett et al. (2008). The Central Adriatic area is also seismically active (Herak et al., 1996), and salt diapirism is probably contributing to the wrench tectonics (Grandić et al., 2001; Geletti et al., 2008; Korbar et al., 2009).

The latest tomographic images depict the position of the fragmented Adria lithosphere beneath the wider Adriatic region suggesting a scenario of divergent subduction of two lithospheric microplates (Piromallo and Morelli, 2003). The NW Adria deepens to the south below the northern Apennines, while the SE Adria deepens to the north below the central and eastern Dinarides (Fig. 7). The scenario highlights the significance of the central Adriatic transform zone that is supposed to strikes generally N–S (Fig. 7). The zone should be interpreted as complex active transform microplate boundary which is inferred also from GPS data (Oldow et al., 2002).

Present-day tectonic stress is generally N–S oriented in NW Dinarides while NE–SW oriented in the SW Dinarides (Bada et al., 2007). This discrepancy could be also related to the Adria fragmentation (Oldow et al., 2002) and proposed counterclockwise (CCW) rotation with respect to Africa since latest Miocene to early Pliocene time (Marton, 2006). However, if the divergent movements of the microplates and the transform zone indeed exist, the process would induce the re-organization of the pre-existing crustal blocks during this latest stage of the Adriatic plate geodynamic evolution.

8. Conclusive remarks

The Mesozoic paleogeography of the NE Adriatic region is still a matter of debate. Generally two regional paleogeographic models have been suggested previously: single carbonate platform (Adriatic = Adriatic–Dinaridic, ADCP) versus two carbonate platforms (Adriatic, ACP and Dinaridic, DCP), separated by the NW extension of the Budva–Cukali basin (BCB; Figs. 1 and 2). Accordingly, estimates of shortening within the region during the Cenozoic compression differ substantially. The single-platform model involves minor shortening achieved by folding and faulting along steep reverse faults. The two-platform model involves significant shortening achieved predominantly by thrust stacking, which resulted in the underthrusting of the interplatform basinal unit.

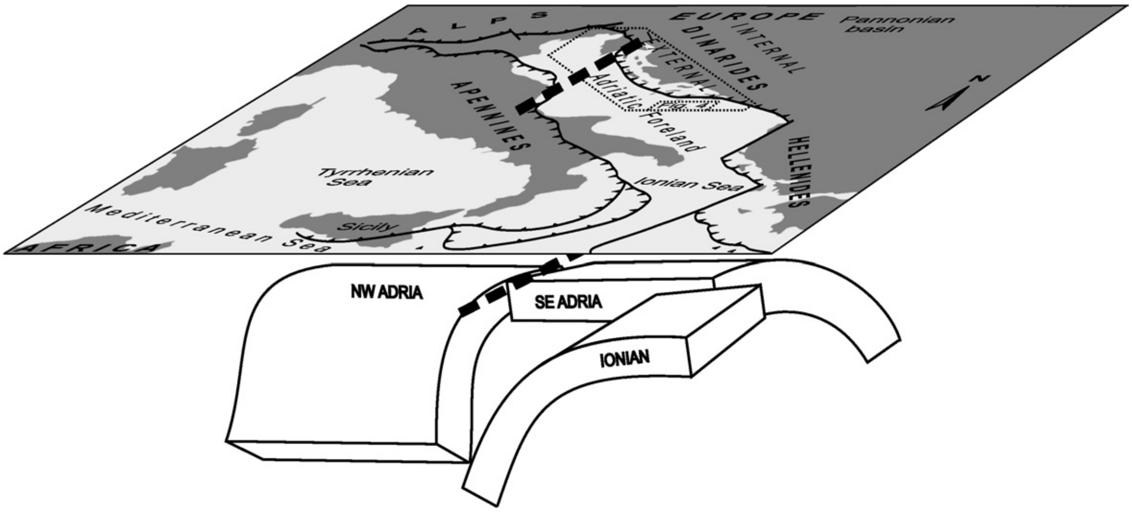

Fig. 7. Sketch of recent lithospheric microplates configuration below the wider Adriatic region (after the P wave tomography of Piromallo and Morelli, 2003). The hypothetical Central Adriatic transform zone is indicated on the map by thick dashed line.

The regional correlation of the Upper Cretaceous to Paleogene carbonates (Figs. 3 and 4), highlights the differences in synsedimentary tectonics, including subsidence (Fig. 5). Five tectonostratigraphic units are recognized (from NE to SW), related either to the DCP or the ACP domain: the Dinaridic NE unit (DNEu) or Inner Karst, the Dinaridic SW unit (DSWu) or High Karst, the NE Adriatic trough (NEAT), the Adriatic NE unit (ANEu) or Dalmatian Karst, and the Adriatic SW unit (ASWu) or Istrian Karst.

The NE Adriatic fault zone (Figs. 4 and 5) marks a deep-rooted Triassic lineament that was active during the pre-orogenic extension, and reactivated during orogenic compression. The lineament delimits two crustal entities of the Adriatic microplate (the Adria): Adriatic and Dinaridic segments. As inferred from position of the deepest seismic horizons, geomorphological and geological data, the segments are fragmented along transversal faults (Figs. 5 and 6). The fragments are today at different elevations, possibly as a consequence of isostatic rebound.

The main assumption of the model presented here is a shift from thin- to thick-skinned tectonic style during the Alpine orogenesis. The upper portions of the sedimentary cover were differentially affected by progressive, southwestward verging thin-skinned deformations during the Paleocene to Eocene (Miocene?). The Adriatic foreland stayed out of the deformations, and is characterized predominantly by wrench and salt tectonics. The along strike differences in tectonic styles are mostly related to the pre-orogenic distribution and stratigraphical position of the weakest horizons, acting as detachments, within the laterally different sedimentary successions.

The successions of the central part of the DNEu were detached during Paleocene within the Permian to Lower Triassic evaporites and clastics, representing the beginning of the early-orogenic, thin-skinned tectonic deformations in the region. The supra-evaporite successions (including the basement of the DCP) were thrust onto the DSWu. The DSWu sedimentary cover was detached during Eocene within the Upper Jurassic to Lower Cretaceous evaporite horizons (Fig. 5b) and thrust further to the SW. The thrust front of the DSWu is recognized offshore, SW of the Dugi Otok island. The Dinaridic overthrust thus propagated to the greatest extent over the Kvarner and Northern Dalmatia fragments of the ANEu, bordered at the NW by the dextral Kvarner fault zone, and at the SE by the Jabuka, Biševo and Vis faults (Figs. 4 and 6).

The inclination between the strikes of older DSWu structures (NW–SE) and younger ANEu structures (WNW–ESE) could be a consequence of the re-orientation of the regional tectonic stress from NE–SW to N–S during the Tertiary.

Intriguing late-orogenic tectonosedimentary features are two regionally important Upper Eocene to Oligocene (Miocene?) sedimentary units: the Promina formation and the Jelar breccias. The Promina formation is related to the propagation of the Dinaridic wedge over the Kvarner and Northern Dalmatia fragments that resulted in the formation of wedge-top (piggyback?) basin in the hinterland (Figs. 4 and 5b). However, the basin could have been formed also as a result of shift from thin- to thick-skinned tectonics. Nevertheless, more than 2000 m thick succession of predominantly clastics was deposited in the present day area of Ravni Kotari and Promina Mt. (Fig. 4). The Jelar breccias are predominantly unsorted polymictic carbonate breccias consisting of Jurassic, Cretaceous and Paleogene fragments. The breccias mostly crop out on Velebit Mt., in the neighbouring Lika region and on some Kvarner islands (Fig. 4). The origin of the Jelar breccias seems to be among the most important issues for the interpretation of the orogenic evolution of the NE Adriatic region. I suggest that the primarily thin-skinned detachments were later reactivated as extensional feature during thick-skinned syncompressional anticlinal uplift of the Dinaridic segment upper crust in the collision zone with the Adriatic one. Related extension and gravity gliding on the limbs of the anticline accommodated a very large amount of heterogeneous breccias originated from collapsed sedimentary successions above the detachment (Fig. 5c). Therefore, the thickness of the Jelar breccias depends on the present-day position of the detachment surface.

The latest-orogenic dextral escape tectonics along predominantly reactivated faults of the NE Adriatic fault zone (NW–SE) resulted in further structural re-arrangements during Neogene (e.g. flower, pop-up, and pull-apart structures, Figs. 4 and 5). The most obvious geomorphological evidence of the tectonic activity along the zone is the mountain range characterized by generally NW–SE (Dinaridic) strike (Fig. 4). A few mm year^{-1} discrepancy between horizontal GPS velocities of the SE part of the Adriatic segment in respect to the Dinaridic one could be accommodated rather by late-orogenic vertical tectonic transport along the NE Adriatic fault zone (transpression, Fig. 5c) than by active thrusting.

A major shortening within the NE Adriatic region must be accommodated by thin-skinned tectonics within and between the detached sedimentary cover of the tectonostratigraphic units during the first phase of the Dinaridic orogenic compression (NE–SW; Fig. 5b). The shortening within the basement of the thin-skinned cover is considered to be minor, since the Mesozoic stretching is generally compensated by the Cenozoic shortening (Fig. 5). The basement is reversely upthrown in the collision zone of the Adriatic and Dinaridic segments, and is interpreted here as a frontal compressional antiform of the Dinaridic one (Figs. 5c and 6).

Alternatively, the ACP and the NW extent of the Budva–Cukali Basin (the NEAT) are deeply underthrust below the Dinaridic thrusts. However, there are neither outcrop nor borehole evidences of the basinal successions. Thus, the only possible way to accommodate underthrust basinal deposits would be deeper detachment placed within the base of the sedimentary units (below Paleozoic on Fig. 5c) or even deeper in the crust.

The latest tomographic images depict the position of the fragmented Adria lithosphere beneath the Adriatic region, suggesting a scenario of divergent subduction of two lithospheric microplates: the SE Adria to the north, and the NW Adria to the south. Consequently, the pre-existing upper crustal structures related to the previous Dinaridic and Apenninic deformations are supposed to have been re-organized during this latest stage of the Adriatic plate geodynamic evolution.

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References

Aljinović, B., 1986. Karta dubina Mohorovičićeva diskontinuiteta na području Jugoslavije (Depth map of the Mohorovičić discontinuity in the Yugoslavian region). Nafta (Zagreb) 37/3, 127–130.
Aljinović, B., Blašković, I., 1981. O plohi dubokih seizmičkih horizonata sjeveroistočnog Jadrana (About the deep seismic horizon in the offshore adriatic area). In: Šolc, A. (Ed.), Kompleksna naftno-geološka problematika podmorja i priobalnih dijelova Jadranskog mora (Complex Oil-geological Aspects for Offshore and Coastal Adriatic Areas), Split, Zbornik radova (Proceedings) I, pp. 363–380.
Aljinović, B., Prelogović, E., Skoko, D., 1987. Novi podaci o dubinskoj geološkoj građi i seizmotektonski aktivnim zonama u Jugoslaviji (New data on deep geological structure and seismotectonic active zone in region of Yugoslavia). Geološki Vjesnik 40, 255–263.
Aubouin, J., Blanchet, R., Cadet, J.P., Celet, P., Charvet, J., Chorowicz, J., Cousin, M., Rampnoux, J.P., 1970. Essai sur la géologie des Dinarides. Bulletin de la Societe Geologique de France 12/6, 1060–1095.
Babić, Lj., Zupanič, J., 1983. Paleogene clastic formations in northern Dalmatia. In: Babić, Lj., Jelaska, V. (Eds.), Contribution to Sedimentology of Some Carbonate and Clastic Units of Coastal Dinarides, Excursion Guide-book, 4th I.A.S. regional meeting, Split, pp. 37–61.
Babić, Lj., Kučenjak, M.H., Ćorić, S., Zupanič, J., 2007. The Middle Eocene age of the supposed late Oligocene sediments in the flysch of the Pazin Basin (Istria, outer Dinarides). Natura Croatica 16/2, 83–103.
Bada, G., Horváth, F., Dövényi, P., Szafián, P., Windhoffer, G., Cloetingh, S., 2007. Present-day stress field and tectonic inversion in the Pannonian basin. Global and Planetary Change 58, 165–180.
Bahun, S., 1974. Tektogeneza Velebita i postanak Jelar-naslaga (The tectogenesis of Mt. Velebit and the formation of Jelar-deposits). Geološki Vjesnik 27, 35–51.
Bahun, S., 1985. Trijaske naslage i Jelar-formacija u dolini Une između Srba i Brotnje (Hrvatska) (Triassic deposits and Jelar Formation in the Una Valley between Srb and Brotnja (Croatia). Geološki Vjesnik 38, 21–30.
Bennett, R.A., Hreinsdóttir, S., Buble, G., Bašić, T., Bačić, Ž., Marjanović, M., Casale, G., Gendaszek, A., Cowan, D., 2008. Eocene to present subduction of southern Adria mantle lithosphere beneath the Dinarides. Geology 36/1, 3–6. doi10.1130/G24136A.1.
Bignot, G., 1972. Recherches Stratigraphiques sur les Calcaires du Crétacé Supérior et de l'Eocene d'Istrie et des Régions Voisines — Essai de Révision du Liburnien. Travaux du Laboratorie de Micropaléontologie, vol. 2. 353 pp.
Blašković, I., 1969. Geološki odnosi središnjeg dijela Ćićarije (Geologische verhältnisse des Mittleren teils von Ćićarija). Geološki Vjesnik 22, 33–54.
Bosellini, A., 1989. Dynamics of Tethyan carbonate platforms. In: Crevello, P.D., Wilson, J.L., Sarg, J.F., Read, J.F. (Eds.), Controls on Carbonate Platform and Basin Development. SEPM Special Publication, vol. 44. pp. 2–13.
Bosellini, A., 2002. Dinosaurs "re-write" the geodynamics of the eastern Mediterranean and paleogeography of the Apulia Platform. Earth-Science Reviews 59 (1–4), 211–234.
Buser, S., 1989. Development of the Dinaric and Julian carbonate platforms and of the intermediate Slovenian basin (NW Yugoslavia): Mem. Soc. Geol. It., vol. 40, pp. 313–320.
Cadet, J.-P., 1978. Essai sur l'évolution alpine d'une paléomarge continentale: les confins de la Bosnie-Herzégovine et du Monténégro (Yougoslavie): Mem. Soc. Géol. France, vol. 133, pp. 1–84.
Cassinis, R., 2006. Reviewing pre-TRANSALP DSS models. Tectonophysics 414, 79–86.
Cati, A., Sartorio, D., Venturini, S., 1989a. Carbonate Platforms in the Subsurface of the Northern Adriatic Area: Mem. Soc. Geol. It., vol. 40, pp. 295–308.
Cati, A., Fichera, R., Cappelli, V., 1989b. Northeastern Italy. Integrated processing of geophysical and geological data: Mem. Soc. Geol. It., vol. 40, pp. 273–288.
Channell, J.E.T., D'Argenio, B., Horvath, F., 1979. Adria, the African promontory, in Mesozoic Mediterranean palaeogeography. Earth-Science Reviews 15, 213–292.
Chorowicz, J., 1974. Le chevauchement du Velebit (Croatie, Yougoslavie). Bulletin de la Societe Geologique de France 7/16, 74–85.
Chorowicz, J., 1975a. Le devenir de la zone de Budva vers le Nord-Ouest de la Yougoslavie. Bulletin de la Societe Geologique de France 7/17, 699–709.
Chorowicz, J., 1975b. Le mécanisme de la structure transversale Split-Karlovac, dans les Dinarides yougoslaves: C. R. Acad. Sc. Paris, vol. (D) 280, pp. 2313–2316.
Chorowicz J., 1977. Étude géologique des Dinarides le long de la structure transversale Split-Karlovac. Thèse Univ. Pierre et Marie Curie, Paris, 322 pp.
Ciarapica, G., Passeri, L., 2005. Late Triassic and Early Jurassic sedimentary evolution of the Northern Apennines: an overview. Bollettino della Societa Geologica Italiana 124/1, 189–201.
Corrado, S., Di Bucci, D., Naso, G., Faccenna, C., 1998. Influence of palaeogeography on thrust system geometries: an analogue modelling approach for the Abruzzi–Molise (Italy) case history. Tectonophysics 296, 437–453.
Ćosović, V., Drobne, K., Moro, A., 2004. Paleoenvironmental model for Eocene foraminiferal limestones of the Adriatic carbonate platform (Istrian Peninsula). Facies 50, 61–75.
Ćosović, V., Premec Fuček, V., Gušić, I., Jelaska, V., Moro, A., 2006. The age of the Tilovica breccias in Central Dalmatia, Croatia. Micropaleontology 52/3, 281–286.
Cousin, M., 1970. Esquisse géologique des confins italo-yougoslaves: leur place dans les Dinarides et les Alpes méridionales: Bull. Soc. Géol. France, vol. 12/6, pp. 1060–1095.
Cucchi, F., Pirini Radrizzani, C., Pugliese, N., 1989a. The carbonate stratigraphic sequence of the Karst of Trieste (Italy): Mem. Soc. Geol. Ital., vol. 40, pp. 35–44.
Cucchi, F., Vaia, F., Finocchiaro, F., 1989b. The geology of T. Rosandra valley (Karst of Trieste, Italy): Mem. Soc. Geol. Ital., vol. 40, pp. 67–72.
Cvetko Tešović, B., Gušić, I., Jelaska, V., Bucković, D., 2001. Stratigraphy and microfacies of the Upper Cretaceous Pučišća Formation, Island of Brač, Croatia. Cretaceous Research 22, 591–613.
D'Argenio, B., Radoičić, R., Sgrosso, I., 1971. A paleogeographic section through the Italo-dinaric external zones during Jurassic and Cretaceous Times. Nafta (Zagreb) 22/4-5, 195–207.
De Capoa, P., Radoičić, R., 2002. Geological Implications of Biostratigraphic Studies in the External and Internal Domains of the Central-Southern Dinarides: Mem. Soc. Geol. It., vol. 57, pp. 185–191.
De Capoa, P., Radoičić, R., D'Argenio, B., 1995. Late Miocene Deformation of the External Dinarides (Montenegro and Dalmatia): New Biostratigraphic Evidence: Mem. Sci. Geol., vol. 47, pp. 157–172. Department of Geosciences, University of Padova.
Del Ben, A., 2002. Interpretation of the CROP M-16 Seismic Section in the Central Adriatic Sea: Mem. Soc. Geol. It., vol. 57, pp. 327–333.
Dercourt, J., Zonenshain, L.P., Ricou, L.E., Kazmin, V.G., Le Pichon, X., Knipper, A.L., Grandjacquet, C., Sbortshikov, I.M., Geyssant, J., Lepvrier, C., Pechersky, D.H., Boulin, J., Sibuet, J.C., Savostin, L.A., Sorokhtin, O., Westphal, M., Bazhenov, M.L., Lauer, J.P., Biju-Duval, B., 1986. Geological evolution of the Tethys belt from the Atlantic to Pamirs since the Lias. Tectonophysics 123, 214–315.
Dercourt, J., Gaetani, M., Vrielynck, B., Barrier, E., Biju-Duval, B., Brunet, M.F., Cadet, J.P., Crasquin, S., Sandulescu, M., 2000. Atlas Peri-Tethys, Palaeogeographical maps. CCGM/CGMW, Paris: 24 maps and explanatory notes: I–XX, 269 pp.
Dragičević, I., Blašković, I., Tišljar, J., Benić, J., 1992. Stratigraphy of Paleogene strata within the Mesihovina–Rakitno Area (Western Herzegovina). Geologia Croatica 45, 25–52.
Dragičević, I., Prelogović, E., Kuk, V., Buljan, R., 1999. Recent tectonic activity in the Imotsko polje Area. Geologia Croatica 52/2, 191–196.
Drobne, K., 1977. Alvéolines paléogènes de la Slovénie et de l'Istrie. Mémoires suisses de Paléontologie, vol. 99. 174 pp.
Drobne, K., Trutin, M., 1997. Alveolinas From the Bunić Section (Lika, Croatia). Geologia Croatica 50/2, 215–223.
Drobne, K., Ogorelec, B., Pleničar, M., Barattolo, F., Turnšek, D., Zucchi-Stolfa, M.L., 1989. The Dolenja Vas Section, a Transition from Cretaceous to Paleocene in the NW Dinarides, Yugoslavia: Mem. Soc. Geol. It., vol. 40, pp. 73–84.
Đurasek, N., Frank, G., Jenko, K., Kužina, A., Tončić-Gregl, R., 1981. Prilog poznavanju naftno-geoloških odnosa u sjeverozapadnom dijelu jadranskog podmorja

(Contribution to the understanding of oil-geological relations in NW Adriatic area). In: Šolc, A. (Ed.), Kompleksna naftno-geološka problematika podmorja i priobalnih dijelova Jadranskog mora (Complex Oil-geological Aspects for Offshore and Coastal Adriatic Areas), Split, Zbornik radova (Proceedings) I, pp. 201–213.

Faupl, P., Pavlopoulos, A., Migiros, G., 2002. Provenance of the Peloponnese (Greece) flysch based on heavy minerals. Geological Magazine 139, 513–524.

Finetti, I., Bricchi, G., Del Ben, A., Pipan, M., Xuan, Z., 1989. Geophysical Study of the Adria Plate: Mem. Soc. Geol. It., vol. 40, pp. 335–344.

Fleury, J.J., 1980. Les zones du Gavrovo–Tripolitza et du Pinde–Olonos (Grèce Continentale et Péloponnèse du Nord). Évolution d'une plate-forme et d'un bassin dans leur cadre alpin (Gavrovo–Tripoli and Pinde–Olonos zone (Continental Greece and North Peleponnese). Evolution of platform and basin within its Alpine development). Publication, vol. 4. Société Géologique du Nord, Villeneuve d'Ascq. 651 pp.

Fuček, L., Jelaska, V., Gušić, I., Prtoljan, B., Oštrić, N., 1991. Padinski turonski sedimenti uvale Brbišnica na Dugom otoku (Turonian slope deposits in the Brbišnica cove, Dugi Otok Island, Croatia). Geološki Vjesnik 44, 55–67.

Geletti, R., Del Ben, A., Busetti, M., Ramella, R., Volpi, V., 2008. Gas seeps linked to salt structures in the Central Adriatic Sea. Basin Research 20, 473–487. doi10.1111/j.1365-2117.2008.00373.x.

GKRH (2009): Geološka karta Republike Hrvatske (Geological Map of the Republic of Croatia) scale 1:300.000, Hrvatski geološki institut (Croatian Geological Survey, Zagreb), 1 sheet.

GKSFRJ (1970): Geološka karta SFR Jugoslavije (Geological Map of the SFR Yugoslavia) scale 1:500.000, Savezni geološki Zavod, Beograd (Federal geological Institute, Belgrade), 1 sheet.

Grandić, S., 1974. Neke naftnogeološke karatkteristike naslaga Vanjskih Dinarida (Some regional petroleum geological characteristics of the External Dinarides deposits). Nafta (Zagreb) 25/3, 111–120.

Grandić, S., Boromisa-Balaš, E., Šušterčić, M., 1997. Exploration concept and characteristics of the stratigraphic and structural models of the Dinarides in Croatian offshore area. Nafta (Zagreb) 48/8–9, 249–266.

Grandić, S., Boromisa-Balaš, E., Šušterčić, M., Kolbah, S., 1999. Hydrocarbon possibilities in the Eastern Adriatic Slope zone of Croatian offshore area. Nafta (Zagreb) 50/2, 51–73.

Grandić, S., Biancone, M., Samaržija, J., 2001. Geophysical and stratigraphic evidence of the Triassic rift structuration in the Adriatic offshore area. Nafta (Zagreb) 52/12, 383–396.

Grandić, S., Veseli, V., Kolbah, S., 2002. Hydrocarbon potential of Dugi otok basin in offshore Croatia. Nafta (Zagreb) 53/6–7, 215–224.

Gušić, I., Jelaska, V., 1990. Stratigrafija gornjokrednih naslaga otoka Brača u okviru geodinamske evolucije Jadranske karbonatne platforme (Upper Cretaceous stratigraphy of the Island of Brač within the geodynamic evolution of the Adriatic carbonate platform). Djela Jugoslavenske akademije znanosti i umjetnosti. OOUR za geologiju, vol. 69. Institut za geološka istraživanja, Zagreb. 160 pp.

Gušić, I., Jelaska, V., 1993. Upper Cenomanian–Lower Turonian sea-level rise and its consequences on the Adriatic–Dinaric carbonate platform. Geologische Rundschau 82/4, 676–686.

Herak, M., 1980. Sustav navlaka između Vrbovskog i Delnica u Gorskom kotaru (The nappe-system between Vrbovsko and Delnice in Gorski kotar (Croatia). Acta Geologica (Zagreb) 10/2, 35–51.

Herak, M., 1986. A new concept of geotectonics of Dinarides. Jugoslavenska akademija znanosti i umjetnosti: Acta geologica, vol. 16, pp. 1–42.

Herak, M., 1987. Relationship Between Adriatic and Dinaric Carbonate Platforms: Mem. Soc. Geol. It., vol. 40, pp. 289–293.

Herak, M., Bojanić, L., Šikić, D., Magdalenić, A., 1961. Novi elementi tektonike u području gornjeg toka rijeke Kupe. Geološki Vjesnik 14, 245–251.

Herak, Ma., Herak, D., Markušić, S., 1996. Revision of the earthquake catalogue and seismicity in Croatia (1908–1992). Terra Nova 8, 86–96.

Ilić, A., Neubauer, F., 2005. Tertiary to recent oblique convergence and wrenching of the Central Dinarides: constraints from a palaeostress study. Tectonophysics 410, 465–484.

Jelaska, V., 2002. Carbonate platforms of the External Dinarides. In: Vlahović, I., Tišljar, J. (Eds.), Evolution of Depositional Environments from the Palaeozoic to the Quaternary in the Karst Dinarides and Pannonian Basin, 22nd IAS Meeting of Sedimentology, Opatija, Field Trip Guidebook, pp. 67–71.

Jelaska, V., Amšel, V., Kapović, B., Vuksanović, B., 1969. Sedimentološke karakteristike klastične gornje krede zapadnog dijela Bosanske Krajine (Sedimentological characteristics of the clastic Upper Cretaceous of the western part of Bosanska Krajina). Nafta (Zagreb) 20/10, 487–495.

Jelaska, V., Gušić, I., Jurkovšek, B., Ogorelec, B., Ćosović, V., Šribar, L., Toman, M., 1994. The Upper Cretaceous geodynamic evolution of the Adriatic–Dinaric carbonate platform(s). Géologie Méditerranéenne 21/3–4, 89–91.

Jelaska, V., Benček, Đ., Matičec, D., Belak, M., Gušić, I., 2000. Geološka povijest i strukturna evolucija Vanjskih Dinarida (Geological history and structural evolution of the Outer Dinarides). In: Vlahović, I., Biondić, R. (Eds.), Hrvatski Geološki Kongres (Second Croatian Geological Congress), Cavtat–Dubrovnik, Vodič ekskurzija (Excursion Guide-Book), A-1, vol. 2, pp. 1–12.

Jelaska, V., Benček, Đ., Cvetko Tešović, B., Ćosović, V., Gušić, I., Ištuk, Ž., Matičec, D., 2003. Platform dynamics during the Late Cretaceous and Early Palaeogene — External Dinarides, Dalmatia. In: Vlahović, I., Tišljar, J. (Eds.), Evolution of Depositional Environments from the Palaeozoic to the Quaternary in the Karst Dinarides and Pannonian Basin, 22nd IAS Meeting of Sedimentology, Opatija, Field Trip Guidebook, pp. 101–107.

Jenkyns, H.C., 1991. Impact of Cretaceous sea level rise and anoxic events on the Mesozoic carbonate platform of Yugoslavia. AAPG Bulletin 75/6, 1007–1017.

Jerinić, G., Jelaska, V., Alajbeg, A., 1994. Upper Cretaceous organic-rich laminated limestones of the Adriatic Carbonate Platform, Island of Hvar, Croatia. AAPG Bulletin 78/8, 1313–1321.

Jurkovšek, B., Toman, M., Ogorelec, B., Šribar, L., Drobne, K., Poljak, M., Šribar, L., 1996. Formacijska geološka karta južnega dela Tržaško-komenske planote. Kredne in paleogenske karbonatne kamnine. 1:50000 (Geological map of the southern part of the Trieste-Komen plateau. Cretaceous and Paleogene carbonate rocks). Inštitut za geologio, geotehniko in geofiziko Ljubljana, 143 pp.

Kapović, B., Bauer, V., 1971. Rezultati stratimetrijskog snimanja gornje krede Dugog otoka i otoka Premude (Results of stratigraphic measurements of Upper Cretaceous on the Dugi Otok and Premuda islands). Nafta (Zagreb) 22/4–5, 467–471.

Korbar, T., 2003. Stratigrafija, taksonomija i paleoekologija radiolitida gornje krede Jadranske karbonatne platforme (Stratigraphy, taxonomy and palaeoecology of Upper Cretaceous Radiolitidae of the Adriatic Carbonate Platform). Unpublished PhD Thesis, University of Zagreb, Croatia (in Croatian with English summary), 242 pp.

Korbar, T., Husinec, A., 2003. Biostratigraphy of Turonian to (?)Coniacian platform carbonates: a case study from the Island of Cres (Northern Adriatic, Croatia). Geologia Croatica 56/2, 173–185.

Korbar, T., Fuček, L., Husinec, A., Vlahović, I., Oštrić, N., Matičec, D., Jelaska, V., 2001. Cenomanian carbonate facies and rudists along shallow intraplatform basin margin — the Island of Cres (Adriatic Sea, Croatia). Facies 45, 39–58.

Korbar, T., Montanari, A., Koch, G., Mariani, S., DePaolo, D., Turchyn, V.A., Mikność, M., Tari, V., 2009. Geologic reconnaissance of the island of Velika Palagruža (central Adriatic, Croatia). Geologia Croatica 62/2, 75–94. doi10.4154/gc.2009.07154.

Lawrence, S.R., Tari-Kovačić, V., Gjukić, B., 1995. Geological evolution model of the Dinarides. Nafta (Zagreb) 46/2, 103–113.

Mamužić, P., Milan, A., Korolija, B., Borović, I., Majcen, Ž., 1969. Osnovna geološka karta SFRJ, list Rab 1:100 000, L 33-114 (Basic Geological Map of SFRY: Sheet Rab, scale 1:100 000, K 33-114). Inst. geol. istraž. Zagreb, 1959–1965., Sav. geol. zavod Beograd, 1 sheet.

Mamužić, P., Sokač, B., Velić, I., 1970. Osnovna geološka karta SFRJ, list Silba, M 1:100 000, L 33-126 (Basic Geological Map of SFRY: Sheet Silba, scale 1:100 000, K 33-126). Inst. geol. istraž. Zagreb (1963–1969), Sav. geol. zavod, Beograd, 1 sheet.

Mandić, O., Pavelić, D., Harzhauser, M., Zupanič, J., Reischenbacher, D., Sachsenhofer, R.F., Tadej, N., Vranjković, A., 2009. Depositional history of the Miocene Lake Sinj (Dinaride Lake System, Croatia): a long-lived hard-water lake in a pull-apart tectonic setting. Journal of Paleolimnology 41/3, 431–452. doi10.1007/s10933-008-9235-1.

Marinčić, S., 1981. Eocenski fliš jadranskog pojasa (Eocene flysch of Adriatic area). Geološki Vjesnik 34, 27–38.

Marjanac, T., Babac, D., Benić, J., Ćosović, V., Drobne, K., Marjanac, Lj., Pavlovec, R., Velimirović, Z., 1998. Eocene carbonate sediments and sea-level changes on the NE part of Adriatic carbonate platform (island of Hvar and Pelješac peninsula). In: Hottinger, L., Drobne, K. (Eds.), Paleogene Shallow Benthos of the Tethys, Dela, vol. 34/2, Slovenska akademija znanosti in umetnosti (SAZU). Znanstvenorazisko-valni center, Ljubljana, pp. 43–254.

Marton, E., 2006. Paleomagnetic evidence for Tertiary counterclockwise rotation of Adria with respect to Africa. In: Pinter, N., et al. (Ed.), The Adria Microplate: GPS Geodesy, Tectonics and Hazards. Springer, pp. 71–80.

Marton, E., Drobne, K., Ćosović, V., Moro, A., 2003. Palaeomagnetic evidence for Tertiary counterclockwise rotation of Adria. Tectonophysics 377, 143–156.

Massoli, D., Koyi, H.A, Barchi, M.R., 2006. Structural evolution of a fold and thrust belt generated by multiple décollements: analogue models and natural examples from the Northern Apennines (Italy). Journal of Structural Geology 28, 185–199.

Matičec, D., 1994. Neotectonic deformations in Western Istria, Croatia. Geologia Croatica 47/2, 199–204.

Matičec, D., Vlahović, I., Velić, I., Tišljar, J., 1996. Eocene limestone overlying Lower Cretaceous deposits of Western Istria (Croatia): did some parts of present Istria form land during the Cretaceous? Geologia Croatica 49/1, 117–127.

Matičec, D., Vlahović, I., Fuček, L., Oštrić, N., Velić, I., 1997. Stratigraphy and tectonic relationships along the Senj–gulin Profile (Velika Kapela Mt., Croatia). Geologia Croatica 50/2, 261–268.

Merlini, S., Doglioni, C., Fantoni, R., Ponton, M., 2002. Analisi strutturale lungo un profilo geologico tra la linea Fella–Sava e l'avampaese adriatico (Friuli Venezia Giulia—Italia): Mem. Soc. Geol. It., vol. 57, pp. 293–300.

Mezga, A., Meyer, C.A., Cvetko Tešović, B., Bajraktarević, Z., Gušić, I., 2006. The first record of dinosaurs in the Dalmatian part (Croatia) of the Adriatic–Dinaridic carbonate platform (ADCP). Cretaceous Research 27/6, 735–742.

Mikes, T., Dunkl, I., Frisch, W., von Eynatten, H., 2006. Geochemistry of Eocene flysch sandstones in the NW External Dinarides. Acta Geologica Hungarica 49/2, 103–124.

Moro, A., Jelaska, V., 1994. Upper Cretaceous peritidal deposits of Olib and Ist islands (Adriatic Sea, Croatia). Geologia Croatica 47/1, 53–65.

Moro, A., Korbar, T., Skelton, P.W., Velić, I., Tišljar, J., Vlahović, I., Fuček, L., Matičec, D., Ćosović, V., 2002. Upper Santonian rudist-bearing lithosomes formed in the transition from deeper to shallower subtidal environments. In: Vlahović, I., Korbar, T. (Eds.), 6th International Congress on Rudists, Rovinj, Abstracts and Excursion Guidebook. Institute of Geology, Zagreb, pp. 133–139.

Oldow, J.S., Ferranti, L., Lewis, D.S., Campbell, J.K., D'Argenio, B., Catalano, R., Pappone, G., Carmignani, L., Conti, P., Aiken, C.L.V., 2002. Active fragmentation of Adria, the north African promontory, central Mediterranean region. Geology 30/9, 779–782.

Otoničar, B., 2007. Upper Cretaceous to Paleogene forbulge unconformity associated with foreland basin evolution (Kras, Matarsko podolje and Istria; SW Slovenia and NW Croatia). Acta Carsologica 36/1, 101–120.

Pamić, J., Gušić, I., Jelaska, V., 1998. Geodynamic evolution of Central Dinarides. Tectonophysics 297, 273–307.

Pavšič, J., 1994. Biostratigraphy of Cretaceous, Paleocene and Eocene clastics of Slovenia. Razprave 4. razr. SAZU (Slovenian Academy of Sciences and Arts), vol. 35. Ljubljana, pp. 65–84.

Picha, F.J., 2002. Late orogenic strike–slip faulting and escape tectonics in frontal Dinarides–Hellenides, Croatia, Yugoslavia, Albania and Greece. AAPG Bulletin 86/9, 1659–1671.

Piromallo, C., Morelli, A., 2003. P wave tomography of the mantle under the Alpine–Mediterranean area. Journal of Geophysical Research 108 (B2). doi10.1029/2002jb001757 (2065).
Placer, L., 1981. Geološka zgradba jugozahodne Slovenije (Geologic structure of southwestern Slovenia). Geologija 24/1, 27–60.
Placer, L., Košir, A., Popit, T., Šmuc, A., Juvan, G., 2004. The Buzet Thrust Fault in Istria and overturned carbonate megabeds in the Eocene flysch of the Dragonja Valley (Slovenia). Geologija 47/2, 193–198.
Pleničar, M., 1959. Tektonski okni pri Knežaku (Tectonic windows at Knežak). Geologija 5, 5–10.
Prelogović, E., Aljinović, B., Bahun, S., 1995a. New data on structural relationships in the Northern Dalmatian Dinaride Area. Geologia Croatica 48/2, 167–176.
Prelogović, E., Kuk, V., Jamičić, D., Aljinović, B., Marić, K., 1995b. Seizmotektonska aktivnost Kvarnerskog područja. In: Vlahović, I., Velić, I., Šparica, M. (Eds.), Proceedings of the First Croatian Geological Congress. Opatija, vol. 2. Croatian geological society and Institute of geology, pp. 487–490.
Prtoljan, B., Jamičić, D., Cvetko Tešović, B., Kratković, I., Markulin, Ž., 2007. The influence of Late Cretaceous synsedimentary deformation on the Cenozoic structuration of the middle Adriatic, Croatia. Geodinamica Acta 20/5, 287–300.
Pugliese, N., Drobne, K., Barattolo, F., Caffau, M., Galvani, R., Kedves, M., Montenegro, M.E., Pirini-Radrizzani, C., Pleničar, M., Turnšek, D., 1995. Micro- and macro-fossils from *K*/*T* boundary through Paleocene in the Northern Adriatic Platform. In: Vlahović, I., Velić, I., Šparica, M. (Eds.), Proceedings of the First Croatian Geological Congress, vol. 1. Croatian geological society and Institute of geology, Opatija, pp. 505–513.
Radoičić, R., 1970. Prilog poznavanju geologije Pelješca i paleogeografije ovog dijela spoljašnih Dinarida (A study of the geology of Pelješac peninsula and the paleogeography of this part of the outer Dinarides). Vesnik (Belgrade) 28, 175–184.
Radoičić, R., DeCapoa, P., D'Argenio, B., 1991. Middle-late Miocenic age of the preorogenic sedimentation in the Dinaric carbonate platform domain of Herzego-vina. Annales Geolgiques de la Peninsule Balkanique 55/2, 1–21.
Robertson, A., Shallo, M., 2000. Mesozoic–Tertiary tectonic evolution of Albania in its regional Eastern Mediterranean context. Tectonophysics 316, 197–254.
Rosenbaum, G., Lister, G.S., 2005. The Western Alps from the Jurassic to Oligocene: spatio-temporal constraints and evolutionary reconstructions. Earth-Science Reviews 69/3–4, 281–306.
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 Geoscience 101, 139–183. doi10.1007/s00015-008-1247-3.
Scrocca, D., Carminati, E., Doglioni, C., 2005. Deep structure of the southern Apennines, Italy: thin skinned or thick-skinned? Tectonics 24/3, 1–20.
Skourlis, K., Doutsos, T., 2003. The Pindos Fold-and-thrust belt (Greece): inversion kinematics of a passive continental margin. International Journal of Earth Sciences 92, 891–903.
Slišković, T., 1968. Biostratigrafija gornje krede južne Hercegovine (Upper Cretaceous biostratigrapy of the southern Herzegovina). Zemaljski muzej Bosne i Hercegovine, Sarajevo: Glasnik, vol. 13, pp. 23–51.
Slišković, T., 1983. Rezultati novijih istraživanja biostratigrafije i paleogeografskih odnosa mlađeg senona u okolici Stoca (Hercegovina) (Results of recent studies on the biostratigraphic and paleogeographic relations of the younger Senonian in the environ of Stolac (Herzegovina). Zemaljski muzej Bosne i Hercegovine, Prirodne nauke, Sarajevo: Glasnik, vol. 22, pp. 1–18.
Sokač, B., Nikler, L., Velić, I., Mamužić, P., 1974. Osnovna geološka karta SFRJ, list Gospić 1:100 000, L 33–127. (Basic Geological Map of SFRY: Sheet Gospić, scale 1:100 000, L 33–127), Inst. geol. istraž. Zagreb, 1963–1967., Sav. geol. zavod Beograd, 1 sheet.
Stache, G., 1889. Die Liburnische Stufe und deren Grenz—Horizonte: Abh. Geol. Reichsanst., vol. 13. 170 pp.
Steuber, T., Korbar, T., Jelaska, V., Gušić, I., 2005. Strontium-isotope stratigraphy of Upper Cretaceous platform carbonates of the island of Brač (Adriatic Sea, Croatia): implications for global correlation of platform evolution and biostratigraphy. Cretaceous Research 26/5, 741–756.
Šiftar, D., 1986. Starost evaporita u području Sinj-gornji tok Une (The age of evaporites in the zone Sinj-upper Una valley). Geološki Vjesnik 39, 55–60.
Šušnjara, A., Sakač, K., Jelen, B., Gabrić, A., 1992. Upper Permian evaporites and associated rocks of Dalmatia and borderline area of Lika and Bosnia. Geologia Croatica 45, 95–114.
Tari, V., 2002. Evolution of the Northern and Western Dinarides: A Tectonostratigraphic Approach. European Geosciences Union: Stephan Mueller Special Publication Series, vol. 1, pp. 223–236.
Tari-Kovačić, V., 1997. The development of the Eocene Platform carbonates from wells in the Middle Adriatic off-shore Area, Croatia. Geologia Croatica 50/1, 33–48.
Tari Kovačić, V., Mrinjek, E., 1994. The role of Palaeogene clastics in the tectonic interpretation of Northern Dalmatia (Southern Croatia). Geologia Croatica 47/1, 127–138.
Tari-Kovačić, V., Kalac, K., Lučić, D., Benić, J., 1998. Stratigraphic analysis of Paleogene beds in some off-shore wells (Central Adriatic Area, Croatia). In: Hottinger, L., Drobne, K. (Eds.), Paleogene shallow benthos of the Tethys, Dela, vol. 34/2, Slovenska akademija znanosti in umetnosti (SAZU). Znanstvenoraziskovalni center, Ljubljana, pp. 203–242.
Tončić-Gregl, R., Prpić, N., 1971. Litološke, petrofizičke, biostratigrafske i kronostrati-grafske karakteristike dubokih istražnih bušotina Ravni Kotari-3, Dugi otok-1 i Premuda-1. Nafta (Zagreb) 22/4–5, 472–484.
Trincardi, F., Cattaneo, A., Correggiari, A., Ridente, D., 2004. Evidence of soft sediment deformation, fluid escape, sediment failure and regional weak layers within the late Quaternary mud deposits of the Adriatic Sea. Marine Geology 213, 91–119.
Turk, M., 1971. Građa tercijarnog bazena u sjeveroistočnom dijelu Jadranskog mora (Structure of Tertiary basin in the northeastern Adriatic). Nafta (Zagreb) 22/4–5, 275–282.
Velić, I., Vlahović, I., 1994. Foraminiferal assamblages in the Cenomanian of the Buzet–Savudria area (northwestern Istria, Croatia). Geologia Croatica 47/1, 25–44.
Velić, I., Bahun, S., Sokač, B., Galović, I., 1974. Osnovna geološka karta SFRJ, list Otočac 1:100 000, L 33–115 (Basic Geological Map of SFRY: Sheet Otočac, scale 1:100 000, L 33–115). Inst. geol. istraž. Zagreb, 1970., Sav. geol. zavod Beograd, 1 sheet.
Venturini, S., 2002. Il pozzo Cargnacco 1: un punto di taratura stratigrafica nella pianura friulana (The well Caragnacco 1: a stratigraphic reference in the Friuli plain (northeastern Italy). Memorie della Societa Geologica Italiana 57, 11–18.
Venturini, S., Sartorio, D., Tentor, M., Tunis, G., 2008. Bauxitic deposits in the Cenomanian–Santonian succession of Monte Sabotino (Gorizia, NE Italy): new stratigraphic data and palaeographic implications concerning the North-Eastern sector of the Friuli Platform. Bollettino della Societa Geologica Italiana (Italian Journal of Geoscience) 127/2, 439–452.
Vlahović, I., Tišljar, J., Velić, I., Matičec, D., 2005. Evolution of the Adriatic Carbonate Platform: palaeogeography, main events and depositional dynamics. Palaeogeo-graphy, Palaeoclimatology, Palaeoecology 220/3–4, 333–360.
Wortmann, U.G., Weissert, H., Funk, H., Hauck, J., 2001. Alpine plate kinematics revisited: the Adria problem. Tectonics 20/1, 134–147.
Zambetakis-Lekkas, A., Pomoni-Papaioannou, F., Alexopoulos, A., 1998. Biostratigra-phical and sedimentological study of Upper Senonian–Lower Eocene sediments of Tripolitza Platform in central Crete (Greece). Cretaceous Research 19, 715–732.
Zappaterra, E., 1994. Source rock distribution model of the Periadriatic region. AAPG Bulletin 78/3, 333–354.