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Understanding fossil fore-arc basins: Inferences from the Cretaceous Adria-Europe convergence in the NE Dinarides

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ABSTRACT

The evolution of relict fore-arc basins and their kinematic relationships with sedimentation is often less well understood due their fragmentation or amalgamation of individual basins and continental units by the subsequent collision or other post-orogenic deformation. One example is the Cretaceous–Paleogene closure and associated sedimentation of the Neotethys Ocean that was located between the European and Adriatic continental units. Our combined structural, lithostratigraphic and sedimentological study in the NE Dinarides of Serbia demonstrates a variable Cretaceous fore-arc deposition on the European plate that correlates with the shallow- to deep-water sedimentation over the subducting Adriatic margin. The fore-arc was affected by an initial Early Cretaceous–Cenomanian period of contraction, followed by Turonian–Santonian extension, the basin being exhumed by contraction during the latest Cretaceous–Early Paleogene collision. The collisional geometry was subsequently fragmented by structures associated with the Neogene evolution of the Pannonian Basin. The correlation with the preserved amount and depositional character of Cretaceous trench sediments documents an interplay between subduction accretion and subduction erosion associated with external tectonic forcing, slab retreat and back arc extension.

1. Introduction

The evolution of presently observed fore-arc basins is generally related to an interplay between subduction mechanics and active magmatism, such as observed at convergent margins around the Pacific and eastern Indian Ocean (e.g., Capitanio et al., 2010; Noda, 2016). Fore-arc basin geometries and sedimentary facies are controlled by processes taking place at the interface between tectonic plates that create subduction erosion or subduction accretion (Clift and Vannucchi, 2004; Fuller et al., 2006; von Huene et al., 2004; Stern, 2011). These subduction processes control changes in the tectonic regime and subsidence of the fore-arc basin, as well as the evolution of associated unconformities and *syn*-kinematic magmatism, as observed for instance in the Andean or Japan subduction systems (e.g., Ishizuka et al., 2006; Melnick and Echtler, 2006; Stern et al., 2012). Fore-arc extension is commonly created by subduction tectonic erosion (e.g., Clift and Vannucchi, 2004) or by slab retreat, locally associated with specific volcanism, as inferred for instance for the Mariana subduction zone (Smellie, 1994; Reagan et al., 2013). This slab retreat is also responsible for the formation and evolution of extensional back-arc basins (e.g., Dewey, 1980; Cawood et al., 2009; Noda, 2016). Understanding subduction mechanics is difficult in relict fore-arc basins that were fragmented by post-orogenic deformation and where slabs are presently absent (e.g., Roure et al., 2010; Santra et al., 2013; Falloon et al., 2014).

Existing studies in Mediterranean mountain chains have demonstrated that extension was driven by the roll-back of associated slabs, resulting in the formation of highly arcuated orogens, as observed in the Carpathians, Alps, Apennines, Rif-Betics or Hellenides (e.g., Horváth et al., 2006; van Hinsbergen and Schmid, 2012; Vergés and Fernàndez, 2012; Faccenna et al., 2014;). These studies have shown that extension has often reactivated the inherited nappe stack during subduction and collision, resulting in exhumation along major detachments (Ratschbacher et al., 1991; Fügenschuh and Schmid, 2005; Georgiev et al., 2010; Matenco and Radivojević, 2012; Jolivet et al., 2013). In these Mediterranean orogens, the kinematics and geometry of the initial oceanic subduction is frequently distorted by the subsequent continental subduction, collision or other post-orogenic deformations, making difficult the reconstruction of earlier fore-arc basins (Brun and

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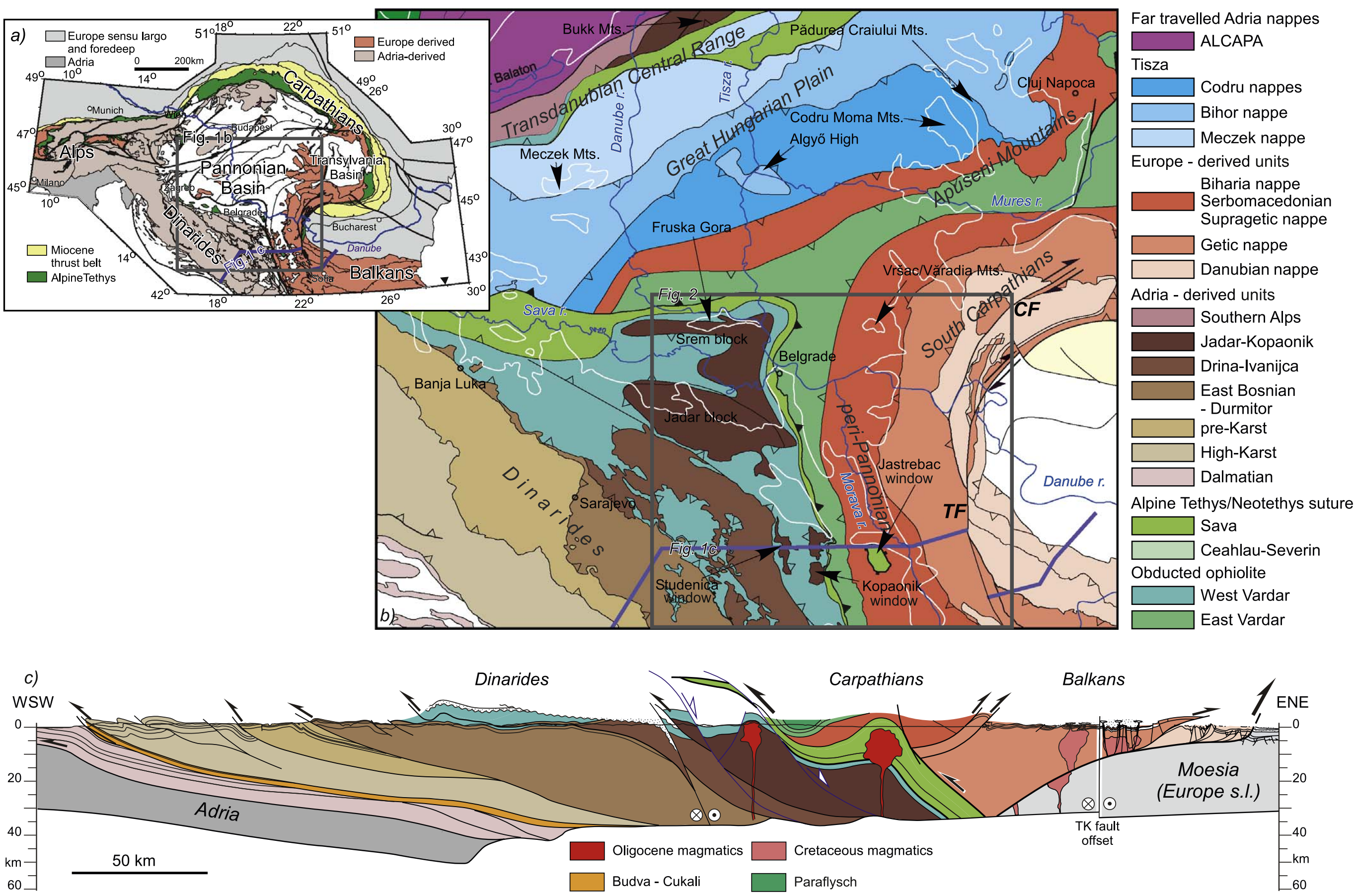

Fig. 1. a) Tectonic map of the Alps – Carpathians – Dinaridic system [simplified after Schmid et al., 2008]. The inset represents the location of Fig. 1b and the thick blue line is the locations of the cross-section in Fig. 1c; b) Tectonic map of the Alps–Carpathians–Dinarides system with the present-day position of the main tectonic units (simplified and modified after Schmid et al., 2008). Note that in this map the Miocene cover of the Pannonian Basin (delimited by white lines) is largely ignored. The blue line represents the location of the cross section in Fig. 1c. The inset represents the location of Fig. 2. TF = Timok Fault; CF = Cerna Fault. c) Cross section over the Dinarides and Carpathians system illustrating the Cretaceous–Eocene nappe stack geometry affected subsequently by the Miocene extension (modified after Matenco and Radivojević, 2012; Schmid et al., 2008). Note the juxtaposition in the Late Cretaceous Sava suture zone between Adria- and Europe-derived continental units and ophiolitic units in a higher structural position. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Faccenna, 2008; Vissers, 2012). The rapid slab retreat also renders problematic the terminological definition of fore-arc and back-arc basins relative to the position of magmatic arcs created during subduction (e.g., Uyeda and Kanamori, 1979; Dewey, 1980), which relies more on the location of peak orogenic contraction that changed its location with time (e.g., Jolivet and Brun, 2010; Carminati et al., 2012; Jolivet et al., 2013; Gallhofer et al., 2015). The kinematics of back-arc basins has been extensively used to derive the evolution of subducted slabs (e.g., Faccenna et al., 2014 and references therein). In contrast, Mediterranean fore-arc basins are equally important for understanding the evolution of the genetically associated subduction zones (e.g., Gürer et al., 2016) and are far less understood.

One interesting area for understanding the evolution of fossil fore-arc basins in the Mediterranean is the contact between European and Adriatic tectonic units in the Dinarides orogen, formed in response to the closure of a northern branch of the Neotethys Ocean (or the Vardar Ocean, Fig. 1, e.g., Stampfli and Borel, 2002). Recent models have inferred that this closure was driven by an initial period of Late Jurassic–earliest Cretaceous obduction followed by the formation of a composite tectonic nappe stack during Cretaceous–Eocene times (Schmid et al., 2008). This one ocean hypothesis in the Dinarides is appealing by its simplicity, but is critically dependent on the interpretation of one suture zone, i.e. the latest Cretaceous Sava Zone of the Dinarides (e.g. Pamic, 2002). This interpretation relies essentially on observations of bimodal magmatism and *syn*-contractional turbidites, presumably deposited in the subduction trench, located at or near the contact between Europe and Adria derived units (Figs. 1 and 2, Schmid et al., 2008; Ustaszewski et al., 2009). Other observations indicate a wider zone of Cretaceous sedimentation covering this contact that was significantly affected by the large-scale Miocene extension of the Pannonian Basin (Fig. 2, Ustaszewski et al., 2010; Matenco and Radivojević, 2012; Stojadinovic et al., 2013; Toljić et al., 2013). Furthermore, the regional distribution of ophiolites and the geochemistry of magmatism show a significant variability in space and with time, inferring locally contrasting geodynamic scenarios resulting in a number of alternative interpretations (see discussions in Robertson et al., 2009; Cvetković et al., 2013; Neubauer, 2015; Prelević et al., 2017). However, all previous studies have ignored the possible evolution of a Cretaceous fore-arc basin that may largely reconcile at least some of these apparently contrasting interpretations and may provide critical inferences on the evolution of the Dinarides subduction zone. Along the Dinarides strike, the Cretaceous–Lower Paleogene sediments of the Sava Zone outcrop well in a wide area near and south of the city of Belgrade in Serbia (Figs. 1 and 2), where a multi-stage deformation has affected a variable shallow to deep water sedimentary facies separated by several regional and local unconformities (e.g., Čanović and Kemenci, 1988; Toljić, 2006).

We aim to define the location and evolution of a Cretaceous fore-arc basin in the NE Dinarides, as well as the implications for understanding orogenic deformation driven by changes in the subduction system. To this aim, we have analysed the Cretaceous–Lower Paleogene sediments exposed in two NE Dinarides areas of Serbia, near the city of Belgrade

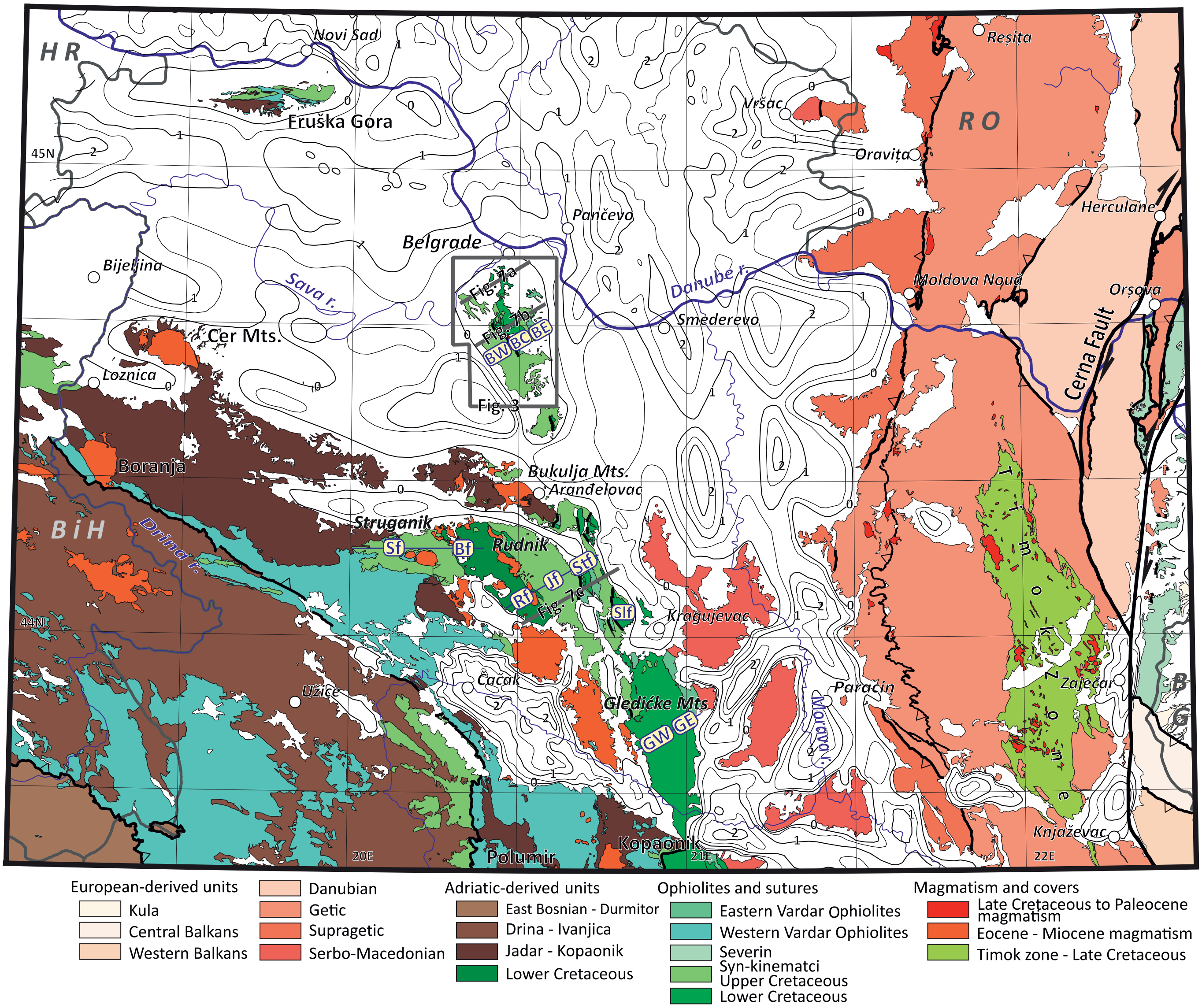

Fig. 2. Tectonic map of the contact area between Europe- and Adria- derived units around and south of Belgrade overlain by the distribution of ophiolitic units and Cretaceous-Miocene magmatism, as well as by the Cretaceous sediments in the Sava Zone and Timok extensional area. The map is compiled after the 1:100.000 maps of Geological Survey of Serbia (Osnovna geoloska karta SFRJ) by using the definition of tectonic units described in Schmid et al. (2008) and Dimitrijević (1997). Isolines are the depth of the pre-Miocene basement in the Pannonian Basin and its prolongation along the Miocene Morava river corridor (in km). Location of the map is displayed in Fig. 1. The inset represents the location of the map in Fig. 3. Grey lines are cross-sections displayed in Fig. 7. Different facies are marked with abbreviations: BW - West Belgrade facies, BC - Central Belgrade facies, BE - East Belgrade facies, Sf - Struganik facies, Bf - Boljkovac facies, Rf - Rudnik facies, Jf - Jermenovac facies, Stf - Stragari facies, Slf - Šljivovac facies, GW - West Gledićke facies, GE - East Gledićke facies. Note the location of the Timok extensional and magmatic zone in the eastern part of the map.

and southwards in the Rudnik - Arandjelovac - Gledićke Mountains (Fig. 2). A new kinematic, lithostratigraphic and sedimentological analysis was combined with new bio-stratigraphic dating. The kinematic analysis is described first in order to understand the tectonic events, regional structure and distribution of fore-arc and trench basins sediments in the area of Belgrade. This analysis was required by the complex structural setting, the initial basins were affected by a polyphase deformation, most notably by large thrusting during the latest Cretaceous collision and fragmentation during the Miocene extension. The kinematic analysis is followed by a detailed study of lithostratigraphic and sedimentological observations in the overall structural context of the two areas, aided by the construction of regional cross-sections by surface to depth projection of kinematic observations. These data constrain a new coupled tectonic and depositional model for the evolution of the Sava Zone and its associated fore-arc, trench and lower Adriatic plate. We subsequently describe the implications of this model for the evolution of the Dinarides and neighbouring Carpathian units in the context of previous geodynamic interpretations, and discuss its generic inferences for the evolution of fore-arc basins.

2. Regional settings of the NE Dinarides

The Dinarides orogen formed in response to the Middle–Late Triassic opening and subsequent Late Jurassic–Cretaceous closure of a northern branch of the Neotethys Ocean that was located between Europe- and Adriatic-derived continental units (or the Vardar Ocean, Dimitrijević, 1997; Karamata, 2006; Robertson et al., 2009; Schmid et al., 2008). The initial continental rifting and drifting have created a wide passive continental margin in the Dinarides, recognised by the gradual deepening of the Middle Triassic-Middle Jurassic sedimentary facies (e.g., Schefer et al., 2010; van Gelder et al., 2015 and references therein). The Late Jurassic–earliest Cretaceous emplacement of ophiolites over these both continental units (Western and Eastern Vardar ophiolites, Schmid et al., 2008, see also Nicolae, 1994; Dimitrijević, 1997; Bortolotti et al., 2002; Nicolae and Saccani, 2003; Resimic-Saric et al., 2004; Karamata, 2006) was followed by the Cretaceous–Paleogene subduction of the Adriatic plate and collision with overriding Europe-derived units (e.g., Dimitrijević, 1997; Schmid et al., 2008). This convergence created an Adriatic nappe stack and formed the Dinarides suture (i.e. the Sava Zone) between the two main continental units during latest Cretaceous times (Fig. 1c, e, g, Pamic, 2002; Ustaszewski et al., 2009). The shortening generally migrated towards the foreland with time, where the Eocene Dinaric event is well documented (e.g., Karamata et al., 2003; Ilic and Neubauer, 2005; Vlahović et al., 2005). The Dinarides were subsequently affected by a Miocene extension associated with the back-arc formation of the Pannonian Basin (Tari and Pamic, 1998; Horváth et al., 2006). The extension created many detachments or low-angle normal faults with large offsets and associated Miocene basins, deforming and partly burying the earlier Cretaceous–Paleogene structure (Fig. 2). The Sava Zone was reactivated by extensional detachments along its entire strike within the Dinarides, which exhumed in their footwalls the previously deeply buried distal Adriatic passive margin (Ustaszewski et al., 2010; Stojadinovic et al., 2013; Toljić et al., 2013; van Gelder et al., 2015). The Dinarides were subsequently affected by contraction during the latest Miocene–Quaternary inversion of the Pannonian Basin, driven by the Adriatic indentation (e.g., Bada et al., 2007; Matenco and Radivojević, 2012; Ustaszewski et al., 2014). This contraction is presently active with larger offsets in the SE external and NW internal parts of the Dinarides along their strike (Fig. 1; e.g., Bennett et al., 2008; Kastelic and Carafa, 2012; Ustaszewski et al., 2014; van Gelder et al., 2015).

The Dinarides subduction, collision and subsequent extension were associated with several successive stages of magmatism that gradually migrated in space and with time towards the foreland (e.g., Cvetković et al., 2013). Large volumes of calk-alkaline magmatism were emplaced at ~92–67 Ma (the Apuseni - Banat - Timok - Srednogorie ABTS belt), locally in extensional back-arc basins (such as Timok, Fig. 2), commonly interpreted to be related to the subduction of the Neotethys (or Vardar) ocean (Cvetković et al., 2000; von Quadt et al., 2005; Gallhofer et al., 2015). Alternatively, the emplacement of the ABTS magmatic belt has also been interpreted to driven by the subduction of the Ceahlau-Severin Ocean that created the neighbouring Carpathians orogen (Neubauer, 2015). However, this hypothesis is rather speculative by assuming oceanic subduction in the Balkans and is at odds with the interpretation of a Late Cretaceous ocean in the Dinarides (Schmid et al., 2008; Neubauer, 2015).

The Dinaridic nappe stack contains thin- and thick-skinned thrust sheets, the three internal-most units (East Bosnian–Durmitor, Drina–Ivanjica and Jadar–Kopaonik) containing in a higher structural position the Western Vardar ophiolites and ophiolitic mélanges obducted over the Adriatic continental unit (Fig. 2). Note that in the one-ocean hypothesis, these ophiolites are separated from the ones obducted over the European-derived continental unit (i.e. the Eastern Vardar ophiolites) by the Sava Zone (Figs. 1 and 2). The Dinarides nappe contacts are often marked by the Cretaceous deposition of *syn*-contractional turbidites (i.e. flysch deposits, Dimitrijević and Dimitrijević, 1987), well developed during the latest Cretaceous (Maastrichtian) moment of collision (Figs. 2 and 3, e.g., Rampnoux, 1970; Dimitrijević and Dimitrijević, 1987; Dimitrijević, 1997; Tari and Pamic, 1998; Mikes et al., 2008; Schmid et al., 2008).

Two areas still preserve widespread Cretaceous sediments exposed in the vicinity of the Sava Zone in the NE Dinarides: the one surrounding the Belgrade city and more to the south in the Rudnik–Arandjelovac–Gledićke Mountains (Fig. 2). In these areas, the Cretaceous sediments are deposited over the Adriatic-derived Jadar-Kopaonik unit, the Sava Zone and the Europe-derived Serbo-Macedonian unit, including their Paleozoic–Triassic basement and cover, and the overlying ophiolites and ophiolitic mélanges (Fig. 1c).

The Cretaceous sediments in the area surrounding the Belgrade city (Fig. 3) were locally deposited over ophiolites and ophiolitic mélanges (the "diabase-chert formation" of Dimitrijević, 1997, see Filipović and Rodin, 1980; Pavlović, 1980, or the "volcanic-sedimentary formation" of Anđelković, 1973; Marković et al., 1985). The age of the outcropping mélange was generally interpreted as Kimmeridgian–Tithonian (Pavlović, 1980), while the containing blocks of radiolarites, cherts and deep water shales cropping out or penetrated by wells (E of Leštane, Fig. 3) have variable Triassic-Late Jurassic ages (Anđelković, 1973; Knežević et al., 1994; Djerić et al., 2010; Bragin et al., 2011). The affiliation of the Belgrade ophiolites and ophiolitic mélanges is rather unclear, being interpreted as part of the Western Vardar Ophiolite unit due to its apparent burial beneath the Cretaceous sediments of the Sava Zone (Schmid et al., 2008). In contrast, this ophiolitic unit is largely overstepped by a typical Lower Cretaceous post-tectonic cover of the Eastern Vardar Ophiolite unit (the "paraflysch" of Dimitrijević and Dimitrijević, 1987, 2009; see also Mitrović, 1967; Anđelković, 1973; Marković et al., 1985; Schmid et al., 2008). The term 'paraflysch' means sediments that resemble the cyclic deposition of turbidites, but lack their gradational and internal organisation characteristics. This Lower Cretaceous transgressive sequence is highly variable, generally composed of a cyclic alternations of Valangianian–Barremian shales and mudstones, and Barremian-Aptian sandstones and limestones, which have sometimes the organisation of immature turbidites (Petković and Marković, 1951; Anđelković, 1973; Filipović and Rodin, 1980; Marković et al., 1985; Dimitrijević and Dimitrijević, 2009). Laterally and upwards, these sediments are replaced by shallow water reef limestones and clastics (Urgonian facies, Petković and Miletić, 1949) and Albian-Cenomanian conglomerates, sandstones, carbonates deposits and continental shales (Anđelković, 1953; Pavlović, 1980). The Upper Cretaceous sequence is thought to be deposited over a regional unconformity with a basal transgressive sequence with conglomerates (Figs. 2 and 3, Marković, 1950; Anđelković, 1973; Toljić and Trivić, 1997; Banjac and Toljić, 1996) overlain by Turonian - Maastrichtian turbidites, which possibly continued their deposition into the Paleogene (Ivković, 1975; Filipović and Rodin, 1980; Pavlović, 1980; Marković et al., 1985; Mihajlović, 1986; Obradović, 1987; De Capoa and Radoičić, 2002; De Capoa et al., 2002; Jevremović and Kuzmić, 2003). Small volumes of mafic and felsic Late Cretaceous magmatism are observed most often as dykes cross-cutting the Lower Cretaceous sediments or as volcanoclastics and re-deposited blocks in Upper Cretaceous sediments (Ilić and Ilić, 1969; Terzić, 1971; Anđelković, 1973; Marković et al., 1985; Karamata et al., 1999). One of these dykes has been dated to an absolute age of ~85 Ma (Dejan Prelevic and Vladica Cvetkovic, personal communication).

South of Belgrade, the Cretaceous sediments observed in a transect in the Rudnik - Arandjelovac area have a large variability, but are generally more shallow in the lower part and to the west and more deep in the upper part and to the east (Fig. 2, Anđelković, 1956; Brković et al., 1980; Filipović et al., 1978; Marković et al., 1968; Dimitrijević and Dimitrijević, 1987). West of the Boljkovac Fault (Fig. 3), the Upper Cretaceous deposits are transgressive over the Jadar–Kopaonik unit of the Dinarides (Fig. 2, Filipović et al., 1978; Dimitrijević, 1997). The Cretaceous sequence of the Gledićke Mountains (Fig. 2) overlies the East Vardar Ophiolites and their underlying Serbomacedonian margin (Schmid et al., 2008). These sediments are characterised by an initial transgression followed by a gradual deepening of the sedimentary facies to Barremian-Aptian turbidites, and subsequent gradual shallowing during Albian–Cenomanian times (Anđelković, 1956; Marković et al., 1968).

3. Approach and methodology

Understanding rapid changes in sedimentation in a fossil subduction system requires first the separation of the former upper plate forearc, subduction trench and lower plate areas that were amalgamated by the subsequent continental collision and/or other deformations. In the two

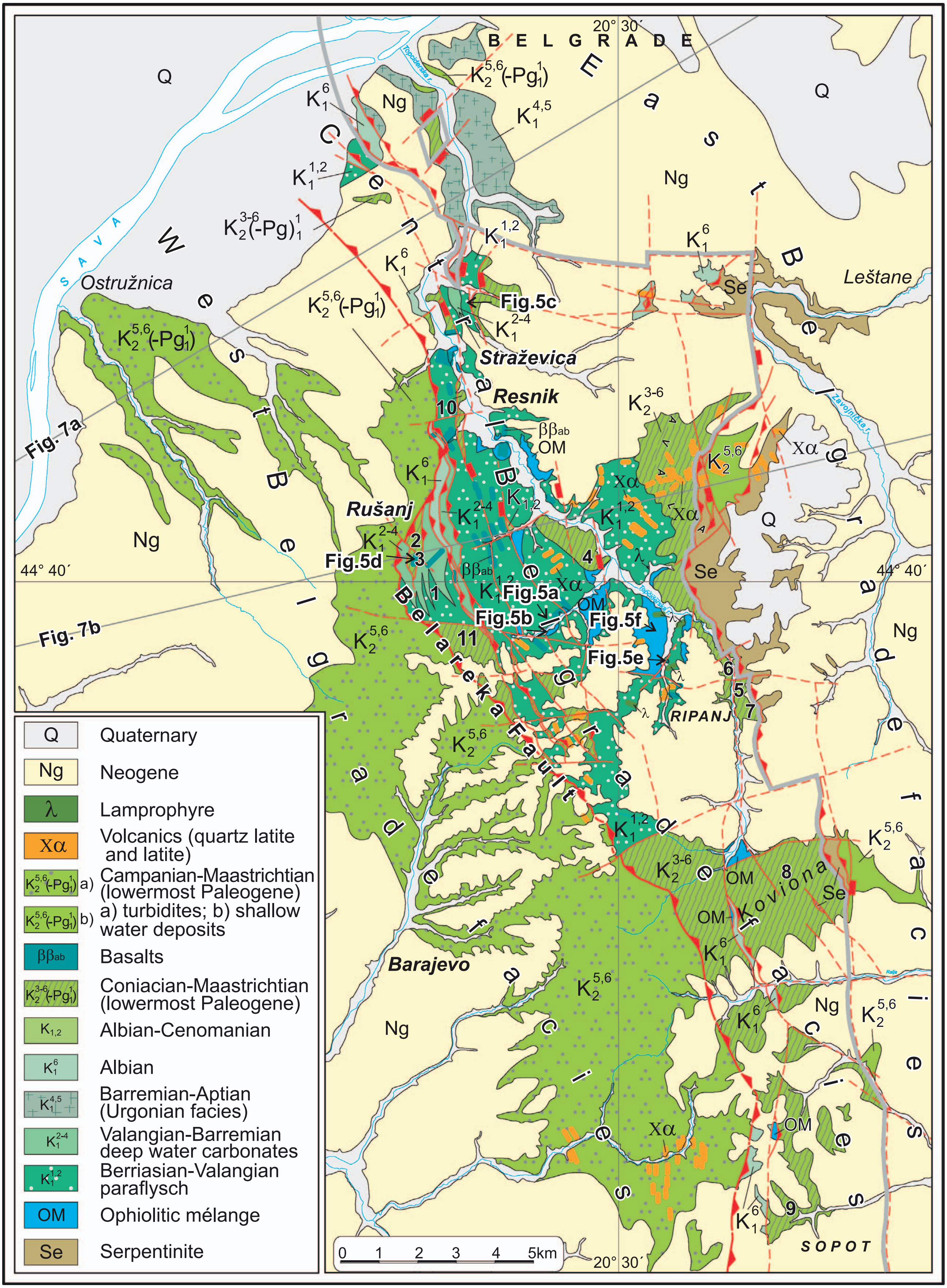

Fig. 3. Simplified geological map of the Belgrade area (modified after Toljić, 2006 and the results of the present study). Grey lines are cross-sections displayed in Fig. 7a, b. Note that the zones of sedimentation of the West Belgrade, Central Belgrade and East Belgrade facies (see Fig. 6) are separated by the Belareka Fault and the thrust underlined by a thick grey line. Note also the location of the outcrops depicted in Fig. 5a–f as well as the locations of the biostratigraphic samples (marked with 1–10 in the figure and Table 1).

studied areas of the NE Dinarides (Belgrade and Rudnik-Arandelovac-Gledićke Mountains, Fig. 2) we have followed the above described genetic interpretation of Schmid et al. (2008), while implications for other geodynamic scenarios are furthermore addressed in the discussion section (see below). In the vicinity of the Sava Zone, this interpretation implies that Cretaceous sediments overlying the Serbomacedonian unit and their overlying Eastern Vardar Ophiolites are part of a fore-arc basin. Cretaceous sediments overlying the Jadar-Kopaonik unit and Western Vardar Ophiolites were deposited over the lower Adriatic continental plate, or were deposited in the subduction trench and amalgamated together with the ones deposited over the Adriatic continental plate during the subsequent collision. This separation is clear in the south, where the close spatial proximity of the two continental units and their overlying ophiolites show that the overlying Cretaceous sediments of the Gledićke Mountains and the correlative eastern part of the Rudnik-Arandelovac transect belong to the fore-arc basin, while the remainder of the Rudnik-Arandelovac transect is located in the trench-lower plate system (Fig. 2). However, the fore-arc sediments and deformation are better observed in the Belgrade area, where the continental basement is not exposed and a separation from the lower plate - trench system is unclear due to conflicting interpretations of exposed ophiolites and their cover (Fig. 2). Therefore, our study has adopted a strategy where field kinematic observations performed in the Belgrade area are described first to understand the structural evolution and the location of the former fore-arc sediments. These data were subsequently combined with field sedimentological, litho- and bio-stratigraphic observations in both studied areas to derive the evolution of the Cretaceous fore-arc - lower plate - trench system.

Kinematic observations in the Belgrade area included measurements of faults and folds, observations of post-kinematic tilting and rotations and observations of major shear zones (e.g., Fig. 4 and 5). We specifically note that we did not performed a paleostress study, which is otherwise not suitable in the studied area given the highly anisotropic character of the observed sedimentary sequence and the often observed *syn*- and post-kinematic strain partitioning or tilting. Given these conditions, we performed a kinematic analysis for deriving transport directions and relationships between faulting and sedimentation. Field kinematic indicators, such as slickensides and Riedel shears, were used to derive the transport directions. Superposition criteria, such as truncations, tilting, deformation of *syn*-kinematic wedges or post-kinematic sedimentation were used to derive the relative or absolute timing of deformation. We observed numerous evidences of syn-kinematic deposition in these Cretaceous sediments, which were used as primary deformation timing constraints. Establishing a more precise timing was obtained by the correlation with a new biostratigraphic analysis performed in carefully selected lithostratigraphic intervals.

We have studied the lithostratigraphic variability of the Cretaceous–Lower Paleogene sediments on several transects in both the area of Belgrade and southwards. We have combined field lithostratigraphic and sedimentological observations with biostratigraphic sampling of sections relevant to derive the age of the main unconformities and the age of syn-kinematic deposition. We have focused on detecting syn-depositional wedges and rapid variations in depositional environment along and across the orogenic strike. These observations were furthermore combined with previous litho- and bio-stratigraphic studies in the areas of Belgrade, Gledićke Mountains and Rudnik–Arandjelovac (Anđelković, 1956; Mitrović, 1967; Marković et al., 1968; Ilić and Ilić, 1969; Terzić, 1971; Anđelković, 1973; Ivković, 1975; Filipović et al., 1978; Filipović and Rodin, 1980; Brković et al., 1980; Pavlović, 1980; Marković et al., 1985; Mihajlović, 1986; Dimitrijević and Dimitrijević, 1987; Sladić-Trifunović et al., 1989; Sladić-Trifunović et al., 1990a; Sladić-Trifunović et al., 1990b; Jevremović and Kuzmić, 2003). Results are summarised in one biostratigraphic table (Table 1) and in one synthetic correlative lithostratigraphic cross section (Fig. 6). Because of incomplete exposures of Cretaceous sediments, 11 lithostratigraphic facies logs were defined in different areas along the orogenic strike, which were projected into the synthetic correlative cross section (Fig. 6). These logs are located in the areas of Belgrade (described as facies west, central and east Belgrade), Gledićke Mountains (described as facies west and east) and the Rudnik–Arandjelovac transect (Figs. 2 and 3). This latter transect is described in 6 lithostratigraphic facies logs (from west to east, Struganik Boljkovac, Rudnik, Jermenovac, Stragari and Šljivovac facies, Fig. 6). There are no Lower Cretaceous sediments deposited over the Adriatic margin cropping out in the Belgrade area (west Belgrade facies, Fig. 6), being most likely covered by subsequent Upper Cretaceous deposition in the footwall and west of the Belareka Fault (Fig. 3). However, the Lower Cretaceous sediments deposited over the Adriatic margin crop out in the Rudnik - Arandjelovac transect. We have paid special attention to the age and lateral variability of unconformities developed during the Early Cretaceous–Cenomanian and Late Cretaceous–Early Paleogene stages of evolution.

Field observations and previous regional studies were combined in three regional cross-sections (Fig. 7). The sections were constructed by a structural surface to depth projection taking into account surface fault kinematics and superposition criteria. The deep part of the cross-sections is speculative because no detailed subsurface information is available at depth in the study area. The style of structural interpretation at depth generally respects previous local or regional depth interpretations and was aided by existing interpretations of reflection seismic lines in neighbouring areas, such as the Morava River corridor (Fig. 2, e.g., Schmid et al., 2008; Matenco and Radivojević, 2012; Stojadinovic et al., 2017).

4. Field kinematics in the Belgrade area

The oldest deformation structures (D1, Fig. 4a) were observed affecting the ophiolites, their underlying mélange and overlying sediments as young as Early Cretaceous. Such sediments outcrop exclusively east of the thrust described as Belareka Fault (Fig. 3). Two thrust fault systems and associated folds formed during this presently NW–SE oriented contraction (Fig. 3). The first one is characterised by NE–SW oriented low-angle thrusts with a top-NW dominant sense of shear and affects only the ophiolites and the ophiolitic mélange (Fig. 4a). Younger thrusts affect also the Lower Cretaceous sediments, are similarly NE–SW oriented, but their sense of shear is dominant top-SW (Fig. 4a).

The second deformation event (D2, Fig. 4b) created a large number of NNW–SSE oriented normal faults, with local variations to N–S and NNE–SSW and oblique components of slip, indicating an overall WSW-ENE direction of extension. The faults are located exclusively east of the Belareka Fault (Fig. 3), have a dominant top-WSW sense of shear, truncate Lower Cretaceous deposits, and are associated with wedge-shaped syn-kinematic sediments in lower Upper Cretaceous deposits. This syn-kinematic character show that the normal faults were associated with the onset of Upper Cretaceous sedimentation in the European sub-basin. The normal faults have centimetres to metres offsets in outcrop scale, while truncations in map view (Fig. 3) suggest offsets to maximum a couple of hundreds of meters. The normal faults are observed to locally reactivate pre-existing Early Cretaceous reverse faults. Some of these faults were intruded or cross-cut by Late Cretaceous mafic and acidic dykes (e.g., Fig. 5e). The normal faults and magmatic dykes are buried beneath the overlying upper part of Upper Cretaceous sediments. These observations indicate that the basaltic dykes were emplaced during this second deformation event.

The largest deformation event observed in the entire Belgrade area (D3, Fig. 4c) formed numerous thrusts, oblique transpressive and strike-slip faults that indicate an overall NE–SW oriented contraction. This event shows a combination between NW-SE to N–S oriented thrusts and strain partitioning along NE–SW oriented tear faults with (oblique) strike-slip components of movement (Figs. 3 and 4c). These faults are associated with NW-SE oriented fold axes and affect all Upper

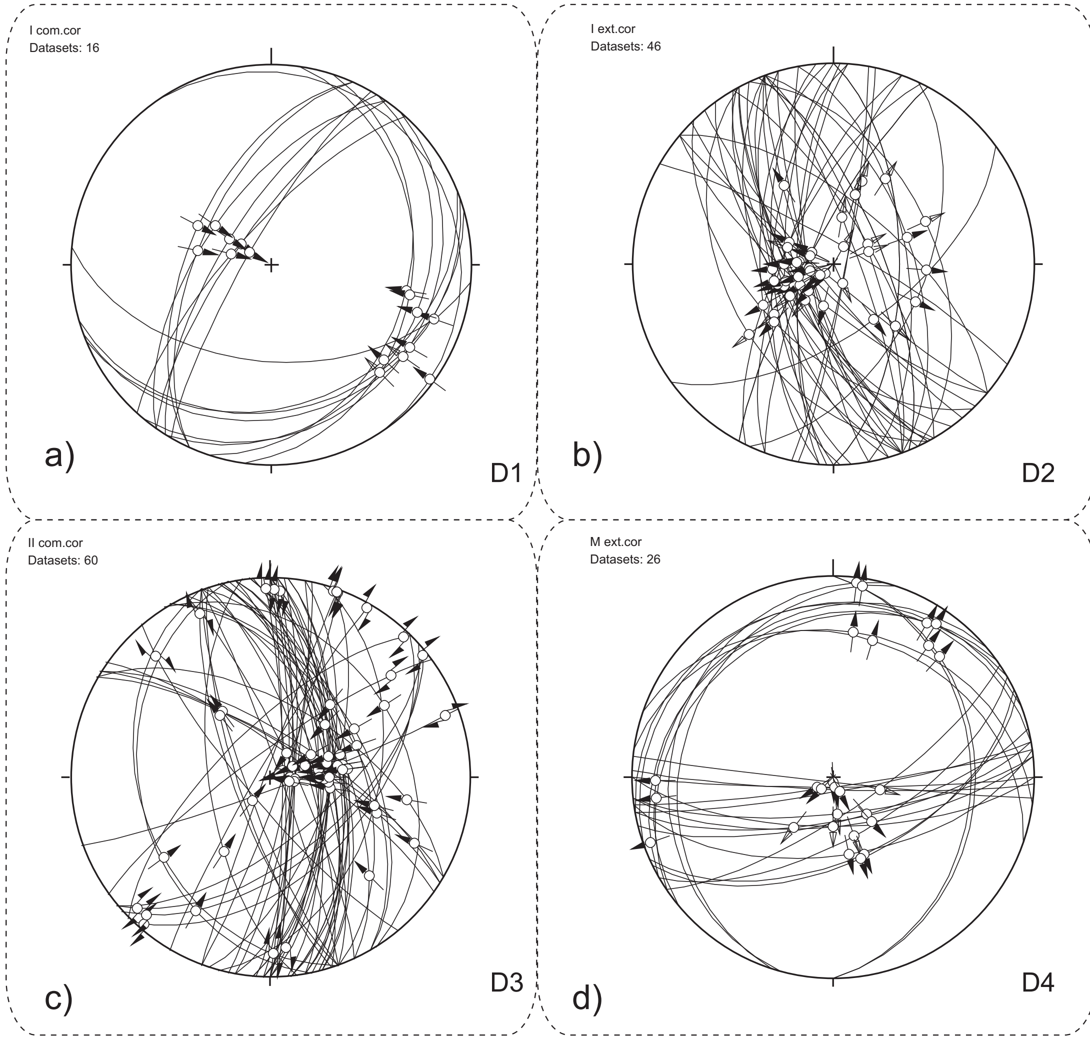

Fig. 4. Structural and kinematic data derived for the various phases of deformation observed in the field in the Belgrade area. Lines with arrows are stereoplots of faults with sense of shear, derived from kinematic indicators (such as slickensides or Riedel shears). a) Kinematic data for the late Early Cretaceous shortening event; b) kinematic data for the Late Cretaceous phase of extension (~80 Ma, Campanian); c) kinematic data for the latest Cretaceous–Eocene phase of contraction; d) kinematic data for the Miocene extensional phase related to the evolution of the Pannonian Basin.

Jurassic–Cretaceous sediments. Syn-kinematic sedimentation is observed only in uppermost Cretaceous (Maastrichtian) turbidites, which were buried beneath the subsequent Lower Paleogene regressive deposits and Neogene sediments. The deformation is highly asymmetric by a dominant top-SW direction of tectonic transport along thrusts or asymmetric folds (Fig. 5a). A few back-thrusts with the opposite top-NE sense of shear and lower offsets have been observed (Fig. 4c). Thrusts are often laterally replaced by high angle reverse faults with oblique- to strike-slip sense of shear. Drag folds with overturned flanks are observed in the footwalls of thrusts that affected turbidites, inferring that break-thrust folds (e.g., Fischer et al., 1992) is the dominant mechanism of deformation. A lateral transition to more dextral strike-slip faults was observed in the central and northern part of the studied area (Fig. 3, dextral faults in Fig. 4c). The large offset SW-verging structures are often associated with thick fault gouges or cataclastic shear zones. The most obvious case of such deformation is the Belareka Fault (Fig. 3) that shows some tens of metres wide cataclastic shear zone associated with tight (drag-)folds and the formation of a pervasive axial plane cleavage in its footwall. This thrust has the largest observed offset, emplacing lowermost Cretaceous 'paraflysch' sediments in the eastern hangingwall over the typical uppermost Cretaceous turbidites of the Sava Zone in the western footwall (Fig. 3). These observations show that the Belareka Fault is the expression of the present-day separation between fore-arc sediments to the east and trench sediments to the west in the Belgrade area.

The last deformation event observed is characterised by normal faults that truncate and are locally buried beneath Miocene sediments (Fig. 3). These faults are generally E–W oriented with some variations to N–S when the fault plane is low angle and more to strike-slip when the fault planes are high angle (Fig. 4d). These Miocene normal faults are less frequent, have lower offsets and generally indicate a NNW–SSE direction of extension. One can infer two directions of extension during Miocene times (more N–S oriented versus more E-W oriented), but the overall number of normal faults measured is too low for a clear separation. In more detail, the N-dipping normal faults are low-angle faults, while the S-dipping ones are high-angle to steep ones (Fig. 4d). Such normal fault geometry observed in outcrops reflects either tilting of a conjugate system post-dating fault deformation or an extensional asymmetry. The latter is likely the case because Miocene strata are not significantly tilted in most observed field situations. The divergence of the Miocene extensional direction from N–S to E–W oriented is otherwise a typical observation along the Dinaridic margin of the Pannonian Basin, created either by successive extensional episodes or by block rotations during of extension (e.g., Ustaszewski et al., 2010; Toljić et al., 2013). This deformation is also associated with felsic volcanics emplaced along normal faults or cross-cutting dykes, most frequently

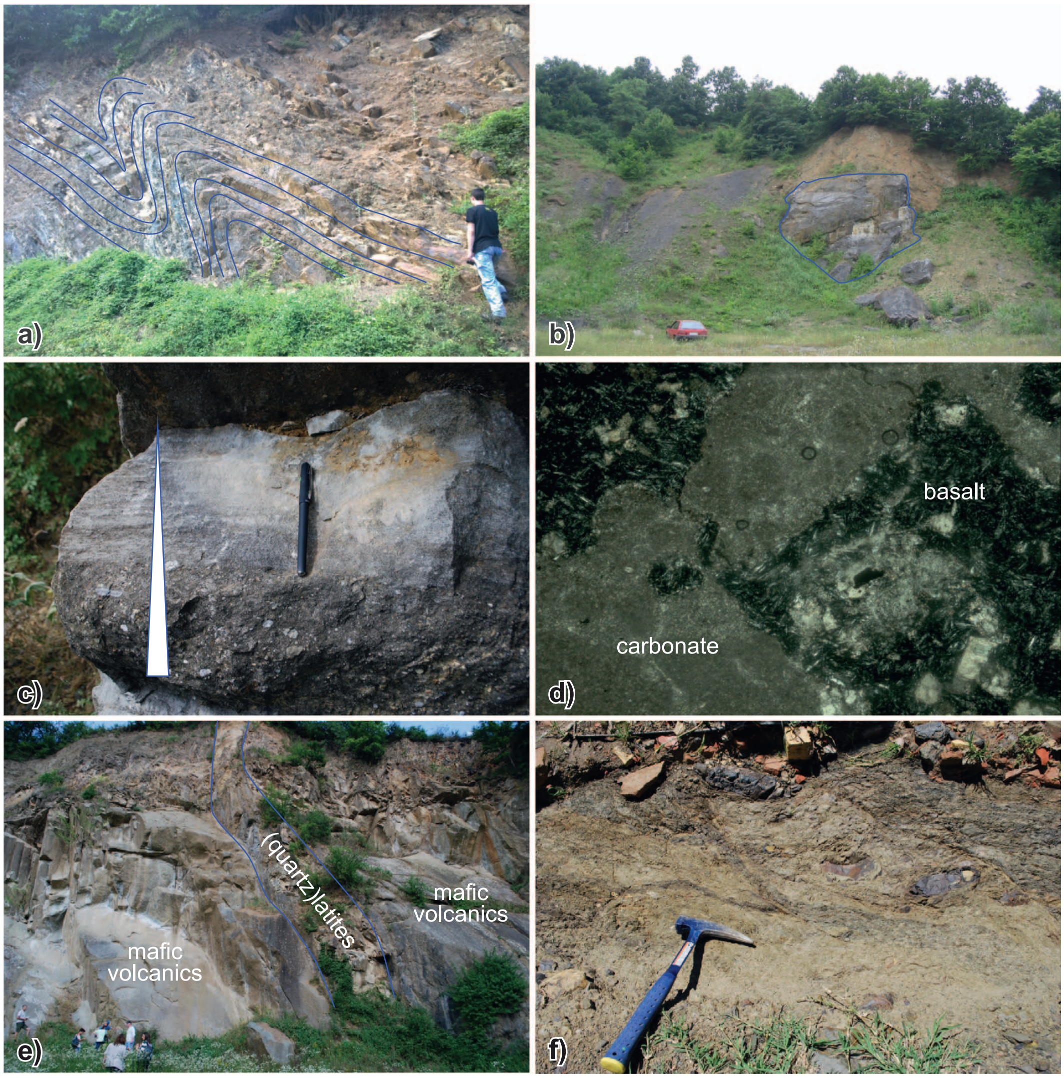

Fig. 5. Field examples of the main deformation and sedimentation events observed in the Belgrade area: a) SW-vergent folds in the Lower Cretaceous paraflysch near Belareka fault; b) olistolite of Tithonian limestones at the base of Upper Cretaceous paraflysch; c) graded calciturbidites of Straževica; d) peperites near the Rušanj locality - basalts associated with Upper Cretaceous limestones with globotruncanids; e) bimodal volcanics of the Tešića quarry – mafic volcanics intruded by a quartz-latite dyke; f) sheared ophiolitic melange near the Ripanj locality overlain by Cretaceous sediments. Location of outcrops is shown in Fig. 3.

observed around the Avala Mountain (Fig. 3, see also Toljić, 2006).

5. The lateral variability of Cretaceous–Lower Paleogene sediments

The separation of the fore-arc sediments east of the Belareka Fault in the Belgrade area has allowed the correlation across a synthetic lithostratigraphic facies section (Fig. 6). This correlation shows the Cretaceous–earliest Paleogene facies in three paleogeographic domains, the European, Adriatic and subduction-collisional trench, which are parts of the same basin or were separated in individual (sub-)basins during their evolution.

5.1. Cretaceous - lowermost Paleogene sediments deposited in the European sub-basin

5.1.1. The Lower Cretaceous–Cenomanian cycle of deposition

The Lower Cretaceous–Cenomanian sediments deposited over the European-derived Serbo-Macedonian margin show a significant depositional variability from distal in the centre of this sub-basin to proximal near its margins (Fig. 6c). The sediments deposited in the centre outcrop well in the central Belgrade and west Gledićke facies, while their eastwards transition to gradually more proximal facies is observed gradually in the Šljivovac, east Gledićke and east Belgrade facies. From the basin centre westwards, the Stragari facies is also more proximal (Fig. 6c).

The unconformable onset of Cretaceous sedimentation requires more detailed explanation. The base of the Lower Cretaceous paraflysch overstepping the ophiolites in the central Belgrade facies (Fig. 6c3) is composed of a poorly sorted coarse conglomeratic and breccia sequence containing olistoliths with a carbonatic cement or a similar matrix. Our field observations show that shallow water limestone olistoliths (Fig. 5b) contain an abundant Tithonian fauna and are often buried in more distal Lower Cretaceous pelagic sediments (such as the Berriasian age of location 1, Table 1). A similar situation is observed in the west Gledićke and Šljivovac facies, where the ophiolitic sequence is overlain above a marked unconformity by Berriasian conglomerates and sandstones (Fig. 6c2, 4, 5, see also Anđelković, 1956, Marković et al., 1968). This observation demonstrates that the previously interpreted Upper Jurassic limestone banks and sandy marls (Mitrović, 1967; Anđelković, 1973; Sladić-Trifunović et al., 1989) are in fact olistoliths buried in the basal Lower Cretaceous transgressive sequence of the ‘paraflysch’ (see also Mitrović, 1967; Anđelković, 1973; Marković et al., 1985; Dimitrijević and Dimitrijević, 1987). Although the basal Cretaceous

Table 1
Localities and biostratigraphic fauna in Cretaceous - Lower Paleogene sediments observed in this study. Location of samples in Fig. 3.

No	Locality	Rock type	Fossils and age
1	Rušanj	Calcrudites	Organic shallow-marine detritus. Matrix contains *Tintinopsella longa* and *Globochaete alpina* Lombard, and in the clasts *Clypeina jurassica* Favre and *Verneuilinidaea.* Fauna found in the matrix defines Berriasian age of these limestones, whereby the faunal content from the clasts actually represents the redeposited Tithonian association.
2	West from Rušanj	Calcrudites	Various bio- and litho-clasts, as well as the fragments of *Globotruncana*, bryozoa, *Marssonella trochus* d'Orbigny and Lenticulinae. Bioclasts contain redeposited Upper Jurassic microfauna (*Clypeina jurassica* Favre) and the fragments of echinodermata. Rocks are not older than Santonian.
3	West from Rušanj	Calcrudites	Association with: *Globotruncana arca* Cushman, *G. concavata* Brotzen, *G. tricarinata* Quer., *G. coronata* Bolli and *G. linneiana* (d'Orbigny). Rocks are not older than Santonian.
4	West to Avala Mt	Biomicrites and calcarenites	Biomicrite fragments contain algae detritus and macrofauna with: *Clypeina jurassica* Favre, altered *Dasycladaceae*, *Verneuilinidae*, *Conicospiriline,* and extraclasts of limestones with rare pelagic Beriassian tintinideae and redeposited Tithonian (*Clypeina jurassica* Favre in the bioclasts). In the limestones, Upper Jurassic and Lower Cretaceous fossils predominate, and these were determined from the redeposited carbonate clasts. Calcarenites, together with the redeposited fauna, foraminifera were found represented by the species *Dicarinella asymetrica* Sigal along with the numerous altered *Pithonella forms* and spheres, defining the age of calcarenites as certainly Santonian.
5	Klenje	Limestone	Association with: *Contusotruncana fornicata* Plummer, *Globotruncana linneiana* d'Orbigny, *Globotruncana lapparenti* Brotzen, *Marginotruncana marginata* Reuss, *Marginotruncana coronata* Bolli, *Dicarinella* cf. *asymetrica* Sigal and globigerinas. The age of pelagic foraminifera association is Santonian.
6	Klenje	Biomicrites	Altered pelagic micro association with: *Marginotruncana sigali* Reichel, *Marginotruncana coronata* Bolli, *Globotruncana linneiana* d'Orbigny, *Contusotruncana fornicata* Plummer, numerous spheres and *Pithonella ovalis* Kaufmann, which stratigraphically defines these limestones as Coniac – Santonian.
7	Klenje	Limestone	Association with: *Globotruncana arca* Cushman, *Globotruncana lapparenti* Brotzen, *Gl. hilli, G. linneiana* d'Orbigny, *Marginotruncana coronata* Bolli, *M. marginata* Reuss, *Contusotruncana fornicata* Plummer, and rare globigerina forms define the age of limestones as Campanian.
8	Koviona	Calcrudites	The faunal remnants are represented by fragments of rudists and globotruncanides: *Globotruncana arca* Cushman, *Contusotruncana fornicata* Plummer, *Siderolites vidali* Douville, *Orbitoides media* d'Archiac, *Pithonella ovalis* Kaufmann, “Hedbergella – Ticinella” group, globigerinas, radiolarians, and altered fragments of mollusks. Stratigraphically, these belong to the Campanian.
9	Sopot	Limestone	Sample contain recrystallised pelagic microfauna and rare tiny benthonic foraminiferas: *Globotruncana arca* Cushman, *Globotruncanita elevata* Brotzen, *Stomiosphaera sphaerica*, globigerinas, and microfauna from the group “Hedbergella – Ticinella” Campanian.
10	Resnik	Marl with volcanoclastic material	Association with *Globotruncana arca* Cushman, *G. linneiana* d'Orbigny, *G. lapparenti* Brotzen, *Contusotruncana fornicata* Plummer: Campanian.
11	Bela reka river	Sandstones in alternation with alevrolites and rare marls	A) Association with rare globotruncanas: *Globotruncana linneiana d'Orbigny, Globotruncana lapparenti Brotzen, Marginotruncana renzi Gandolfi,* and *Dicarinella asymetrica Sigal,* which define the age of litharenites as certainly Upper Cretaceous-Senonian (most probably Santonian). B) Upwards the carbonate layers contain a microfaunal asssociation: *Globotruncana linneiana d'Orbigny, Globotruncana lapparenti Brotzen, Marginotruncana coronata Bolli, globigerinas,* and heterohelicides, which define certainly Santonian. C) In the same outcrop but more to the west, Santonian age was confirmed based on poor association of the pelagic globotruncanas in the marly-sandy turbidites: *Globotruncana stuartiformis Dalbiez, G. linneiana d'Orbigny, G. fornicata Plummer,* globigerinas, and the group “Hedbergella – Ticinella”.

sequence is not exposed in a more proximal fore-arc facies (Fig. 6c6), we infer that the ‘paraflysch’ transgression widened gradually the basin during Early Cretaceous times.

The coarse transgressive sequence was rapidly overlain in the central part of the sub-basin by distal shelf and proximal slope sediments (central Belgrade facies, Fig. 6c3). The latter are observed as immature turbidites, such as for instance at Straževica (Fig. 3), where Berriasian–Valangianian high-density calci-turbidites crop out and show fining upwards and erosional structures indicating slope deposition (Fig. 5c). Composition of clasts always indicates a source area located in the neighbouring Serbomacedonian basement, pre-Cretaceous cover and their tectonically overlying ophiolites. Frequent Upper Jurassic shallow-water organogenic limestones are observed to be buried in a fine matrix or carbonatic cement. These deposits were overlain by Valanginian–Barremian deep water limestones with cherts and marls with cephalopods. Sedimentation continued with typical clastic-carbonatic paraflysch cycles, intercalations of turbidites and distal carbonates with a typical Barremian–Aptian fauna (Fig. 6c3, see also Anđelković, 1973). A similar rapid deepening of Lower Cretaceous facies is observed in the west Gledićke facies (Fig. 6c2), where the Berriasian conglomerates and shallow water clastics are rapidly deepening to a Valanginian–Barremian distal shelf and proximal slope deposition by cyclic clastic-carbonatic sediments and proximal turbidites, followed by Aptian laminated sandstones. Although the proximal Lower Cretaceous of the European sub-basin in the east Belgrade facies is incompletely exposed (Figs. 3, 6c6), the base of the exposed sequence shows shallow water limestones that ultimately led to the deposition of a typical Urgonian reef facies with high fauna content during Barremian–Aptian times (see also Petković and Miletić, 1949). A similar shallow water Barremian–Aptian proximal facies can be observed in the western proximal facies of the sub-basin (the Stragari facies, Fig. 6c1), where the Urgonian reef limestones are locally intercalated with proximal sandstones. The east Gledićke and Šljivovac facies (Fig. 6c4, 5) shows an intermediate depth deposition, where more rapid (Šljivovac) or gradual deepening of facies (east Gledićke) took place as a function of their position in the sub-basin. This is observed by the rapid or gradual transition to Valaginian–Hauterivian limestone with cephalopods, or by inter-fingering between the cyclic clastic-carbonatic deposition with the Barremian–Aptian Urgonian facies in the east Gledićke facies.

The overlying Albian–Cenomanian sequence is regressive in the European sub-basin, but still maintains a differentiation between its centre and the margins. Except for the westernmost Stragari facies (Fig. 6c1), this sequence is observed beneath an overlying unconformity. In the centre of the sub-basin (e.g., near Rušanj, Fig. 3), pelagic Albian sediments are overlain by Upper Albian–Cenomanian shallow water littoral sandstones and conglomerates containing paleoflora (central Belgrade facies, Fig. 6c3). These sediments are laterally

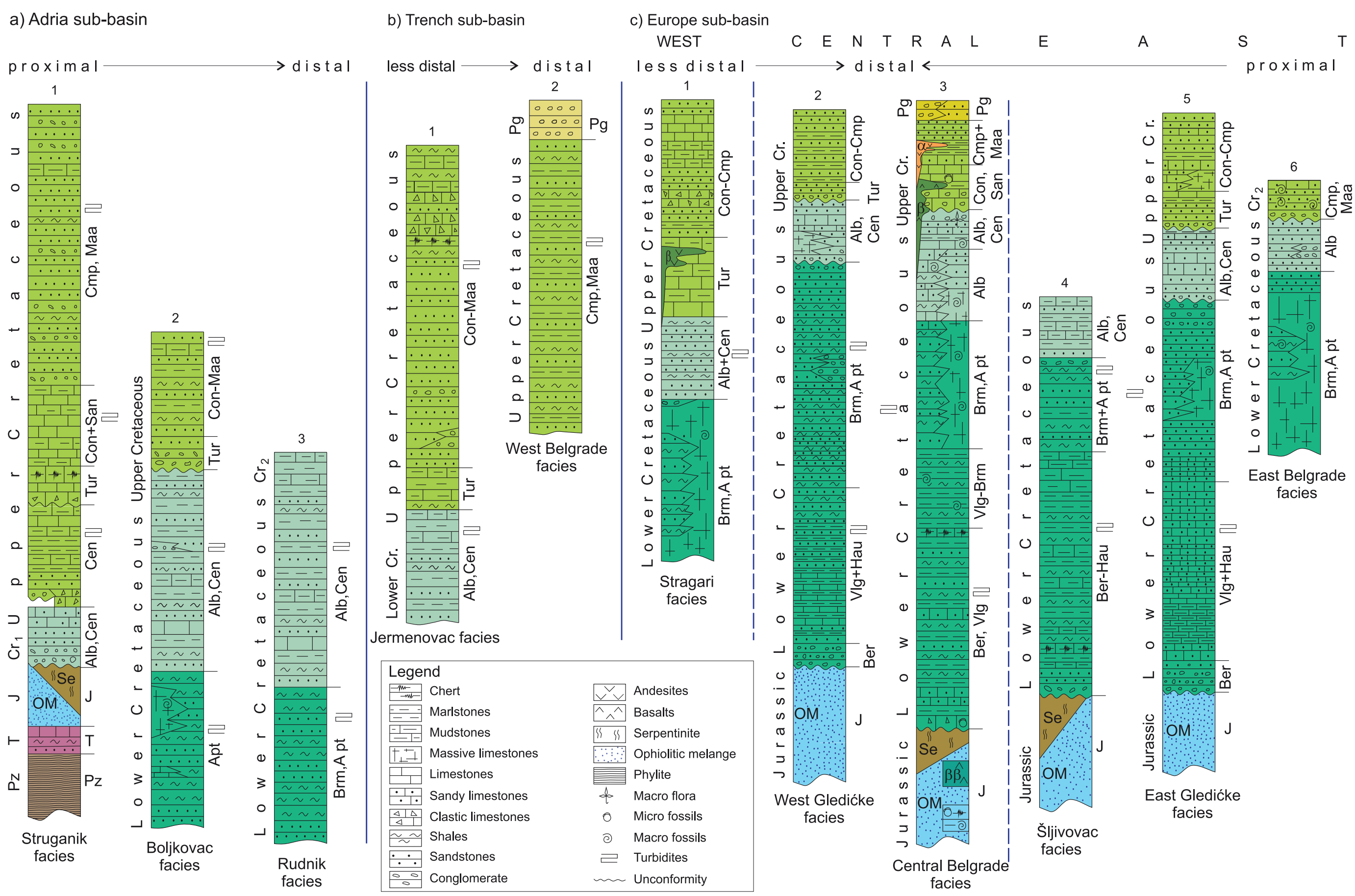

Fig. 6. Correlative-stratigraphic scheme of the Cretaceous - Early Paleogene fore-arc - trench - lower plate sedimentation made up by lithological and sedimentological columns in the areas of Belgrade, Rudnik - Arandelovac and Gledićke Mountains. Adria sub-basin is correlated between the Struganik, Boljkovac and Rudnik facies (1–3), the trench sub-basin is correlated between Jermenovac and West Belgrade facies (1–2), the Europe sub-basin is correlated between the Stragari, West Gledićke, Central Belgrade, Šljivovac, East Gledićke and East Belgrade facies (1–6). Abbreviations: Pz - Paleozoic, T - Triassic, J - Jurassic, OM - Ophiolitic melange, Cr1 – Early Cretaceous, Cr2 - Late Cretaceous, Ber - Berriasian, Vlg - Valanginian, Hau - Hauterivian, Brm - Barremian, Apt - Aptian, Alb - Albian, Cen - Cenomanian, Tur - Turonian, Con - Coniacian, San - Santonian, Cmp - Campanian, Maa - Maastrichtian, Pg - Paleogene.

replaced by Albian reef limestones (west Gledićke facies, Fig. 6c2). More intermediate-depth areas (Šljivovac and east Gledićke facies, Fig. 6c4, 5) show a transition from mudstones and laminated shelf sandstones. The eastern proximal part of the basin (east Belgrade facies, Fig. 6c6) shows an Albian shallow marine to littoral and continental deposition, dominated by conglomerates and glauconitic, ferruginous and oolitic sandstones (near Belgrade city) that alternates with shallow water reefs with high content of corals, crinoids and gastropods (near Koviona, Fig. 3, see also Pavlović, 1980; Anđelković, 1953; Marković et al., 1985; Toljić, 2006). In the western part of the sub-basin (Stragari facies, Fig. 6c1), the shallow water deposition continued by Albian–-Cenomanian clastic shelf to littoral sediments.

In summary, the European sub-basin shows a Berriasian–Aptian retrogradation followed by aggradation and progradation associated with a period of regression to an almost complete basin fill during Albian–Cenomanian times. Field observations show that this cycle of deposition is associated with the D1 thrusting event mapped in the Belgrade area.

5.1.2. The Upper Cretaceous–lowermost Paleogene cycle of deposition

The European sub-basin shows deeper marine Upper Cretaceous - lowermost Paleogene sediments in its centre (central Belgrade and west Gledićke facies), while gradual shallowing eastwards (Šljivovac, east Gledićke and east Belgrade facies) and westwards (Stragari facies) (Fig. 6c). This variability is better observed in the Belgrade area (east of the Belareka Fault), where the west and east Belgrade facies are separated by a local thrust (grey line in Fig. 3). This thrust is offset by a tear fault north of the Straževica locality and can be followed southwards along the entire studied area. The basal unconformity of the Upper Cretaceous–lowermost Paleogene sequence is diachronous in age both along and across the strike of the basin. This unconformity is erosional in most of the studied areas, except for the westernmost Stragari facies. Here, a correlative conformity separating the upper regressive part of the Lower Cretaceous–Cenomanian sedimentation from the transgressive part of the Upper Cretaceous–lowermost Paleogene cycle of deposition must be present in the shallow-water Turonian clastic limestones (Fig. 6c1).

In the central parts of the basin, the transgression started in all situations with continental and marine conglomerates and breccias, overlain by shallow marine coarse sandstones and limestones of variable thickness. These limestones in the central Belgrade facies (Fig. 6c3) contain clasts with an Upper Jurassic and locally Lower Cretaceous fauna, while the matrix contains a Coniacian–Santonian association of foraminifera (Fig. 3 and Table 1, Nos. 2, 3). In the same facies, similar limestones previously interpreted as Cenomanian or Coniacian–Maastrichtian (Mitrović, 1966; Marković, 1950; Ivković, 1975) yielded a pelagic foraminifera associations of post-late Santonian age (Fig. 3, Table 1, Nos. 6–9). Similarly, clastic limestones deposited over the basal conglomerates have a foraminifera association of Santonian age (west of Avala Mountain, Fig. 3 and Table 1, No. 4). The unconformity is overlain in the proximal east Belgrade facies (Fig. 6c6) by breccia limestones with clasts and fragments of marbles, or

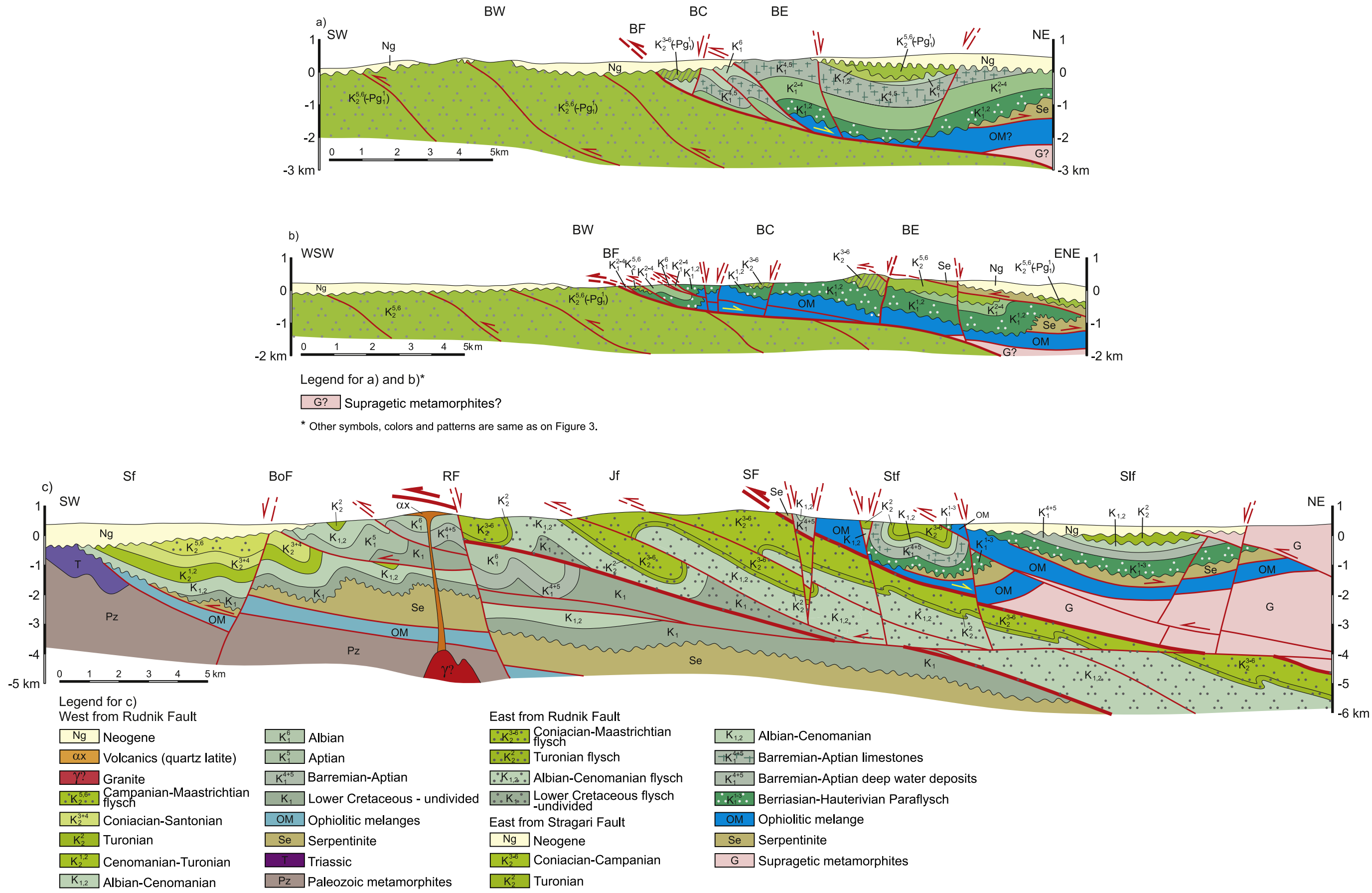

Fig. 7. – Geological and lithofacial cross-sections illustrating the Cretaceous structure of the Sava Zone in transects in the areas of Belgrade, Rudnik - Arandelovac and Gledićke Mountains. a) Cross-section in the northern part of the Belgrade area; b) cross-section in the southern part of the Belgrade area; c) cross-section in the area of Rudnik–Arandelovac and Gledićke Mountains. BF - Belareka Fault; BoF - Boljkovac Fault; RF - Rudnik Fault; SF - Stragari Fault. Possible Miocene reactivation shown in yellow half arrows. Location of cross-sections in Figs. 2 and 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

olistostromes composed of angular clasts of marbles, quartzites, and other metamorphic rocks, derived from the neighbouring Serbomacedonian basement (such as around Sopot, Fig. 3). These rocks contain a rudist fauna of Campanian–Maastrichtian age. South of Belgrade, the deposition in the central part of the sub-basin started with Turonian conglomerates (west and east Gledićke facies, Fig. 6c2 and 5). These observations demonstrate that the transgressive onset of the Late Cretaceous–earliest Paleogene deposition was diachronous. It started during Turonian to Coniacian in the central parts of the sub-basin over an erosional unconformity and arrived during the Campanian near its eastern margin, while westwards the erosional unconformity is replaced by a (Late?) Turonian correlative conformity between a regression and a transgression. This unconformity reflects a sequence boundary between the Lower Cretaceous–Cenomanian and Upper Cretaceous–lowermost Paleogene cycles of deposition.

Our field observations show that the onset of Upper Cretaceous sedimentation was associated with the D2 normal faulting event mapped in the Belgrade area. It was also associated with small volumes of volcanism (basalts and andesites, associated with trachyandesites and latites) that truncate and is intercalated in Coniacian–Santonian sediments in the central Belgrade facies (Fig. 6c3, see also Anđelković and Milojević, 1964). For instance, near Rušanj (Fig. 3) mudstones with a Late Cretaceous foraminifera association contain *syn*-depositional sharp, angular fragments of non-altered basalts (Fig. 5d) and display typical fracturing during cooling in non-consolidated sediments (peperite, Skilling et al., 2002). One other example (Tešića quarry, near Ripanj, Fig. 3) shows Lower Cretaceous clastic-carbonatic paraflysch sediments intruded by mafic volcanics and cross-cut by a dyke of leucocratic (quartz-)latites (Fig. 5e, see also Ilić and Knežević, 1969). Volcano-clastic and pyroclastic deposits are gradually replaced upwards by marls that contain a pelagic foraminifera association (Globotruncana and Globigerina) of Campanian age (Table 1, No. 10). South of Belgrade in the Rudnik–Arandjelovac transect (Stragari facies, Fig. 6c1), a similar volcanism is observed by sills or dykes of basalts, associated locally with peperites, which are intercalated in and covered by mudstones and marls of Early Turonian age.

The overall basal conglomeratic to shallow water sequence is gradually replaced upwards by deeper water sediments in the central and western parts of the European sub-basin (central Belgrade, and west Gledićke, and Stragari facies, Fig. 6c3 and 1, respectively). These are distal clastic sediments or immature turbidites deposited in the deeper parts of a shelf. The age of these sediments is Campanian–Maastrichtian in the central Belgrade facies and Coniacian-Campanian in the southern Stragari and west Gledićke facies (Fig. 6c). The contrast between the Campanian–Maastrichtian deep and shallow water facies is evident in the Belgrade area. While the east Belgrade facies remained in proximal settings (e.g., Toljić and Trivić, 1997), the coeval central Belgrade facies display a gradual transition to deeper water marls and mudstones to turbidites (such as west of Avala Mountain, Fig. 3), which started already during (Late) Santonian times (Fig. 3 and locality 11, Table 1). South of Belgrade, the transition between the central deeper and eastern more proximal facies can be observed in the east Gledićke facies where the earlier Turonian transgression is followed by a Coniacian–Santonian lateral transition between shallow reef and more distal platform carbonates (Fig. 6c5). To the west, the Upper Turonian–Campanian sequence overlying the volcanics in the Stragari facies (Fig. 6c1) shows a gradual deepening facies to turbidites (Fig. 6c1, see also Brković et al., 1980).

Similar with the earlier transgression, the Campanian–earliest Paleogene regression is also diachronous along strike of the basin. In the south, the regression took place during the Campanian times (Stragari and east Gledićke facies, Fig. 6c1 and 5, respectively). In the northern area of Belgrade, the regression is Campanian–Maastrictian, passing gradually from slope turbidites to shallow water coarse sandstones and conglomerates, the deposition possibly extending into the Lower Paleocene (see also Anđelković, 1973). The regressive pattern of complete basin fill has molasse-type characteristics and was deposited during the final moments of coeval D3 thrusting.

5.2. Cretaceous–Paleogene sediments deposited over the Adriatic margin (including trench deposition)

The sediments of the Adriatic margin show a gradual eastwards deepening of facies that was likely the result of an initial westwards transgression and final eastwards regression, recognised from Struganik to Boljkovac, Rudnik, Jermenovac and west Belgrade facies (Fig. 6a, b). Superposed over this first order pattern, two cycles of deposition (Lower Cretaceous–Cenomanian and Turonian–Paleogene) can be defined and are coeval with similar sedimentary cycles deposited over the European margin.

The sediments deposited during initial transgression crop out in the westernmost Struganik facies, where Albian- Cenomanian continental conglomerates overlie unconformably the ophiolites, their melange and Triassic sediments of the internal Jadar-Kopaonik unit of the internal Dinarides (Fig. 2). The overlying Albian–Cenomanian sequence remains in shallow water conditions (sandstones, breccia limestones and marls), interrupted by local unconformities (Fig. 6a1). The upper part of this sequence is truncated beneath a large erosional unconformity. The more distal facies (Boljkovac and Rudnik, Fig. 6a2, 3) shows a gradual Barremian–Aptian transition upwards and eastwards from distal shelf laminated clastic and carbonatic sediments (Boljkovac facies) to slope and distal turbidites (Rudnik facies). An Aptian episode of shallow water reef deposition in the Boljkovac facies indicates a more proximal position when compared to the Rudnik facies. The upper part of the Albian–Cenomanian sequence is regressive to distal shelf laminated clastics and carbonates, which are truncated by an overlying unconformity in the Boljkovac facies (Fig. 6a2, 3). The Lower Cretaceous–Cenomanian deposition in the eastward neighbouring trench is largely unknown (Fig. 6b1, 2). Only the Jermenovac facies exposes Albian–Cenomanian laminated clastics and carbonates (Brković et al., 1980; Dimitrijević, 1997) in a proximal shelf environment, which is the equivalent in deeper water environment of the same regression that ended the Lower Cretaceous–Cenomanian cycle over the Adriatic margin. In other words, the Albian–Cenomanian shallow water sediments of the Jermenovac facies contains the correlative conformity separating the upper regressive part of the Lower Cretaceous–Cenomanian cycle from the transgressive part of the Upper Cretaceous–earliest Paleogene cycle.

The transgression of the second cycle is well visible in the proximal sediments of the Adriatic Struganik and Boljkovac facies by Turonian continental conglomerates, breccias, shallow water sandstones and organogenic limestones deposited over an erosional unconformity. The sequence deepens rapidly to Turonian limestone with cherts and a thick succession of limestones and marls with radiolarites, previously dated to Coniacian-Santonian (Derić and Gerzina, 2014). The basin deepened and enlarged westwards by the ultimate deposition of the Campanian–Maastrichtian proximal slope high density turbidites (Ljig flysch) that is laterally replaced with more distal equivalents east of the Boljkovac Fault (Fig. 7c), i.e. in the Boljkovac facies (Fig. 6a1, 2). The upper part of Campanian–Maastrichtian sequence is regressive by a gradual increase of shallower water sandstones and conglomerates (Fig. 6a1).

The second depositional cycle is well observed in the trench deposition of the Jermenovac facies (Fig. 6b1, see also Brković et al., 1980; Dimitrijević, 1997). This area contains distal Turonian mudstones that are overlain by distal Coniacian–Maastrichtian clastic sediments with intercalations of olistrostromes made up by large blocks of Upper Cretaceous massive limestones, Jurassic cherts and sandstones. These are followed upwards in the stratigraphy by clastic-carbonatic turbidites. The upper part of this Coniacian–Maastrichtian deposition is made up by a transition from turbidites to deep and shallow water mudstones carbonatic breccias and other clastic deposits (see also Brković et al., 1980).

Deeper water trench deposition is also observed in the west Belgrade facies that exposes a Campanian–Paleogene sequence (Fig. 6b2). In agreement with previous interpretations (Obradović, 1987; Anđelković, 1973; Dimitrijević, 1997), we also interpret a deep-water low- to high-energy base slope clastic and carbonatic turbidites with frequent channels and coarse-clastic olistostrome intercalations. The more pelagic and finer clastic parts of these turbidites contain an association of nannoplankton previously dated as Early-Middle Maastrichtian (Mihajlović, 1986). The upper part of this sequence is rapidly regressive to coarse proximal marine or continental conglomerates. Previously dated nannoplankton and dinoflagellates in this upper part of the west Belgrade facies around Ostružnica (Fig. 3, De Capoa and Radoičić, 2002; De Capoa et al., 2002) infer an Oligocene age of deposition. Although such a young age is unique and has not yet been confirmed elsewhere, it is likely that the shallow water deposition in the upper part of this sequence continued at least during the Paleocene (see also Anđelković, 1973).

6. Interpretation and discussion

Our data demonstrate that the Cretaceous–earliest Paleogene deposition was associated with different styles of deformation in the studied orogenic segment crossing the Sava Zone. This differentiation is observed across a major structure that connects the Belareka Fault in the Belgrade area with its southward prolongation. In this prolongation, this major structure separates the west and east Gledićke together with the Stragari and Šljivovac lithostratigraphic facies from other facies located more westwards in the Rudnik - Arandelovac transect (Figs. 2, 3 and 7).

East of this structure, Cretaceous continental to shallow water shelf and proximal slope sediments were deposited in a basin that was shallower at its west and east margins. These sediments were deposited over the European Serbomacedonian basement and its Triassic Jurassic cover, including East Vardar Ophiolites obducted during Late Jurassic times in an area that was adjacent to the Sava Zone. These are clear characteristics of a fore-arc basin deposited over the continental basement and cover of an upper tectonic plate during subduction and collision.

West of this structure, Cretaceous continental to deep marine sediments were deposited in another basin presently overlying the Adriatic continental margin. The long-term deposition of thick deep-water turbidites locally associated with thrusting shows the continuous creation of accommodation space by contraction. In the context of the above-mentioned one ocean hypothesis this relationship can only be the result of subduction in a trench system that gradually evolved into a foredeep basin during the final regression. The Cretaceous transgression and shallow-water sedimentation over the Adriatic margin means deposition over a passive continental margin, where subsidence accelerated with the approaching trench during subduction. A clear separation between depositions in the trench and over the lower continental plate is not possible in our study due to juxtaposition during the subsequent collision.

While the trench to foredeep deposition still recorded only shortening associated with the overall transgression over the subducting Adriatic plate, the fore-arc basin started contractional during the Early Cretaceous–Cenomanian, switched to extensional during

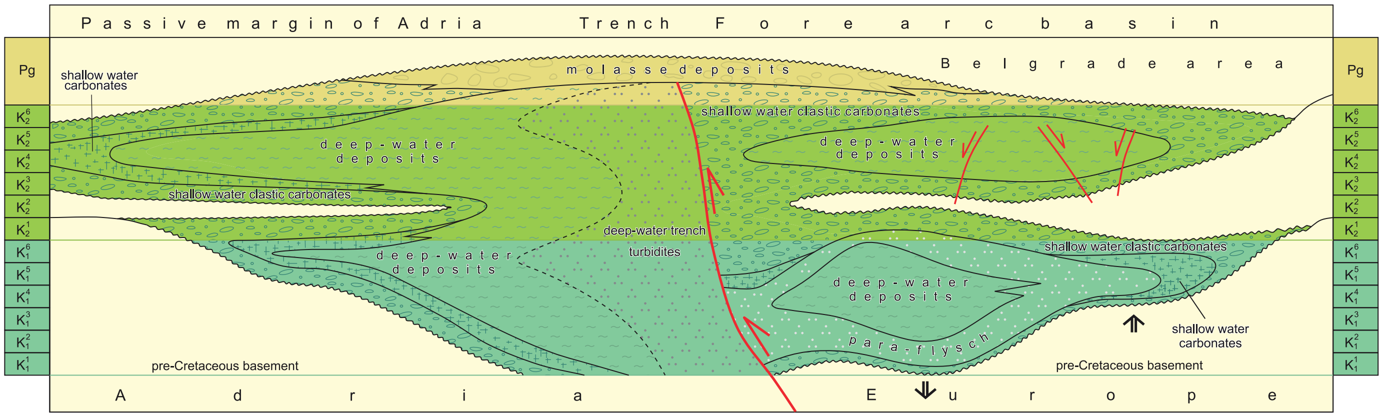

Fig. 8. Lithological and facial correlative interpretation of Cretaceous - Lower Paleogene sediments near the contact between Europe- and Adriatic-derived units along the Sava zone in the NE Dinarides derived from the data of the present study.

Turonian–Santonian, while it became again contractional during the Campanian–Early Paleogene collision. We further discuss more in details this tectonic and depositional evolution of the subduction system during Cretaceous times, which provides constraints for understanding the regional Dinarides orogenic system and provides also generic inferences for the evolution of fore-arc basins.

6.1. The fore-arc–trench–foreland system

Deposition started in the fore-arc basin at short times after the Late Jurassic emplacement of ophiolites. The Berriasian onset of coarse conglomeratic deposition is observed in all areas close to the basin centre (Fig. 6c). Although the base of the sequence is not exposed near the basin margins, the shallow-water proximal Barremian–Aptian facies and the overall subsidence suggests that the onset of transgression took place at later times in marginal areas, possibly during Valanginian–Hauterivian (Fig. 8). The overall transgression was associated with widespread NW–SE oriented contraction, as indicated by numerous Early Cretaceous thrusts observed in the field. An Albian–Cenomanian regression associated with a decrease in thrust faulting filled up gradually the depositional space created by the earlier subsidence. This filling resulted in the creation of an unconformity near the basin margins, laterally correlated with a correlative conformity in its deeper parts (Fig. 8). These observations demonstrate that the Early Cretaceous fore-arc evolution was driven by regional contraction. Despite numerous *syn*-depositional faults observed in the field, regional scale Early Cretaceous thrusts are less evident (Fig. 7) due to reactivations during the subsequent Campanian–Early Paleogene shortening event. Such reactivations can be demonstrated for the Belareka Fault and its hanging-wall imbricated system (Fig. 7a, b).

A new cycle of fore-arc sedimentation started during Turonian–Santonian times, the subsidence being associated with the onset of WSW–ENE to E–W oriented extension and associated volcanism (Fig. 8). This onset is diachronous along the orogenic strike, being Turonian in the south and Coniacian-Santonian in the northern Belgrade area. The Turonian–Campanian subsidence is higher in the fore-arc centre, the sedimentary facies gradually transgressing over its margins. A number of Late Cretaceous normal faults dipping both E- and W-wards has larger offsets, inferring a graben-type of structure that initiated deposition (Figs. 7, 8). Starting with Campanian times, normal faulting was replaced in the fore-arc by NE–SW oriented contraction and associated uplift. This uplift created a regression that filled up the basin during Maastrichtian–Early Paleogene times (Fig. 8).

The sediments overlying and thrusted over the Jadar-Kopaonik unit of the Adriatic margin recorded continuous contraction during the entire Cretaceous–early Paleogene evolution. The coeval facies gradually deepens in an E- to ENE-ward direction, i.e. in the direction of the former contractional trench, from more proximal at farther W to WSW distances over the Jadar-Kopaonik unit to more distal in an E to ENE direction (Figs. 6a, b, 8). Superposed over this regional pattern, two cycles are observed to be separated by a period of Albian–Cenomanian regression followed by a subsequent Turonian transgression. The separating erosional unconformity is visible in proximal deposition, being replaced by a correlative conformity in more distal areas (Fig. 8). Due to subsequent covering and reactivation, the regional Early Cretaceous thrusting was likely larger than what can be directly documented, for instance the thrust situated west of the Rudnik Fault (Fig. 7c). The upper part of the Cretaceous - Lower Paleogene sediments is regressive, has the character of a molasse sequence and, therefore, was deposited during the final collisional fill of the basin.

The Campanian–Early Paleogene thrusting coupled the deformation in the fore-arc with the one in the trench-foreland system (Fig. 7c). Large offset thrusts can be mapped regionally, such as the Belareka, Rudnik or Stragari faults (Fig. 7). Break-thrust folding is the main mechanism of deformation, such structures being often out-of-sequence, truncating an earlier deformed stratigraphy (Fig. 7c). Miocene normal faults ultimately truncated this entire orogenic structure. Surprisingly, these normal faults have lower offsets when compared with detachments affecting neighbouring areas, such as the Bukulja Mountains (Fig. 2, see Stojadinovic et al., 2013). The largest documented Miocene normal fault offsets the frontal part of the Rudnik thrust (Fig. 7c).

6.2. Regional correlations

We show that ophiolites and their melange are covered by a sequence that includes the Lower Cretaceous paraflysch (sensu Dimitrijević and Dimitrijević, 2009) in all the western areas of Belgrade and Arandjelovac–Gledićke Mountains (Figs. 5f and 7). Given the deposition of the paraflysch over the Serbo-Macedonian margin (Schmid et al., 2008), these ophiolites are, therefore, part of the Eastern Vardar Ophiolite unit that overlies the European margin in an area that was adjacent to the subduction zone during Early Cretaceous times. In other zones of the Dinarides and Apuseni Mountains of Romania, this ophiolitic unit is commonly overstepped by an Upper Jurassic sequence that gradually shallows to (Kimmeridgian?) conglomerates and/or Kimmeridgian–Tithonian reef limestones (e.g., Kukoč et al., 2015and references therein). In our study area, the shallow water limestones clasts, blocks and olistoliths containing Tithonian fauna found in the basal Cretaceous sequence infer that such an overstepping Upper Jurassic carbonatic sequence must have existed and was removed by erosion prior to the observed Berriasian onset of basin deposition.

The Early Cretaceous shortening recorded both by the fore-arc and the trench/lower plate system is a new observation in the NE Dinarides

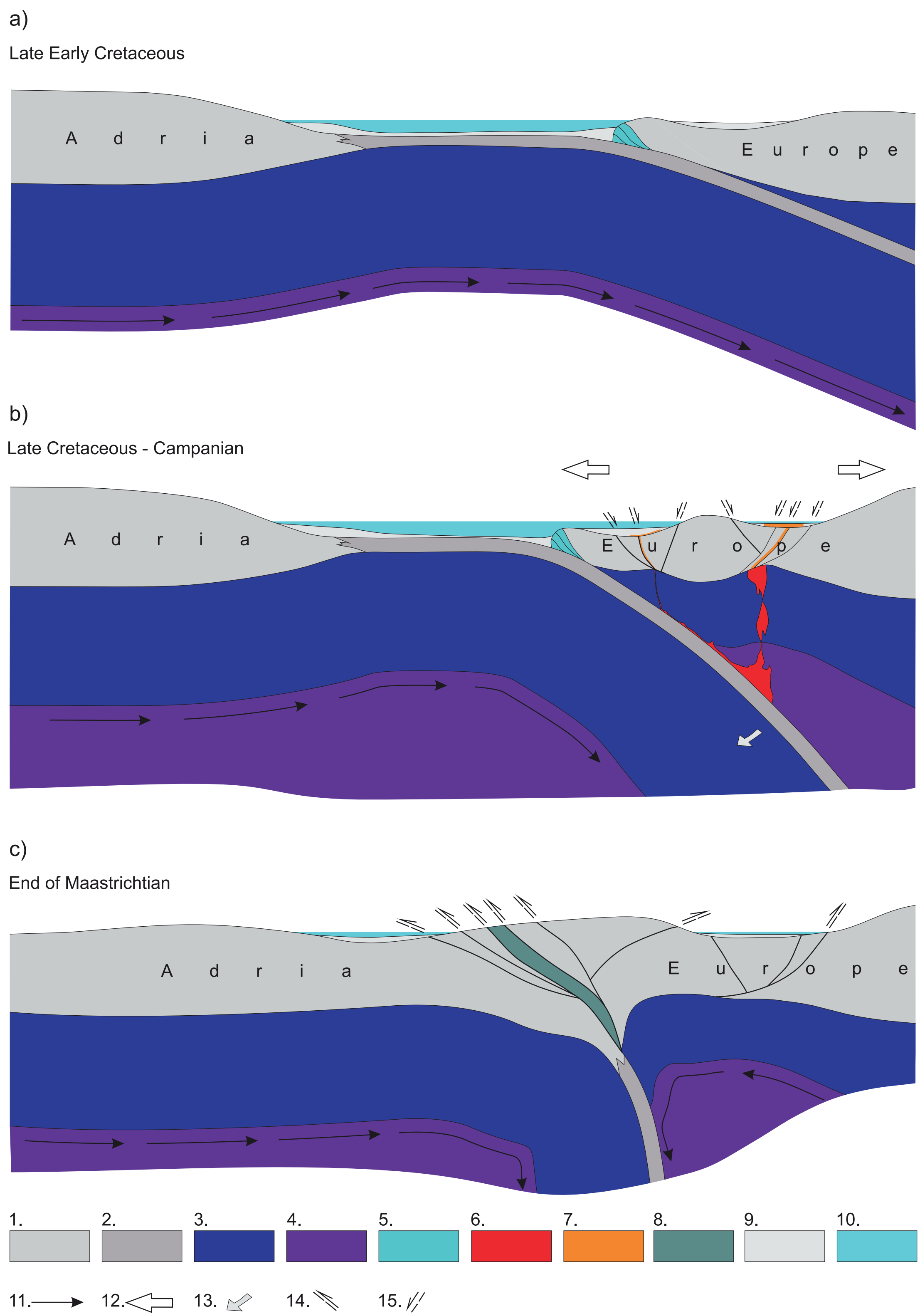

Fig. 9. Conceptual sketch of evolution of the subduction-fore-arc-back-arc system during Cretaceous–Early Paleogene times in the NE Dinarides. The sketch was built by combining the depositional model of Fig. 8 with generic numerical modelling of subduction and fore-arc systems (Gerya et al., 2008; Sizova et al., 2014), constrained by available interpretations of Dinarides tectonic evolution (Schmid et al., 2008). a) Latest Early Cretaceous times: low-angle subduction associated with accretion, subsidence and subsequent uplift of the fore-arc basin; b) Late Cretaceous (Santonian-Campanian) times: the extensional evolution of the fore-arc basin driven by initiation of slab roll-back and asymmetric asthenospheric uprise associated with partial melting and magmatism in the back-arc and fore-arc basins; c) Latest Cretaceous times: continental collision associated with contraction and exhumation in the fore-arc and the accretionary wedge, while the roll-back is continuing. Legend: 1. continental crust, 2. oceanic crust, 3. lithospheric mantle, 4. asthenospheric mantle, 5. accreted sediments, 6. melting and migration of melts, 7. volcanism, 8. suture zone, 9. sediments, 10. water, 11. asthenospheric circuit, 12. direction of extension, 13. direction of slab roll-back, 14. thrust fault, 15. normal fault.

and can be correlated with the shortening and/or metamorphism observed elsewhere. Late Early Cretaceous detrital white mica ages were previously reported in the Ljig flysch of our studied area (Ilic and Neubauer, 2005), which indicate that the observed Campanian - Maastrichtian deposition post-dated significant deformation and metamorphism of its source area. A post-Aptian erosional unconformity is observed elsewhere in the footwall of internal Dinarides thrusts to predate the Turonian onset of sedimentation (e.g., Dimitrijević, 1997). This unconformity is coeval with the Albian–Cenomanian regression observed in all our studied areas. Early Cretaceous burial or high-pressure metamorphic ages have been observed in Internal Dinarides in Fruska Gora (Fig. 2) and Medvednica Mountains of Croatia or Mid-Bosnian Schists Mountains of Bosnia and Herzegovina (e.g., Milovanovic et al., 1995; Pamic et al., 2004; Tomljenović et al., 2008; van Gelder et al., 2015). In the eastern neighbouring Carpathian-Balkanides orogen, this deformation correlates with a regional late Early Cretaceous shortening event (Iancu et al., 2005; Kounov et al., 2010). All these indicate that the Albian–Cenomanian regression observed in the study area was coeval or post-dated a regional tectonic contraction and associated uplift that affected both European and Adriatic margins.

The Turonian–Campanian extension and associated minor volcanism migrated with time along the orogenic strike from south to north and was restricted in space to the European fore-arc basin. Based on similar ages and lithofacies characteristics, similar Upper Cretaceous sediments are often referred in the Dinarides as Gosau deposits (Borojević Šostarić et al., 2012; Neubauer, 2015; Tomljenović et al., 2008) analogous to coeval and similar deposits widely observed in the Eastern Alps. The onset of deposition of these Gosau sediments in the Eastern Alps took place in response to syn-orogenic normal faulting (Neubauer et al., 1995; Wagreich and Decker, 2001), interpreted to reflect either the collapse of thickened and gravitational unstable continental crust (Willingshofer et al., 1999; Neubauer, 2015) or, alternatively, related to back-arc extension (Froitzheim et al., 1997). Many of sediments previously attributed to Gosau sedimentation in the Dinarides are only syn-contractional, observed along nappe contacts (see Dimitrijević, 1997; Dimitrijević and Dimitrijević, 1987; Matenco and Radivojević, 2012; Toljić et al., 2013; Schmid et al., 2008). Therefore, the generalisation of a regional orogenic collapse cannot be made in the Dinarides, the Late Cretaceous extension being localised either in areas of interference with the Eastern Alps (such as Medvednica Mountains, van Gelder et al., 2015) or in the European forearc, as shown in our study.

The coeval emplacement of minor amounts of volcanics was structurally controlled by the extension. Late Cretaceous magmatism with similar Turonian–Santonian ages has been observed in other areas of the Dinarides located in the vicinity of the Sava Zone, such as Moslavačka Gora or Kozara of Croatia and Bosnia and Herzegovina (Anđelković, 1973; Brković et al., 1980; Čanović and Kemenci, 1988; Pamic et al., 1989; Pamic et al., 2000; Karamata et al., 1999; Toljić, 2006; Grubić et al., 2009; Ustaszewski et al., 2009; Cvetković et al., 2014), although their genesis is rather debated in these studies. One other relevant example of magmatism located in a similar position near the Sava Zone are the Klepa basalts of Macedonia (FYROM), far south of our studied area. These basalts were geochronologicaly dated at ~80–81 Ma (Campanian), interpreted to result from either ridge subduction creating fore-arc magmatism or intracontinental volcanism related to transtensional tectonics (Prelević et al., 2017). The subduction hypothesis associated with transtension correlates well with our data of coeval volcanism and extension. More importantly, the minor extensional controlled Turonian–Santonian volcanism of our studied area was almost coeval with the emplacement of much larger volumes of back-arc calk-alkaline magmatism and extension. This magmatism and extension took place at ~90–87 Ma in the Timok extensional structure of eastern Serbia (Fig. 2), commonly interpreted to be driven by the Neotethys subduction (Cvetković et al., 2000; Cvetković et al., 2013; Gallhofer et al., 2015; von Quadt et al., 2005). This correlation means that the emplacement of Turonian–Santonian magmatism was controlled by regional back-arc and fore-arc extension in the Serbian Dinarides-Carpathians orogenic transect (Fig. 1c).

The Campanian–early Paleogene period of contraction and final collision of the Dinarides is rather well described at the scale of the entire orogen and is at least partly coeval with the shortening recorded along many other Dinarides thrusts (e.g., Schmid et al., 2008; Schefer et al., 2010; Ustaszewski et al., 2010). Our study infers that the contraction continued at least during the Early Paleogene near the Sava Suture Zone, albeit at much lower rates.

When considering the one-ocean hypothesis of Schmid et al. (2008), our interpretation results in a geodynamic scenario that assumes Cretaceous oceanic subduction followed by continental collision, while the evolution of the fore-arc was controlled successively by contraction, extension and, ultimately, back to contraction during collision (Fig. 9). Alternative hypotheses that do not account for a (Late) Cretaceous oceanic subduction (e.g., Robertson et al., 2009 and references therein, see also discussions in Cvetković et al., 2014; Prelević et al., 2017) must account for the Cretaceous subduction of a wide and thinned Adriatic thinned passive continental margin to account for our data. Rapid temporal changes in the kinematics of a fore-arc basin overlying a continental subduction zone are less likely due to the inherent buoyancy of such a system. Therefore, our observations are rather in agreement with the interpretation of a Cretaceous oceanic subduction system that predated the latest Cretaceous continental collision.

6.3. Inferences for the generic evolution of fore-arc areas

The balance between tectonic erosion and accretion, the magmatism and the evolution of subduction zones (e. g. Capitanio et al., 2010; Melnick and Echtler, 2006; Noda, 2016; Stern, 2011), are the relevant parameters controlling the fore-arc subsidence and trench deposition in our study. The accumulation of a thick Early Cretaceous accretionary wedge partly overlying the fore-arc is widely known in oceanic subduction systems that are associated with tectonic accretion, possibly taking place at low convergence velocities (e.g., Clift and Vannucchi, 2004; Regalla et al., 2013). The switch to a regressive facies and less accretion of sediments observed in Albian–Cenomanian times cannot represent a switch to tectonic erosion because of the associated uplift in the fore-arc basin and the overall contraction that is recorded in the entire orogenic transect. Because there are no slab effects known for this time interval, it is likely that the Albian–Cenomanian switch is an effect driven by external factors. For instance, given the fact that the Europe - Africa convergence takes place at relatively constant rates (Kreemer et al., 2003), the switch can be a far-field effect of the onset of the orogenic collision and slowing the convergence recorded by the neighbouring Carpathian orogen that may have accelerated the subduction of the Neotethys, reduced the tectonic accretion and initiated regional contractional uplift. Such far field effects are otherwise known in other areas of the Africa–Europe convergences, for instance the initiation of subduction in the Piedmont-Liguria segment of the Alpine Tethys due to the opening of its Valaisan branch (e.g., Schmid et al., 2004).

The Turonian–Santonian switch to subsidence, extension and magmatism in the fore-arc and back-arc associated with reduced tectonic accretion and/or tectonic erosion in the subduction system was associated with a period of slab retreat and steepening. The change was less significant when compared with typical switches between sedimentation and erosion in modern accretionary wedges (Ishizuka et al., 2006). While classical models of magma generation during oceanic subduction assume the formation of wide magmatic arcs (e.g., Cawood et al., 2009; Dewey, 1980), more recent quantitative models demonstrate that hydration and partial melting along subducting slabs can be generated in multiple ways that may include, for instance, the formation of asthenospheric circuits, Rayleigh–Taylor instabilities evolving into partially molten diapiric structures, or tectonic underplating of trench sediments beneath magmatic arcs (e.g., Babeyko et al., 2002; Ducea et al., 2009; Vogt et al., 2012; Zhu et al., 2013). Migration of magmas towards the fore-arc by mechanisms such as relamination or eduction is observed during dynamic slab processes, such as roll-back, delamination or slab-detachment, their emplacement can be triggered during period of upper plate exhumation or extension (e.g., Faccenda et al., 2009; Gerya et al., 2008; Menant et al., 2016; Sizova et al., 2014). The Dinaridic slab retreat and steepening was not only responsible for the large magmatic emplacement and extension in the main Late Cretaceous magmatic arc (von Quadt et al., 2005; Gallhofer et al., 2015), but also facilitated extension associated with minor volcanism in the fore-arc.

The ultimate Campanian–Early Paleogene switch was associated with large-scale shortening accompanied by larger tectonic accretion, deformation coupled the entire fore-arc, accretionary wedge and down-going lower plate system. Given its timing in the context of our data and previous interpretations (e.g., Schmid et al., 2008; Ustaszewski et al., 2010), this switch was initiated by the continental collision. The change between subsidence and uplift in the fore-arc and trench took place during Maastrichtian time, when the entire oceanic crust was already consumed.

7. Conclusions

The contact between Adriatic and European-derived tectonic units observed in the NE Dinarides is a key area to understand the evolution of a complex structural-depositional system that evolved during the closure of the Neotethys Ocean. In order to understand the evolution of the Neotethys subduction system and its Cretaceous European fore-arc basin, we have employed a combined structural, kinematic, stratigraphic and depositional study in the NE Dinarides of Serbia. Our study has demonstrated a complex interplay between the subduction dynamics and the evolution of the overlying sedimentary basins in the Cretaceous–Early Paleogene fore-arc, trench and lower plate system that was subsequently modified by the Miocene extension of the Pannonian Basin.

Following the widespread obduction and emplacement of ophiolites, deposition associated with contractional deformation took place in the trench–accretionary wedge system and over the Adriatic margin throughout entire Cretaceous–Early Paleogene times. Deposition in the European fore-arc basin started with contraction during the earliest Cretaceous and was interrupted by regional Albian–Cenomanian moment of regression that took place at the scale of the entire system. The fore-arc kinematics and associated sedimentation changed with time from Early Cretaceous–Cenomanian contraction to Turonian–Santonian extension. The Campanian–Early Paleogene thrusting during continental collision inverted the fore-arc basin and ultimately locked the entire subduction system from the European fore-arc to the Adriatic lower plate. The new understanding of a fore-arc system that recorded variable deformation during Cretaceous times has important consequences for understanding the regional evolution of the Dinarides. The regional extension affecting the entire fore-arc and back-arc European domain has facilitated the emplacement of the Turonian–Santonian magmatism in the studied collisional segment of the Dinarides and was triggered most likely by slab roll-back and steepening. We show that key constrains on the evolution of subduction and collision can be obtained by the study of such fossil fore-arc–trench systems, such as periods of generalised uplift, fore-arc magmatism and understanding switches in tectonic regimes and associated sedimentation.

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