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Geodynamic interpretation of the Late Cretaceous syn-depositional magmatism in central Serbia: Inferences from biostratigraphic and petrographical investigations

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Abstract: High-resolution biostratigraphic dating of (hemi)pelagic limestones stratigraphically adjacent to syn-depositional bimodal magmatites in central Serbia, based on planktonic foraminiferal assemblages, determines that the magmatism occurred during Coniacian to Santonian. This bimodal magmatism, which includes both basaltic magmas with associated peperites and trachydacitic magmas, was associated with syn-subductional extension, which was triggered by roll-back and steepening of subducting Neotethys oceanic lithosphere, located between the converging continental margins of Adria and Europe. The Late Cretaceous extension led to subsidence and formation of a fore-arc basin above the subduction zone. Co-genetic magmatic occurrences, including basalts, trachydacites, and lamprophyres, are distributed in the same fore-arc domain along the entire European continental margin. The fore-arc magmatism migrates in space and time from the south towards the north and north-west.

Keywords: syn-subductional extension, bimodal magmatism, biostratigraphy, fore-arc basin, central Serbia.

Introduction

Evolution of fore-arc basins, due to their unique position above the subduction zones, is directly controlled by subduction-related processes. These processes induce different types of sedimentation, variable deformation styles, and also control features and intensity of associated magmatism (Reagan et al. 2010; Noda 2016). Subduction-induced magmatism in the upper plate of a subduction system is manifested in the island arc, and fore- and back-arc basins (Stern et al. 2014; Gallhofer et al. 2015). Although an active subduction system, as an area of convergence, is generally exposed to compression, extensional strain can exist in the fore-arc, island arc, or the back-arc, as a result of a retreat of the subducting slab (Jolivet et al. 2013; Andrić et al. 2018). The ongoing subduction is often followed by slab rollback (Jolivet et al. 2013). This is followed by plate decoupling, extension, and magmatism that often affects the upper plate (Acocella 2014; Bettina et al. 2014).

A Cretaceous closure of the northern branch of Neotethys Ocean resulted in formation of the Sava suture zone between Adriatic- and European-derived continental units (Pamić 2002; Karamata 2006; Schmid et al. 2020). The interplay between ongoing convergence and roll-back of the subducting slab controlled geodynamic evolution of basins formed on and near the Adriatic passive margin, trench and the fore-arc basin on the active European margin (Toljić et al. 2018). Sedimentary infill of the fore-arc basin was associated with syn-depositional bimodal magmatism (Toljić 2006; Toljić et al. 2018). However, the ages of extension and associated magmatism are still not fully constrained. In this study, we use high-resolution biostratigraphy based on planktonic foraminifera combined with petrographical observations to study the geodynamic evolution of a fossil fore-arc system, situated along the active European continental margin in central Serbia.

Geological setting of the fore-arc basin in the active European margin

The present-day complex architecture of the Adria–Europe suture (Fig. 1) is the result of Mesozoic evolution in the northern branch of Neotethys Ocean (i.e. Meliata–Maliac–Vardar Ocean of Schmid et al. 2020; or Vardar Ocean of Dimitrijević 1997). The effects of tectono-depositional evolution of the Neotethys Ocean and the adjoining Adriatic and European continental margins can be recognized in three major tectonic units characterized by contrasting lithostratigraphic and structural features. Going from the west towards the east there are: (i) Jadar–Kopaonik Unit of the Adriatic passive margin with obducted Western Vardar ophiolites; (ii) Sava suture zone and (iii) the European margin with obducted Eastern Vardar ophiolites (Fig. 1b, Dimitrijević 1997; Schmid et al. 2020). These three tectonic units represent three different domains in which

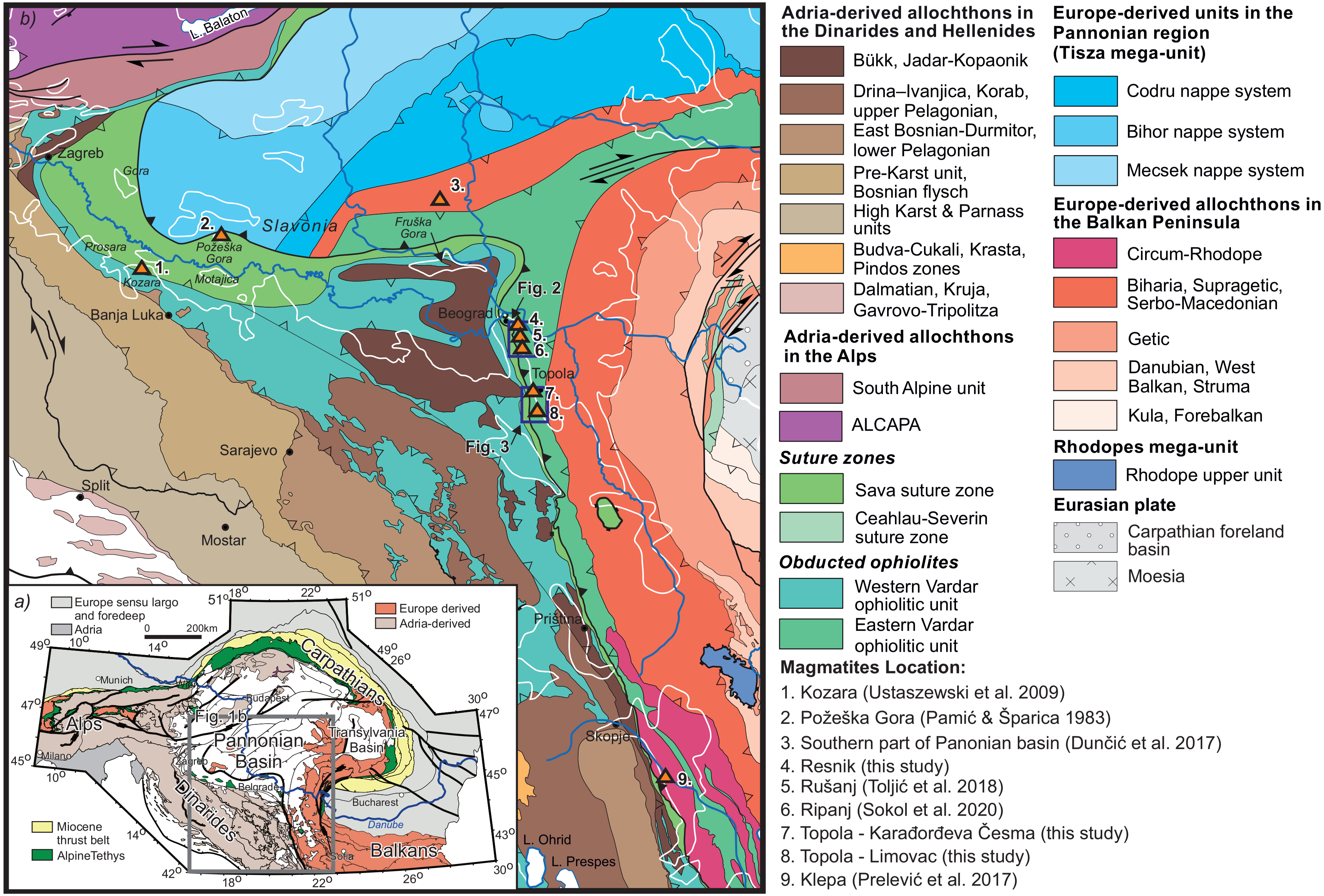

Fig. 1. a — Tectonic map of the Alps–Carpathians–Dinarides system with the main tectonic units (modified after Schmid et al. 2008). The grey rectangle indicates the location of Fig. 1b. Tectonic map of the contact area between Europe- and Adria-derived units in central Serbia (after Schmid et al. 2020). The map shows locations of magmatites (orange triangles) along the Adria-Europe suture. The black arrows and rectangles indicate the locations of Figs. 2 and 3.

their Cretaceous sedimentary covers were deposited. From west to east, these domains are basin(s) of the Adriatic passive margin, subduction trench, and fore-arc basin of the European active margin (Toljić et al. 2018).

Cretaceous sediments of the Adriatic margin, located west from the study area, record Albian–Cenomanian transgression and Late Cretaceous subsidence that resulted in a gradual deepening of the sedimentary facies (Toljić et al. 2018). In the Belgrade area the trench basin infill, located in the footwall of the basal thrust of the Eastern Vardar ophiolitic unit (i.e. the Bela Reka Fault), is Upper Cretaceous deep water turbidites and Paleogene molasse sequence (Fig. 2). Recently in the hanging wall of the Bela Reka Fault, the fore-arc basin sequences of the active European margin overlie obducted ophiolites and their mélange. The basin was primarily filled with Lower Cretaceous calciturbidites gradually passing upward into shallow water Urgonian Limestone. The Urgonian carbonate platform sedimentation was subsequently replaced by the deposition of regressive Albian–Cenomanian clastic sequences (Toljić 2006). Albian–Cenomanian contraction and rock uplift of the fore-arc basin were followed by Upper Cretaceous phase of extension, which caused a new subsidence and sedimentation of carbonates associated with fragments of trachydacites and their volcaniclastics (Karamata et al. 1999; Toljić 2006), basalts (Toljić et al. 2018) and intrusions of lamprophyres (Sokol et al. 2020). This volcano-sedimentary sequence was replaced upward by Campanian–Maastrichtian calciturbidites and Paleogene molasses. South from Belgrade, the basal thrust of the Eastern Vardar ophiolitic unit (Stragari Fault, Fig. 3; Dimitrijević 1997) separates Upper Cretaceous flysch deposits of the Sava suture zone in the footwall from Lower and Upper Cretaceous sediments of the fore-arc basin in the hanging wall eastward (Toljić et al. 2018). The immediate basement of the Cretaceous fore-arc basin is built-up of Upper Jurassic ophiolites and ophiolitic mélange that outcrop significantly in the area south of Topola (Fig. 3). The initial Lower Cretaceous basinal infill is made up by Beriassian to Albian–Cenomanian turbiditic sequence and shallow-water carbonates (Dimitrijević 1997). In contrast to the Belgrade area, Albian–Cenomanian contractional episode did not expose sedimentary infill of the fore-arc basin to subaerial conditions. The subsequent extension and subsidence was associated with the deposition of (hemi)pelagic marls and marly limestones, along with the syn-depositional basaltoid volcanics (Brković et al. 1980). Further deepening of the basin during the Late Cretaceous resulted in the deposition of clastic turbidites. This phase was followed by sedimentation of post-Campanian regressive sequences which consist of breccias, breccia limestones, olistostromes, and coarse-grained clastic deposits (Brković et al. 1980, Toljić et al. 2018).

The Late Cretaceous bimodal magmatism

The Upper Cretaceous bimodal magmatites, which include rhyolites, andesites, basalts, and lamprophyres, can be traced along the entire European margin from the north-west to the south-east (Fig. 1b). These magmatites were previously interpreted as a part of the Vardar Zone (Dimitrijević 1997; Karamata et al. 1999), Sava suture zone (e.g Ustaszewski et al. 2009; Prelević et al. 2017), or as a result of magmatism in the fore-arc basin of the active European margin (Toljić et al. 2018). The westernmost occurrence of such bimodal magmatites, reported from the Kozara Mts. (1 in Fig. 1b), consists of Upper Cretaceous isotropic gabbros, doleritic dikes, basaltic pillow lavas, and rhyolites incorporated in the regional thrust system at the south-western edge of the Sava suture zone in the vicinity of the Adriatic passive margin. These magmatites are interpreted as products of intra-oceanic magmatism in the ocean-island or the back-arc setting (Ustaszewski et al. 2009). To the north-east of the Kozara Mts., Upper Cretaceous sediments in the Požeška Gora Mts. (2 in Fig. 1b) associated with syn-depositional basalts and rhyolites (Pamić & Šparica 1983), were intruded by dolerites and granites that are interpreted as products of magmatism in an extensional zone within the continental crust (Belak et al. 1998). Bimodal volcanics were also drilled beneath the Neogene cover of the Pannonian Basin north from the Fruška Gora Mts. (3 in Fig. 1b). In this location, sediments associated with basalts and/or pyroclastic breccias, which include fragments of diabases, spilites, rhyolites and associated tuffs, were products of synchronous multi-phase submarine Late Campanian–Early Maastrichtian volcanism (Dunčić et al. 2017). In addition to the Upper Cretaceous sediments and volcanics, well logs below Cretaceous deposits also show the presence of Upper Jurassic ophiolites and ophiolitic mélange of the Eastern Vardar ophiolitic unit (Dimitrijević 1997; Schmid et al. 2020). Further to the south, Jurassic ophiolites, ophiolitic mélange, Lower Cretaceous "paraflysch" sediments, and lithologically heterogeneous Upper Cretaceous sediments and volcanics, can be traced from Belgrade towards Greece. All these sequences are part of the Eastern Vardar ophiolitic unit whose tectonic position corresponds to the active European margin (Dimitrijević 1997; Schmid et al. 2020). Bimodal volcanics and their pyroclastics in the Belgrade area (4–6 in Fig. 1b) are also Late Cretaceous in age (Karamata et al. 1999; Toljić et al. 2018; Sokol et al. 2020). These volcanics show calc-alkaline character (Karamata et al. 1999). Hence, it seems plausible that initial mantle-derived magma (Sokol et al. 2020 and references therein) was contaminated with continental crust material which could represent the fundament of the active European margin fore-arc basin. Further to the south, syn-depositional basaltoid volcanism in the Topola area (7, 8 in Fig. 1b) has Turonian age (Brković et al. 1980). The southernmost occurrences of syn-depositional basalts in Klepa locality (9 in Fig. 1b) were stratigraphically defined as Turonian (Rakićević et al. 1973), while novel isotopic dating sets their age to Campanian (Prelević et al. 2017). In the Klepa area, shallow-water Turonian deposits are transgressive over Paleozoic metamorphics, Triassic sediments, and Jurassic ophiolites, and are tectonically separated from the Upper Cretaceous flysches of the Sava suture zone (Rakićević et al. 1973; Schmid et al. 2008). Therefore, the Turonian sediments, along with

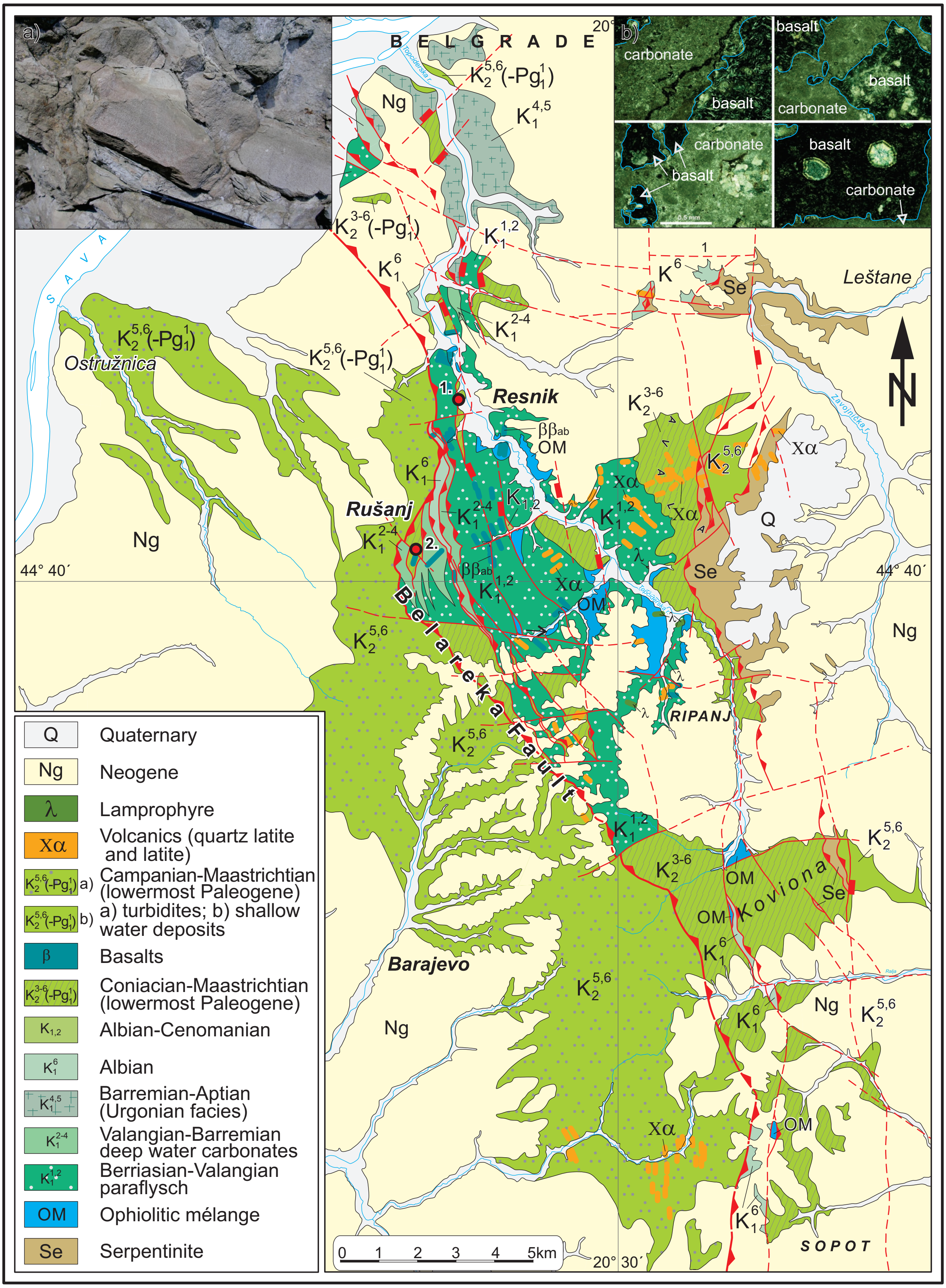

Fig. 2. Simplified geological map of the Belgrade area (modified after Toljić 2006). The map contains locations of outcrops with Upper Cretaceous magmatites (red circles): 1 — Resnik area with the volcanoclastics of trachy-dacites; 2 — Rušanj area with syn-depositional basalts. Inserts: **a** — Field photo of trachy-dacitic volcaniclastics associated with Upper Cretaceous marls from the locality near Resnik. **b** — Peperites thin-section – basalts associated with Upper Cretaceous limestones from locality near Rušanj. The blue line separates basalts and carbonate parts in peperite.

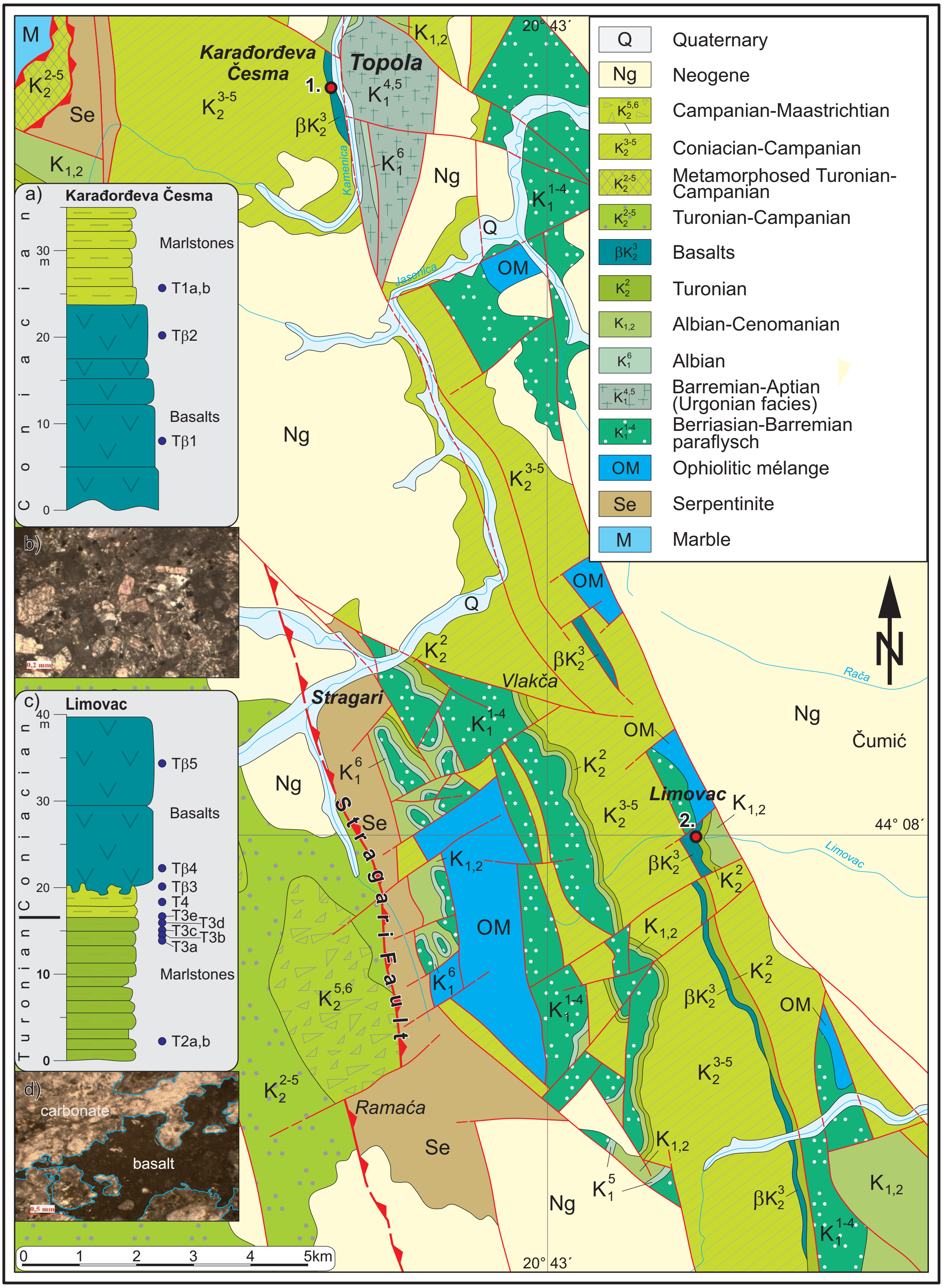

Fig. 3. Simplified geological map of the Topola area (modified after Brković et al. 1980). The map contains locations of outcrops with Upper Cretaceous basalts and sediments (red circles): 1 — Karađorđeva Česma; 2 — Limovac area. Inserts: **a** — Local geological column with basalts and sediments at locality Karađorđeva Česma. **b** — Photomicrograph of clinopyroxene phenocrysts in basalt from the location Karađorđeva Česma (xpl). **c** — Local geological column with sediments and basalts at the locality Limovac. **d** — Dendritic contact (blue line) in peperites between basalt and Upper Cretaceous marlstones at the location Limovac.

the associated basalts in the Klepa, most likely belong to the Eastern Vardar ophiolitic unit and were deposited in the fore-arc domain (Toljić et al. 2018).

Methodology

Late Cretaceous extension in the fore-arc basin located on the active European margin was associated with magmatism. Taking into consideration the syn-depositional nature of one part of the volcanics and their spatial interferences with sediments, we conducted biostratigraphical and petrographical investigations of such sediments associated with volcanics in order to determine their stratigraphic position. A similar methodological approach was successfully implemented in dating of volcanic rocks in the Late Cretaceous Kapanboğazı formation of the Pontides in northern Turkey (Tüysüz et al. 2016). The research was conducted in two areas (Fig. 1b), the northern one represents the Belgrade area (Fig. 2), while the one situated further to the south belongs to the wider area of the town of Topola (Fig. 3).

Biostratigraphic methods

A total of 18 thin-sections produced of (hemi)pelagic to volcano-sedimentary rocks from three locations have been investigated by thin-section analysis with an optical microscope to determine the microfossils. The thin-sections are housed in the collections of the Geological Survey of Serbia and at the Faculty for Mining and Geology in Belgrade, under inventory numbers which are referred to in the text.

Two-dimensional well-cut views of planktonic foraminifera as the main components in all microscopic assemblages were studied and identified in thin-sections. Identification of twenty-nine species belonging to the genera *Marginotruncana*, *Dicarinella*, *Whiteinella*, *Falsotruncana, Globotruncana* and *Contusotruncana* has led to the recognition of three biostratigraphic zones, in ascending order: *Marginotruncana sigali*–*Dicarinella primitiva* Zone, *Dicarinella concavata* Zone and *Dicarinella asymetrica* Zone. The bases for the identification, age determination and definition of planktonic foraminifera biozones are results of Robaszynski & Caron (1979, 1995), Caron (1985), Sliter (1989), Premoli-Silva & Sliter (1994), Robaszynski et al. (2000), Premoli-Silva & Verga (2004). The obtained results were furthermore correlated with recent northern Tethyan Upper Cretaceous planktonic foraminifera zonal schemes (e.g. Radoičić & Buser 2004; Sari 2006; Ljubović-Obradović et al. 2011).

Petrographical methods

In addition, petrographic investigations of 5 basalt and peperite samples have been conducted at the Faculty of Mining and Geology in Belgrade. Thin-sections of the selected samples were optically analyzed using a petrographic polarized microscope for transmitted light (Leica DMLSP), connected to a Leica DFC290 HD camera over the application LAS V4.1. All photomicrographs were made under crossed polars (xpl).

Results

Results of biostratigraphic investigations

Belgrade area

The sampling campaign for biostratigraphic analyses was conducted in the Belgrade area from the localities Ripanj, Rušanj and Resnik (Fig. 2, locality 1, 2). Near Resnik we sampled two sequences of marls with tuffs together with their cover. Sample R1 comes from the lower part of the first marl sequence, samples R2 to R7 are from the second marl sequence, while sample R8 was collected in tectonized marls 20 metres further to the east from the main outcrop. Marls and marly limestones associated with trachy-dacitic volcaniclastics (Fig. 2a, locality 1) contain microfossil association. In thin sections planktonic foraminifera were recognized as the main component, followed by microplankton – calcisphaeres including pithonellae, radiolaria, relatively rare and small rotaliform, miliolid or other benthic foraminifers, crinoids or echinoderm plates, bivalve fragments etc. Total abundance and species diversity of planktonic foraminifers varies from moderate (in sediments with admixtured volcaniclastic material) to high (in pelagic limestone), while preservation also varies from poor to moderate.

The important identified planktonic foraminifera are in the lower part of the section: *Marginotruncana renzi*, rare *Marginotruncana* cf. *angusticarinata* and *Marginotruncana coronata*, *Globotruncana lapparenti*, *Globotruncana arca*, *Globotruncana* cf. *bulloides*, *Contusotruncana fornicata*. In the upper part of the section, the significant species are: *Marginotruncana* cf. *sigali*, more frequent *Marginotruncana coronata*, *Marginotruncana* cf. *pseudolinneiana*, *Globotruncana hilli*, *Dicarinella concavata* and *Whiteinella baltica*. The most important bioevent is a first occurrence of *Dicarinella* aff. *asymetrica* in R3b thin-section (Fig. 4, for accompanying species please see Appendix – Table A1).

Topola area

The sampling campaign in the Topola area was conducted at the localities Karađorđeva Česma and Limovac (Fig. 3). The carbonates which are overlying basalts were sampled at the location Karađorđeva Česma (T1). At the location Limovac, marls and peperites located immediately below basalts were collected (T4, T3/a–d samples for sediments) along with marl samples from deeper levels situated some 20 metres further east (samples and thin-sections number T2). A part of the column where T3 samples were collected is characterized by abundant microfossil fauna, and therefore 5 different thin sections (T3a, T3b, T3c, T3d and T3e) were prepared from these samples.

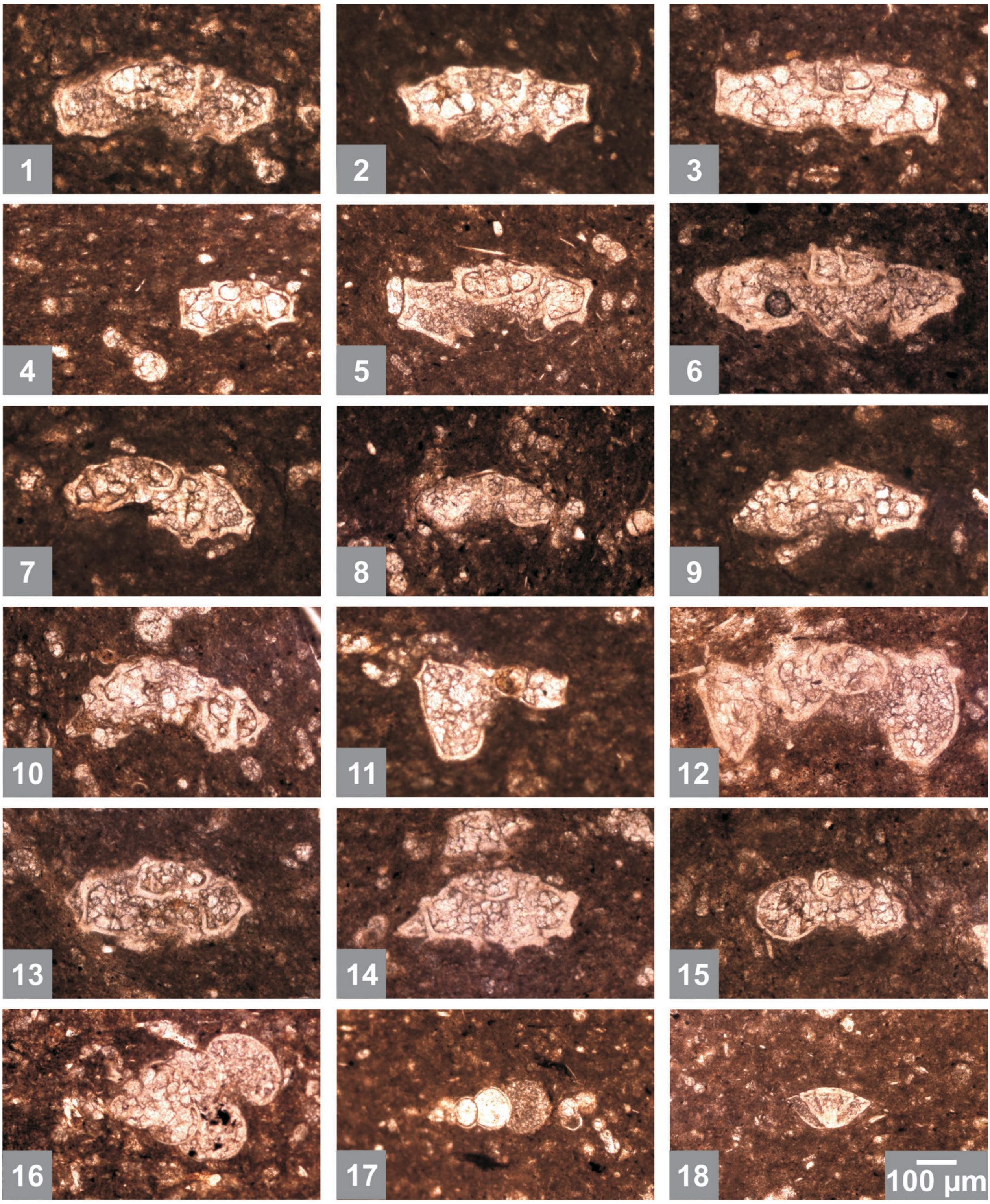

Fig. 4. Foraminifera from marls and marly limestones associated with volcanoclastics from Resnik: **1** — *Globotruncana linneiana* (D'Orbigny) section no. R3a; **2** — *Globotruncana lapparenti* (Brotzen) section no. R4; **3** — *Marginotruncana pseudolinneiana* (Pessagno) section no. R4; **4** — *Globotruncana linneiana* (D'Orbigny) and *Macroglobigerinelloides bolli* (Pessagno) section no. R4; **5** — *Globotruncana* ex gr. *pseudo-linneiana-linneiana*, section no. R8; **6** — *Marginotruncana renzi* (Gandolfi), section no. R2; **7** — *Marginotruncana coronata* (Bolli), section no. R5; **8** — *Dicarinella* sp., section no. R8; **9** — *Marginotruncana* cf. *renzi* (Gandolfi), section no. R5; **10** — *Contusotruncana fornicata* (Plummer), section no. R3b; **11** — *Dicarinella concavata* (Brotzen), section no. R3b; **12** — *Dicarinella* aff. *asymetrica* (Sigal), section no. R3b; **13** — *Globotruncana arca* (Cushman), section no. R3b; **14** — *Globotruncana arca* (Cushman) (transitional form to *G. orientalis*), section no. R3b; **15** — *Whiteinella baltica* (Douglas & Rankin), section no. R5; **16** — *Heterohelix globulosa* (Ehrenberg), section no. R4; **17** — *Heterohelix reussi* (Cushman), section no. R8; **18** — *Rotalia* sp., section no. R8.

West of the town of Topola, at the Karađorđeva Česma, a relatively poor foraminifera association that includes *Dicarinella primitiva*, *Marginotruncana sigali*, *Whiteinella archaeocretacea*, *Whiteinella* cf. *paradubia*, ?*Helvetoglobotruncana* sp., with other dicarinellids, rare globigerinoids, hedbergellids and pithonellas was discovered in reddish marls at their contact with basalts (Fig. 3a, samples T1a and T1b, Appendix – Table A2). At the locality Limovac, south of Topola, the thin-sections of sediments show an extremely numerous and diverse Upper Cretaceous planktonic foraminifera association (Fig. 5, Appendix – Table A2). In addition to the association from the locality Karađorđeva Česma, the index species: *Marginotruncana sigali* and *Dicarinella primitiva* have been recognized in the lower part of the section of reddish limestone. Important species also include: *Marginotruncana paraconcavata*, *Marginotruncana marginata*, *Marginotruncana* cf. *undulata*, *Marginotruncana* cf. *schneegansi*, *Dicarinella imbricata*, *Dicarinella* cf. *hagni*, *Falsotruncana* cf. *maslakovae*, sporadic *Whiteinella archaeocretacea*, *Whiteinella paradubia,* globotruncanas accompanied by rare benthic foraminifer *Marssonella trochus*, calcisphaerae, hedbergellids, heterohelicids, globigerinoid forms, radiolaria, as well as infrequent bioclasts of echinoderms and rudists.

Results of petrographical investigations

Upper Cretaceous basalts in interference with sediments were investigated in the Topola area from the locations: Karađorđeva Česma and Limovac (Fig. 3). Basalts were sampled at the location Karađorđeva Česma (Tβ1, Tβ2). At the location Limovac peperites located immediately below basalts and basalts above this contact were collected (samples and thin-sections number Tβ3, Tβ4 and Tβ5 for basalts; T4, T3/a–d samples for sediments).West of the town of Topola, at the locality Karađorđeva Česma, volcanics were sampled in the higher part of the basalts flow (Fig. 3a, sample Tβ2). They display hypocrystalline porphyritic texture and vesicular to amygdaloidal texture. Groundmass is dominantly composed of yellowish, partially devitrified glass, palagonite. Plagioclase appears either as saussiritized phenocrysts being replaced by zoisite and epidote aggregates or as needle-shaped microlites. Phenocrysts of clinopyroxene are unaltered and commonly euhedral. The low abundance of phenocrysts reveals to the rock sample attribute aphyric (andesite)basalts (Fig. 3b), whereas the texture reflects the shallow-water environment.

South from Topola, at the locality Limovac (Fig. 3, location 2), samples were collected from basalts, marls and marly limestones, that underlie basalts (Fig. 3b). Rocks at the immediate contact of basalts and marls (Fig. 3c, sample Tβ3) are identified as peperites. A chaotic mix of lava and the invaded sediment resulted in the blocky structure with variable amounts and shapes of particles from these two mingled components. Glassy lava inclusions show fluidal texture and massive to amygdaloidal texture, occasionally with closely mingled amygdales and rarely visible phenocrysts. In places where carbonate material prevail the basalt particles are tiny and angular resembling glass shards. The carbonate part of peperite is commonly mantled by opaque substance in response to rapid cooling of lava at their immediate interface. Carbonate particles incorporated within the lava are commonly oval- and ellipsoidal-shaped, up to 2 mm in diameter, but those of dendritic structure were also noted (Fig. 3d). Terrigenous quartz clasts noted sporadically support the concept of a shallow-water environment. Recrystallization of carbonate component occurred locally.

Discussion

Biostratigraphic interpretation

Relatively abundant and diversified marginotruncanids in the lower part of the section in the Belgrade area as well as occurrence of species *Dicarinella* aff. *asymetrica* in the upper part of section as an important bioevent recognized in thin-section R3b in association with aforementioned marginotruncanids, globotruncanids and contusotruncanids correspond to the Santonian stage of sediments (transition of *D. concavata* Zone to *D. asymetrica* Zone). These facts, along with absence of planktonic foraminifers typical of the Campanian (such as *Globotruncanita elevata*, *Globotruncana ventricosa*) set the Santonian age of trachy-dacitic volcanism in Belgrade surroundings. In addition, very rare benthic foraminifera (thin section number R1 contains rotaliid species *Rotalia* sp. incorporated in volcaniclastic material) are also encountered.

In the Topola area, the Lower Coniacian age of rocks was determined based on their fossil association and reconstructed superpositional relations in the field. Very frequent pithonellas in some levels are characteristic for the interval after the Cenomanian–Turonian anoxic event (Arthur et al. 1987; Luft-Souza et al. 2018). The full faunal recovery, progressive diversification and maximum of morphological diversity especially of abundant marginotruncanids and dicarinellids (Tur 1996; Petrizzo 2002), together with occurrence of the association with *M. sigali*, *D. primitiva* and sporadic *F.* cf. *maslakovae* in the lower parts of the section points to an Upper Turonian–Lower Coniacian age of the sediments (corresponding to upper levels of *Marginotruncana sigali–Dicarinella primitiva* Zone, e.g Premoli-Silva & Sliter 1994; Premoli-Silva & Verga 2004; Ljubović-Obradović et al. 2011). Together with presence of *M. marginata* and *M.* cf. *sinuosa*, the first appearance datum of *Dicarinella concavata* in the following topmost sediments (T3e thin-section) has very high biostratigraphic importance. It implies that the marly limestone directly underlying the basalts marks the transition towards the Coniacian *Dicarinella concavata* Zone (described by many authors, including Robaszynski et al. 1984; Caron 1985; Premoli-Silva & Sliter 1994; Robaszynski et al. 2000; Premoli-Silva & Verga 2004). An association of Turonian foraminifera, although not so numerous, was also determined in thin-sections from stratigraphically deeper levels of sediments (Appendix – Table A2,

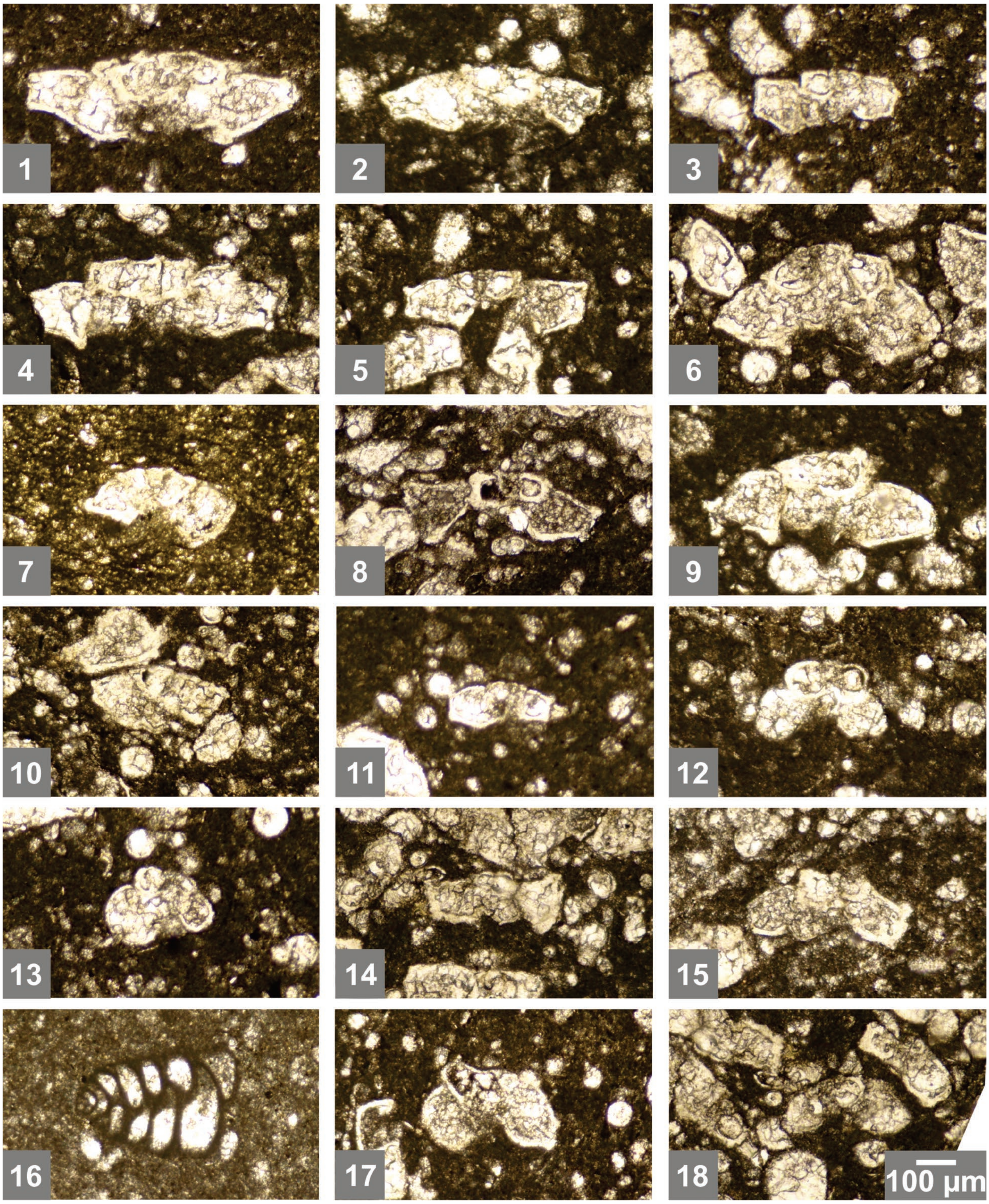

Fig. 5. Foraminifera from sequences of marls, which underlie and overlie basalts in the Topola area: **1** — *Marginotruncana coronata* (Bolli), section no. T3a; **2** — *Marginotruncana coronata* (Bolli), section no. T3d; **3** — *Globotruncana linneiana* (D'Orbigny), section no. T3a; **4** — *Marginotruncana pseudolinneiana* Pessagno, section no. T3c; **5** — *Marginotruncana pseudolinneiana* Pessagno, section no. T3c; **6** — *Marginotruncana sigali* (Reichel), section no. T3a; **7** — *Marginotruncana sigali* (Reichel), section no. T1a; **8** — *Marginotruncana renzi* (Gandolfi), section no. T3a; **9** — *Marginotruncana* cf. *sinuosa* (Porthault), section no. T3d; **10** — *Marginotruncana paraconcavata* (Porthault), section no. T3b; **11** — *Marginotruncana marginata* (Reuss), section no. T3d; **12** — *Whiteinella paradubia* (Sigal), section no. T3d; **13** — *Whiteinella paradubia* (Sigal), section no. T3c; **14** — *Dicarinella concavata* (Brotzen), section no. T3a; **15** — *Dicarinella canaliculata* (Reuss), section no. T3a; **16** — *Marssonella trochus* (D'Orbigny), section no. T2a; **17** — *Dicarinella imbricata* (Mornod), section no. T3e; **18** — *Dicarinella* cf. *imbricata* (Mornod) and *Dicarinella canaliculata* (Reuss), section no. T3a.

Fig. 2c, samples T2a and T2b). Hence, the Lower Coniacian age of basalt volcanism in the Topola area was determined based on biostratigraphic analyses of the foraminifera association.

Timing of extension and distribution of magmatism in the fore-arc basin of the active European margin

In the Belgrade area trachydacites, andesitic tuffs, basalts, and lamprophyres are Late Cretaceous in age (Toljić 2006; Toljić et al. 2018; Sokol et al. 2020; this study). Trachydacitic volcaniclastic debris flows are incorporated in marls with determined Santonian age (Fig. 2, location 1), while the tuffs and fragments of andesites represent segments in a thick succession of Santonian marls (Toljić et al. 2018). Syn-depositional basalts are associated with shallow-water Santonian limestones (Fig. 2, location 2, Toljić 2006; Toljić et al. 2018). In addition, around the Rušanj area (see Fig. 2), numerous dykes of basalts intruded and altered the surrounding marls Albian in age (Toljić 2006). Extension and associated volcanism in Topola area are early Coniacian events. This timing constraint is based on zonal species characteristic for Turonian–Coniacian boundary, which is positioned immediately below the contact between basalts and underlying marls (Fig. 3b). Hence, we infer that extension and associated bimodal volcanism in the fore-arc domain at the European active margin in central Serbia occurred in Coniacian to Santonian times.

In the regional context of the entire Adria–Europe suture, syn-depositional Upper Cretaceous magmatism in the fore-arc, recognized by the basalts and rhyolites associated with sediments within the basin can be distinguished from magmatism developed in the domains outside the fore-arc basin (Toljić et al. 2018). Beside magmatic occurrences in central Serbia, products of magmatism can be recognized in the Klepa area situated further to the south (Prelević et al. 2017), as well as along the southern margin of the Pannonian Basin north of the Fruška Gora Mts. and in the Požeška Gora Mts. (Pamić & Šparica 1983; Dunčić et al. 2017). In the Belgrade area, lamprophyres in Tešića Majdan are Coniacian–Santonian (around 86 Ma, Sokol et al. 2020). Our results show that trachydacites in Resnik are of Santonian age, which is also the age of basalts from the nearby Rušanj (Toljić et al. 2018). Bimodal volcanics north of the Fruška Gora can be placed in the Campanian to Campanian–Maastrichtian (Dunčić et al. 2017). Bimodal volcanics in the Požeška Gora Mts. are Maastrichtian in age (Pamić & Šparica 1983). Novel geochemical and petrological investigations of A-type granites from the Požeška Gora Mts. indicate that these were formed in an extensional tectonic environment and set their age to the Early Campanian (Balen et al. 2020). Therefore, we suggest that the fore-arc volcanism migrates in space and time from the south towards the north and north-west.

Interestingly, the age of magmatism in the fore-arc basin of the active European margin is temporally correlative with the calc-alkaline subduction-related volcanism in the Apuseni–Banat–Timok–Srednogorie (ABTS) magmatic belt, which was situated further to the east, in a back-arc position in the Sava subduction system (Gallhofer et al. 2015).

Conclusions

New biostratigraphic evidence, mainly based on the study of planktonic foraminiferal assemblages, indicates Coniacian to Santonian age of deposition and coeval trachydacitic and basaltic volcanism in central Serbia. Co-genetic magmatic occurrences are distributed along a 600 kilometre belt, which corresponds to the extensional fore-arc domain, and can be traced along the entire active European margin. The fore-arc volcanism shows spatial and temporal migration north- to north-westward.

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Appendix

Table A1: Biostratigraphy of Upper Cretaceous sediments associated with trachy-dacitic volcanism in locality Resnik.

Sample No.	Petrology and micropaleontological content	Stratigraphic age
R1	Medium grained volcaniclastites with fragment of rotaliid foraminifera – *Rotalia* sp.	**Senonian**
R2	MS-WS with planktonic foraminifera, with segments of volcaniclastic material. *Globotruncana arca* (CUSHMAN), *Globotruncana lapparenti* BROTZEN, *Globotruncana linneiana* (D'ORBIGNY), *Globotruncana* cf. *bulloides* VOGLER, *Contusotruncana fornicata* (PLUMMER), *Marginotruncana* cf. *renzi* (GANDOLFI), *Marginotruncana* sp., hedbergellids, *Heterohelix* sp., Heterohelicidae,	**Early Santonian**
R3a	MS-WS with planktonic foraminifera, with segments of fine-grained volcaniclastic material. *Globotruncana linneiana* (D'ORBIGNY), *Globotruncana lapparenti* BROTZEN, *Marginotruncana* cf. *angusticarinata* (GANDOLFI), *Marginotruncana coronata* (BOLLI), *Marginotruncana* renzi (GANDOLFI), ?*Dicarinella* sp., *Heterohelix globulosa* (EHRENBERG), *Heterohelix* sp., Heterohelicidae, Rotaliidae	**Early Santonian**
R3b	WS with *Globotruncana arca* (CUSHMAN), hedbergellids, *Globotruncana linneiana* (D'ORBIGNY), *Marginotruncana* cf. *pseudolinneiana* PESSAGNO, *Marginotruncana coronata* (BOLLI), *Marginotruncana* cf. *sigali* (REICHEL), Rotaliidae, *Globotruncana "bulloides-hilli"*, *Heterohelix* sp., *Contusotruncana fornicata* (PLUMMER), *Dicarinella concavata* (BROTZEN), *Dicarinella* aff. *asymetrica* (SIGAL), *Whiteinella* sp.	**Santonian**
R4	Clayish MS-WS with plankton that marks parallel lamination, segments with volcaniclastites. *Globotruncana arca* (CUSHMAN), *Globotruncana linneiana* (D'ORBIGNY), *Globotruncana lapparenti* BROTZEN, *Contusotruncana fornicata* (PLUMMER), *Marginotruncana pseudolinneiana* (PESSAGNO), *Globotruncana* cf. *bulloides* VOGLER, *Dicarinella* cf. *concavata* (BROTZEN), *Macroglobigerinelloides bolli* (PESSAGNO), *Dicarinella* sp., *Whiteinella* sp., hedbergellids, *Heterohelix globulosa* (EHRENBERG), Heterohelicidae.	**Santonian**
R5	MS with *Globotruncana linneiana* (D'ORBIGNY), *Globotruncana hilli* PESSAGNO, *Globotruncana arca* (CUSHMAN), *Marginotruncana coronata* (BOLLI), hedbergellids, Heterohelicidae, Rotaliidae, *Pseudotextularia* sp., *Whiteinella baltica* (DOUGLAS & RANKIN)	**Santonian**
R6	Volcaniclastites of arenite fraction without fossil content	–
R7	Volcaniclastites of arenite fraction without fossil content	–
R8	MS-WS with planktonic foraminifera, segments with fine-grained volcaniclastites. *Globotruncana* gr. *pseudolinneiana-linneiana*, *Globotruncana* cf. *bulloides* VOGLER, *Globotruncana* cf. *arca* (CUSHMAN), hedbergellids, *Dicarinella* sp., *Marginotruncana* sp., *Heterohelix reussi* (CUSHMAN), *Rotalia* sp., Rotaliidae, Heterohelicidae, ?*Saccocoma* sp.	**Santonian**

Table A2: Biostratigraphy of Upper Cretaceous sediments associated with basalts in Topola area.

Sample No.	Petrology and micropaleontological content	Stratigraphic age
Karađorđeva Česma		
T1a	MS with plankton. *Whiteinella* cf. *paradubia* (SIGAL), *Dicarinella canaliculata* (REUSS), *Dicarinella primitiva* (DALBIEZ), *Heterohelix globulosa* (EHRENBERG), *Marginotruncana sigali* (REICHEL), rare globigerinoids, hedbergellids, rare pithonellas	**Early Coniacian**
T1b	MS with plankton. *Whiteinella archaeocretacea* PESSAGNO, *Whiteinella* sp., *Heterohelix* sp., *Pithonella* sp., Heterohelicidae, globigerinoids, redeposited? Mayncinidae	**Early Coniacian**
Limovac		
T4	Altered, silicified marls without fossil content.	–
T3e	WS with plankton. *Marginotruncana marginata* (REUSS), *Marginotruncana coronata* (BOLLI), *Marginotruncana* aff. *pseudolinneiana* PESSAGNO, *Marginotruncana sigali* (REICHEL), *Marginotruncana* cf. *sinuosa* PORTHAULT, *Marginotruncana renzi* (GANDOLFI), *Whiteinella paradubia* (SIGAL), *Whiteinella archaeocretacea* PESSAGNO, *Dicarinella* cf. *imbricata* (MORNOD), *Dicarinella canaliculata* (REUSS), *Dicarinella concavata* (BROTZEN), *Globotruncana linneiana* (D'ORBIGNY), *Pithonella sphaerica* (KAUFMANN), *Heterohelix globulosa* (EHRENBERG), Heterohelicidae, hedbergellids	**Coniacian**
T3d	WS with plankton. *Marginotruncana coronata* (BOLLI), *Globotruncana lapparenti* BROTZEN, *Marginotruncana renzi* (GANDOLFI), *Marginotruncana sigali* (REICHEL), *Marginotruncana paraconcavata* PORTHAULT, *Marginotruncana marginata* (REUSS), *Marginotruncana* cf. *undulata* (LEHMANN), *Marginotruncana* sp., *Whiteinella baltica* DOUGLAS & RANKIN, *Dicarinella imbricata* (MORNOD), *Dicarinella* cf. *primitiva* (DALBIEZ), *Whiteinella archaeocretacea* PESSAGNO, *Whiteinella* cf. *paradubia* (SIGAL), *Heterohelix* sp., *Falsotruncana* cf. *maslakovae* (CARON), *Pithonella sphaerica* (KAUFMANN), hedbergellids, globigerinoids, *Marssonella* sp.	**Late Turonian– Early Coniacian**
T3c	WS with plankton. *Globotruncana linneiana* (D'ORBIGNY), *Marginotruncana pseudolinneiana* PESSAGNO, *Marginotruncana coronata* (BOLLI), *Marginotruncana sigali* (REICHEL), *Marginotruncana marginata* (REUSS), *Marginotruncana* cf. *schneegansi* (SIGAL), *Marginotruncana* cf. *marginata* (REUSS), *Dicarinella* cf. *hagni* (SCHEIBNEROVA), *Dicarinella imbricata* (MORNOD), *Dicarinella* cf. *primitiva* (DALBIEZ), *Whiteinella paradubia* (SIGAL), *Pithonella sphaerica* (KAUFMANN), *Heterohelix globulosa* (EHRENBERG), globigerinoids	**Late Turonian– Early Coniacian**
T3b	WS-MS with plankton. Numerous *Marginotruncana coronata* (BOLLI), *Marginotruncana renzi* (GANDOLFI), *Marginotruncana marginata* (REUSS), *Marginotruncana* cf. *sinuosa* PORTHAULT, *Whiteinella archaeocretacea* PESSAGNO, *Whiteinella baltica* DOUGLAS & RANKIN, *Whiteinella paradubia* (SIGAL), *Dicarinella imbricata* (MORNOD), *Dicarinella* sp., *Globotruncana linneiana* (D'ORBIGNY), *Pithonella sphaerica* (KAUFMANN), hedbergellids	**Late Turonian– Early Coniacian**
T3a	Partly recrystallized WS-MS with plankton. *Marginotruncana coronata* (BOLLI), *Marginotruncana pseudolinneiana* PESSAGNO, *Marginotruncana* cf. *renzi* (GANDOLFI), *Dicarinella* cf. *canaliculata* (REUSS), *Dicarinella imbricata* (MORNOD), *Whiteinella baltica* DOUGLAS & RANKIN, *Whiteinella* sp., hedbergellids, *Heterohelix reussi* (CUSHMAN), *Heterohelix globulosa* (EHRENBERG), *Pithonella sphaerica* (KAUFMANN), globigerinoids.	**Late Turonian– Early Coniacian**
T2a	MS-WS with plankton. *Marginotruncana coronata* (BOLLI), *Marginotruncana pseudolinneiana* PESSAGNO, *Marginotruncana marginata* (REUSS), *Marginotruncana renzi* (GANDOLFI), *Marginotruncana sigali* (REICHEL), *Marssonella trochus* (D'ORBIGNY), *Globotruncana linneiana* (D'ORBIGNY), *Whiteinella* cf. *baltica* DOUGLAS & RANKIN, *Whiteinella* cf. *archaeocretacea* PESSAGNO, *Pithonella ovalis* (KAUFMANN), re-deposited *Nezzazatinella* sp.	**Late Turonian– Early Coniacian**
T2b	MS-WS with plankton. *Dicarinella primitiva* (DALBIEZ) *Marginotruncana coronata* (BOLLI), *Dicarinella canaliculata* (REUSS), *Heterohelix globulosa* (EHRENBERG), *Marssonella trochus* (D'ORBIGNY), *Marginotruncana* sp., re-deposited fragment of *Nezzazata* cf. *conica* (SMOUT)	**Turonian– Early Coniacian**