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Late Cretaceous turbidite systems of southern Belgrade outskirts: Constraints on the Santonian convergence onset, evidence from the Sava Suture Zone (Guberevac-Babe, northern Šumadija, Serbia)

Zgornjekredni turbiditi južnega obrobja Beograda: Podrobna opredelitev začetka santonijske konvergence, dokazi iz Savske šivne cone (Guberevac-Babe, severna Šumadija, Srbija)

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Ključne besede: Savska šivna cona, zgornjekredni turbiditi, gubanje in narivanje, Guberevac-Babe-Ropočevo, reaktivacija stika

Abstract

As ancient depositional systems associated with active continental margins, turbidites may provide crucial information on orogenic evolution. This paper offers new stratigraphic and structural data on one of the late Alpine turbidite systems of the Late Cretaceous age (Guberevac-Babe-Ropočevo area; Serbia). The two opposite yet juxtaposed tectonic systems were initially deposited within the Sava Suture Zone and East Vardar Zone, whereby the former experienced Upper Cretaceous contractional- and extensional-type deformations. The new biostratigraphic dating constrains the age of mapped compressional structures, which indicates their Santonian age. This deformed segment of the newly dated Santonian clastic-carbonate turbidite sequence near the Guberevac site exposes new important compressional structures. The folds, reverse faults, and tectonic stylolites are allocated several kilometers from the primary deformation (Bela Reka thrust fault), positioned within the crustal footwall of the overriding East Vardar Zone.

The complexity of the geological processes in the Guberevac-Babe-Ropočevo area is further revealed by the previously mapped layering of Upper Cretaceous strata, exposed within the wider investigated area. Our combined field study provides a new statistical analysis of structural elements such as faults, folds, and bedding planes, adding to the depth of the understanding of the Sava Suture Zone. The observed contractional structures, mesoscopic folds, thrust faults, two-generation cleavage planes, as well as the produced statistical structures, are mostly imprinted into the out-of-deformation front or within the mixed clastic-carbonate turbidites of the Sava Suture Zone (Guberevac-Babe area). The composite study shows that the investigated footwall segment, represented by the deformed Sava Suture Zone turbidites, underwent tectonic shortening during Santonian (convergence onset). After the main crustal thickening event ceased, the Guberevac-Babe-Ropočevo suture segment was reactivated several times (post-orogenic extension). The investigated segment of the Neotethyan Vardar paleosuture experienced a total of four deformation stages spanning Late Cretaceous to Miocene times. These include the Late Oligocene reactivation and emplacement of the Glavčina-Parlozi Late Oligocene subvolcanic body and the slightly younger Stenička bara Miocene igneous system.

Izvleček

Turbiditi, kot sedimentacijski sistemi, vezani na aktivne robove celin, so turbiditi nosilci pomembnih podatkov o orogenem razvoju območja. V tem članku so predstavljeni novi stratigrafski in strukturni podatki o enem od alpskih turbiditnih sistemov iz časa pozne krede (območje Guberevac-Babe-Ropočevo; Srbija). Znotraj Savske šivne cone in Vzhodne Vardarske cone sta bili odloženi dve sinorogeni zaporedji, pri čemer je bilo prvo podvrženo poznokrednim kompresijskim in ekstenzijskim deformacijam. Glede na nove biostratigrafske podatke je do nastanka kompresijskih struktur prišlo v santoniju. V deformiranem delu santonijskega klastično-karbonatnega turbiditnega zaporedja v bližini Guberevaca so vidne nove pomembne kompresijske strukture. Gube, reverzni prelomi in tektonski stiloliti so vidni nekaj kilometrov stran od primarne deformacije (nariv Bela Reka), v talnini narinjene Vzhodne Vardarske cone.

O kompleksnosti geoloških procesov na območju Guberevac-Babe-Ropočevo pričajo tudi plasti zgornjekrednih kamnin, ki so bile predhodno kartirane na širšem območju. V sklopu naše terenske študije smo izvedli statistično analizo strukturnih elementov, kot so prelomi, gube in plasti, kar prispeva k boljšemu razumevanju Savske šivne cone. Opazovane kompresijske strukture, kot so mezoskopske gube, narivi in klivažne ravnine dveh generacij, kot tudi pridobljeni statistični podatki o strukturah, se večinoma pojavljajo v prednarivnem čelu ali znotraj mešanih klastično-karbonatnih turbiditov Savske šivne cone (območje Guberevac-Babe). Celotna študija kaže, da je bil preiskovani segment talnine, ki ga predstavljajo deformirani turbiditi Savske šivne cone, izpostavljen tektonskemu krčenju v santoniju (začetek konvergence). Po koncu glavnega dogodka debeljenja skorje je bil šivni segment Guberevac-Babe-Ropočevo večkrat reaktiviran (postorogena ekstenzija). Preučevani segment neotetidine vardarske paleosuture je med pozno kredo in miocenom skupaj doživel štiri faze deformacij. Te vključujejo pozno-oligocensko reaktivacijo ter umestitev pozno-oligocenskega subvulkanskega telesa Glavčina-Parlozi in nekoliko mlajšega, miocenskega magmatskega sistema Stenička bara.

Introduction and problem statement

One of the most intriguing issues in the reconstruction of the complex geodynamic evolution of the Jurassic and/or Cretaceous "northwestern branch" of the peri-Neotethyan oceanic realm (Dimitrijević, 2001) is related to the evolution of collisional Sava Suture Zone (SSZ; Schmid et al., 2008, 2020; Spahić & Gaudenyi, 2022; Fig. 1). In the literature, SSZ is also known as the "Sava Vardar Zone" of Pamić (2002), "Sava Zone" of Schmid et al., (2008), or "Central Vardar Zone" of Dimitrijević (1997) and Toljić et al., (2019). Nevertheless, much prior definition of the Vardar Zone by Dimitrijević (1997) or Pamić's (2002), "Sava Vardar Zone", given in the paper published in 1973 by Anđelković SSZ is indicated. This early paper shows that the complex geology of the Belgrade area contains the magmatism that is of Cretaceous age. Investigated scarcely developed magmatic episode is younger or of Upper Cretaceous age, emplaced much later than it was previously mapped and designated (Jurassic; see Spahić, 2022, for a review). A 1000 km long composite tectonic zone either belongs to a "relic Neotethyan ocean" (e.g., Karamata et al., 2000; Schmid et al., 2008; Ustaszewski et al., 2009, 2010) or represents a former post-Neotethyan Cretaceous marine (strike-slip; Grubić, 2002; Pamić et al., 2002; Handy et al., 2015; Köpping et al., 2019) corridor intervening Dinarides and European margin (Spahić & Gaudenyi, 2022).

The Late Cretaceous post-Neotethyan-type deep marine corridor exposes bimodal-type magmatic, metamorphic, and turbidite complexes, inclusive of the segment positioned near the city of Belgrade (Anđelković, 1973; Toljić et al., 2018; Spahić & Gaudenyi, 2022; Fig. 1). The investigated SSZ segment is an exhumed crustal fragment represented by a fault bounded km-scale block, which is connecting the tectonic units derived from the (i) Eurasian (Europe) and (ii) mixed Gondwana/Adria/Dinarides. The convergent assembly includes Vardar Zone oceanic and continental plates (Fig. 2a,b). The mapped segment of the SSZ exposes the two almost identical Upper Cretaceous turbidite sequences that originate from two different Late Cretaceous–Paleogene tectonic-paleogeographic realms: (i) foredeep suture-trench associated with the aforementioned narrowing marine corridor (K_2-SZ at Fig. 2b), and (ii) overriding foreland basin turbidites of the East Vardar Zone (K_2-EV at Fig. 2b; Schmid et al., 2020; Toljić et al., 2018, Spahić & Gaudenyi, 2022).

Before the latest Cretaceous–Paleogene continent-continent collision and the precursory production of two turbidite systems, the origin of modern-day SSZ ("Piemont-Liguria, Vahic, Inacovce-Kriscevo, Szolnok, Sava unit" at Fig. 1) can be interpreted following the two different lithospheric-scale mechanisms or plate tectonic scenarios. The first option poses the orthogonal subduction model, elaborated by a „closing" Neotethys Vardar ocean, also referred to as the "Sava Ocean" (Schmid et al., 2008). The second proposes the model of a renewed strike-slip oblique subduction having occurred along the Cretaceous corridor intervening Adria and Europe (Spahić & Gaudenyi, 2022). In the study area, these imprints are well-hidden by the two different Upper Cretaceous turbidite sequences. Near city of Belgrade, turbidites have just recently been separated into the two tectonic domains divided by the NNW-SSE striking west-vergent Bela Reka reverse fault (Toljić et al., 2018; Fig. 2b). The Bela Reka thrust fault separates the Western Vardar Zone including Sava Suture Zone (Adria-derived units), from the Eastern Vardar turbidite-ophiolitic units of European affinity (Schmid et al., 2008, 2020; Boev et al., 2018; Toljić et al., 2018; Fig. 1). With regards to the two contemporaneous turbidite sequences, these exhibit different levels of deformation, and are very challenging for clear field recognition (Anđelković, 1973; Toljić et al., 2018; Fig. 2b). As study will show, the investigated near Belgrade suture segment further exposes some previously

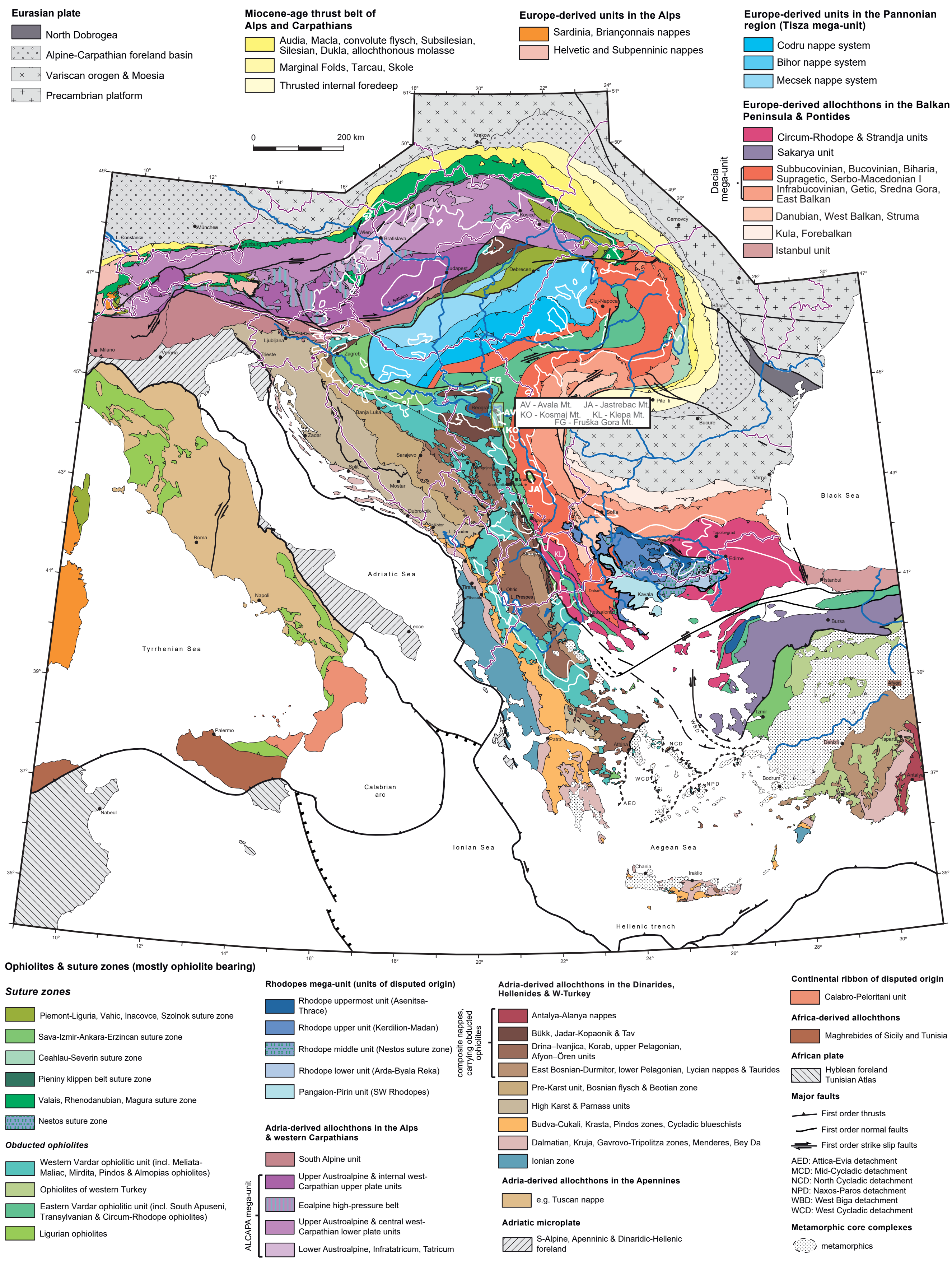


Fig. 1. The position of the investigated segment of the Sava Suture Zone, central Balkan Peninsula, Central Serbia, including the surrounding Alpine (modified after Schmid et al., 2008, 2020).

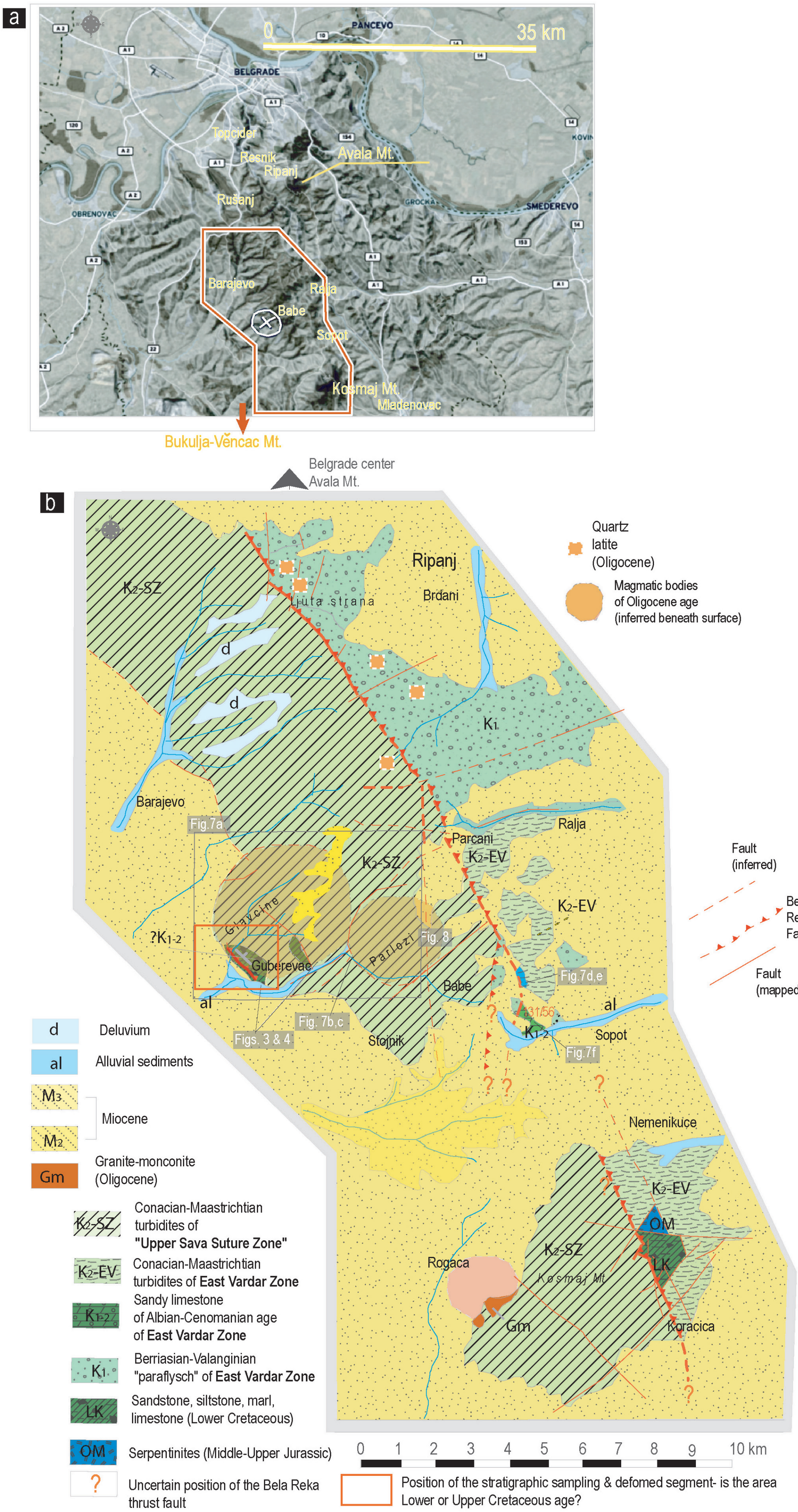


Fig. 2. a. The relief map of the wider southern Belgrade area, including the position of the figure 2b and key locations; b. Simplified geological sketch map of the Ripanj-Ropočevo-Kosmaj Mt. segment (significantly modified after inset of Radulović, 1987). The geological sketch-map includes the collected field mapping data, including the position Bela Reka fault proposed by Toljić et al. (2018).

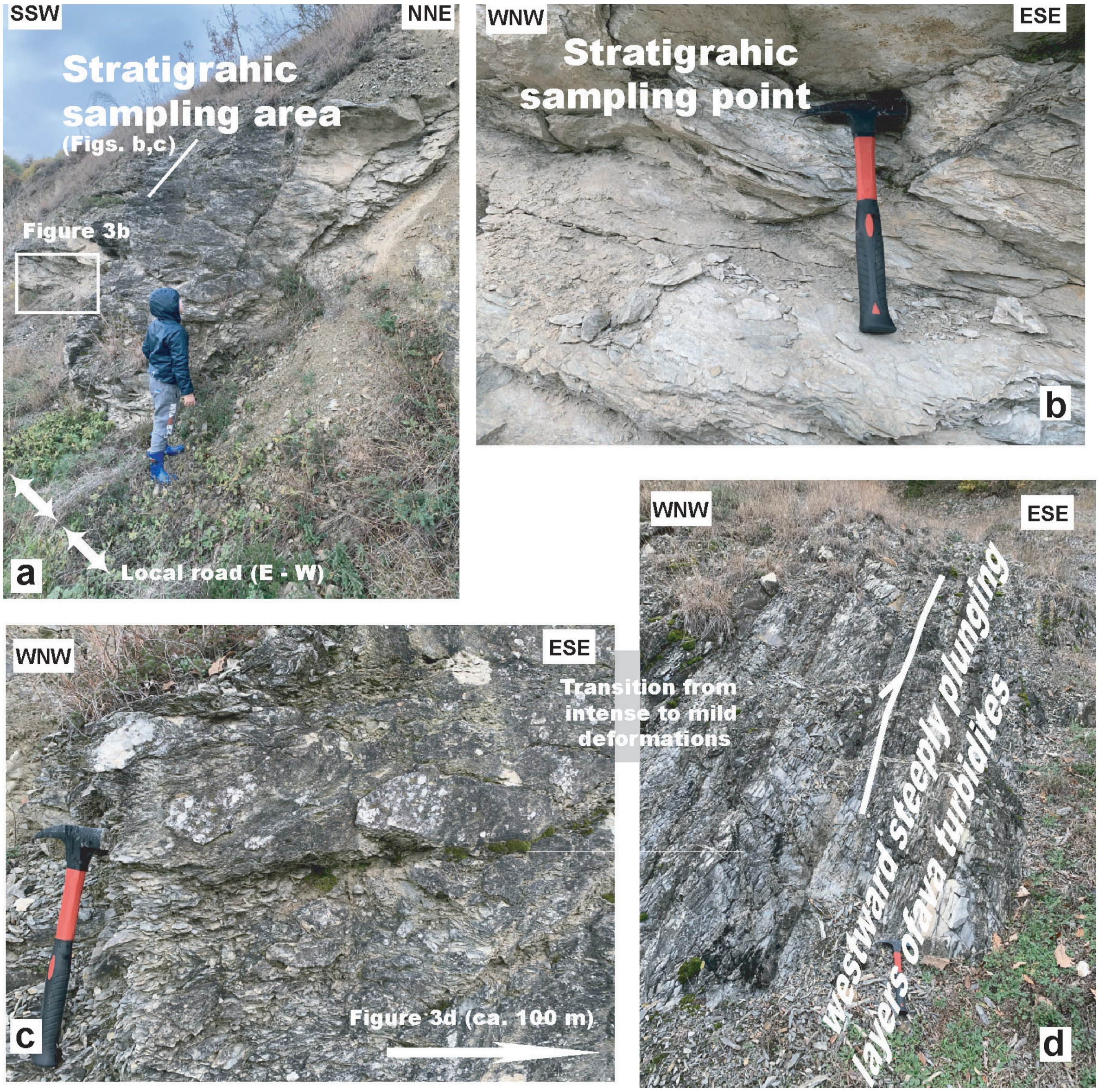


Fig. 3. a. The photos taken near Guberevac village, exposing the intensive folding (photo taken by D. Spahić). b. Intensely deformed rock, sampling area. c. The peculiar outlook of the outcropping deformed rock of questionable age: is the rock of latest Jurassic age or Late Cretaceous? d. Ca. 100 m towards the east (by road) Sava Suture Zone turbidites have regular layered form steeply plunging towards the west (likely induced by the Glavčina ring structure).

non-mapped compressional-type structures that are important for deciphering the exact convergence onset. The investigated tectonic relations (Fig. 2b) are additionally discussing the observed two-staged post-collisional extension-related tectonic episodes (Late Oligocene and Miocene times, e.g., Radulović, 1987; Vasković, 1987; Márton et al., 2022).

The primary purpose of this study is to provide a new stratigraphic and structural contribution to the ongoing debate revolving around the exact onset of the Neotethys Vardar-related late Alpine convergence. The convergence connects the (Adria) Dinarides and the former southern Eurasian margin (Robertson et al., 2008; Schmid et al., 2008). The field mapping and data collection is based upon the W–E-directed transect (Guberevac-Babe area). The measurements cover the exposed and deformed (former) Neotethyan lower plate. The lower plate is represented by a turbidite set that belongs to the SSZ(K_2-SZ) (Figs. 2a, b, red rectangle, and Figs. 3, 4, 5). In addition, the field mapping results shows that the investigated Guberevac-Babe area exposes a few inconsistencies relevant to final (Neo)Tethyan termination and late Alpine collision. The first is the exact age of the K_2-SZ / "Upper SSZ" sequence or Sava Suture Zone at the Guberevac-Babe area, which has been interpreted either as of the Jurassic age (sandy limestone; Radulović, 1987; Fig. 2b, 3a,b,c,d) or as the Lower Cretaceous flysch (Filipović et al., 1973; Fig. 6a). The inconsistency is further spiced by a recent sketch map of Toljić et al. (2018), which shows that a Miocene veneer overlies the highly deformed Guberevac-Babe turbidites. Aiming to solve these inconsistencies, the following regional geological study provides essential new stratigraphic data on the age of the newly discovered deformed Guberevac-Babe lower plate, i.e., its youngest SSZ turbidite sequence (K_2-SZ; Fig. 2b). The importance and the tectonic activity of this Sava Suture Zone segment is additionally indicated by imprints related to the post-orogenic Oligocene and Miocene magmatic stages.

Regional geology

Crosscutting the central part of the Balkan Peninsula along the W-E-trending Sava River, in the form of isolated outcrops (Hungary, Croatia, Bosnia & Herzegovina; Pamić et al., 2000, 2002; Pamić, 2002; Hrvatović, 2006; Grubić et al., 2009, 2010; Ustaszewski et al., 2009, 2010; Milošević, 2017; Maffione & van Hinsbergen, 2018; Farics et al., 2019; Gerčar et al., 2022), the Sava Suture Zone is passing near the Jadar block (e.g., Gerzina, 2010; Spahić & Gaudenyi, 2020). It further strikes across the Pannonian Basin and the Fruška Gora Mt. (Stojadinović et al., 2013, 2022; Dunčić et al., 2017; Toljić et al., 2019; Fig. 1), whereby this suture complex crops out in the immediate surrounding of the city of Belgrade, Serbia (southern city outskirts; Fig. 1, 2a,b; Toljić et al., 2018, 2021; Sokol et al., 2019; Márton et al., 2022; Spahić, 2022; Fig. 1, 2,b). The investigated Upper Cretaceous-Paleogene turbidites are striking across Central Serbia (Jastrebac Mt., Marović et al., 2007a; Petrović et al., 2015; Erak et al., 2016), crossing into North Macedonia (Klepa Mt., Prelević et al., 2017; Köpping et al., 2019; Spahić et al., 2019), Greece and Turkey (Axios-Vardar Zone transferring into the İzmir-Ankara-Sava suture; e.g., van Hinsbergen & Schmid, 2012; Fig. 1). The investigated Upper Cretaceous complex *s.l.* (Fig. 6a), including the displaced mafic-type Jurassic magmatic sequences of the reactivated NeoTethyan suture, constitutes a regional bedrock system accommodated mostly underneath the broader area of Belgrade and its surroundings (e.g., Anđelković, 1973; Marinović & Rundić, 2020).

The wider Belgrade Alpine tectonic amalgamation comprises: (i) older Neotethyan magmatic-sedimentary complex or Jurassic ophiolites belonging to the Western and East Vardar Zones, including the associated ophiolitic mélange of the Jurassic age (Dimitrijević et al., 2003; Schmid et al., 2008; Bragin et al., 2011, 2019; Toljić et al., 2018, 2021; Marinović & Rundić, 2020; Spahić, 2022; Fig. 1). The older crustal elements of the Middle Jurassic age are tectonically emplaced on top of the younger Late Jurassic, or middle Oxfordian to a late Tithonian interval. Deep wells show depths of over 1500 m in the Pančevo area, which is positioned across the Danube River (Marinović & Rundić, 2020; Fig. 2a). Unconformably placed on top of the East Vardar Jurassic oceanic formations, the Tithonian limestones and the Lower Cretaceous "Paraflysch" were deposited (Anđelković, 1973; Dimitrijević & Dimitrijević, 2009; Toljić et al., 2018; Marinović & Rundić, 2020; Spahić et al., 2023).

In the overlying position on top of the Tithonian-Lower Cretaceous Vardar Zone s.s. (both Western- and East Vardar Zone) are unconformable clastic sequences represented by the two similar turbidite units of the Upper Cretaceous age. Two turbidite belts have almost identical color and are of similar composition (Toljić et al., 2018; K2-SZ *vs.* K2-EV; Fig. 2). In their lower basal sections, the turbidites may contain different remnants of scarce bimodal basic and acidic magmatic signals (e.g., Anđelković, 1973; Karamata et al., 1997, 2005; Sokol et al., 2020). A recent study subdivided Sava Suture Zone into a lower-positioned slightly older SSZ segment containing the bimodal magmatics which is referred to as the "Lower SSZ" (Fig. 1, yellow rectangles), while the Upper Cretaceous turbidites are referred to as the "Upper SSZ" (turbidites that outcrop to the west of Bela Reka fault line; Fig. 2, K_2-SZ; Spahić & Gaudenyi, 2022). To the east of the Bela reka fault are East Vardar Upper Cretaceous turbidies (Fig. 2b).

However, surface mapping of the two flysch-type units of the Upper Cretaceous age permits a poor distinguishing of the tectonic boundary separating the latter turbidites (Fig. 2b; also in Radulović, 1987). The Bela reka thrust faults disconnecting the two turbidite systems inferred during field work. To subdivide turbidites we use the following surface-subsurface markers: (i) the presence of Jurassic-Lower Cretaceous markers belonging to the footwall of both turbidite systems, inclusive the (ii) underlying NNW-SSE striking deep subsurface geophysical lineaments (Vukašinović, 1973a,b; Spahić et al., 2023). Constraints include (iii) the visualized localized aeromagnetic anomalies that are allowing insight into the near-surface configuration, in particular into the hidden magmatic areas (Vukašinović, 1973a,b; Spahić et al., 2023).

With regards to the recurring magmatism that is localized along the strike of this regional-scale tectonic interface, the investigated Ripanj-Ropočevo-Kosmaj Mt. area belongs to a belt striking from the Avala Mt. at the north, over Rudnik Mt. (Kostić, 2021) further towards south including

Željin and Kopaonik Mts. (Figs. 1, 2a). The Guberevac-Babe-Ropočevo area exposes Cretaceous rocks with some evidence of Cretaceous magmatism to the north in Ripanj (Sokol et al., 2020; Fig. 6, Fig. 7a-f). The postdating subvolcanic magmatic activity in the Oligocene induced the formation of Glavčina and Parlozi volcano-tectonic ring structures having a diameter of 2.5–3 km (Radulović, 1987; Fig. 2b, 7a-c). The emplacement of Oligocene magmatics resulted in a number of round-shaped morphological features (Fig. 2b). The intrusion further induced a steep inclination of roofing turbidite layers (e.g., layers that are outcropping near Guberevac, vicinity of Glavčina intrusive feature; Fig. 3d, 7b). Another intrusion along the tectonic lineament is very near Kosmaj Mt. (Oligocene monzogranite, K-Ar on two whole rock samples yielded 30-29 Ma; Lovrić, 1982/83 in Vasković, 1987; Fig. 2a,b). The roofing turbiditic sequence contains predominantly quartz, mica-type minerals, feldspars, and fragments of these Tertiary igneous rocks (Radulović, 1987). In summary, the following regional geological study aims to define the intermittent Late Cretaceous–Miocene lithospheric-scale activities along the proposed tectonic boundary, bondary, that disconnects the investigated two Upper. Cretaceous–Paleogene turbidite systems.

Methods

Taking into consideration the controversial age relations of the stacked turbidite complexes (Anđelković, 1953; Radulović, 1987; Toljić et al., 2018), in particular, deformation age, we conducted the biostratigraphical and structural investigations of the exposed highly deformed mainly folded and thrust turbidite deposits of the SSZ (Figs. 4, 5). The data was collected by mapping the W – E transect connecting the Guberevac area with the Ropočevo quarry site (Fig. 2b).

Biostratigraphic methods

Several thin sections were produced from the pelagic highly-deformed rocks collected in the Guberevac area (Figs. 2, 3). These thin sections were investigated by the optical microscope to determine the presence of microfossils by applying magnifications of 2.5× and 10× (Fig. 5). Sampled turbidite could be defined as a calciturbiditic bed. Thin sections show that planktonic foraminifera are the main constituent of all analyzed microfossil assemblages.

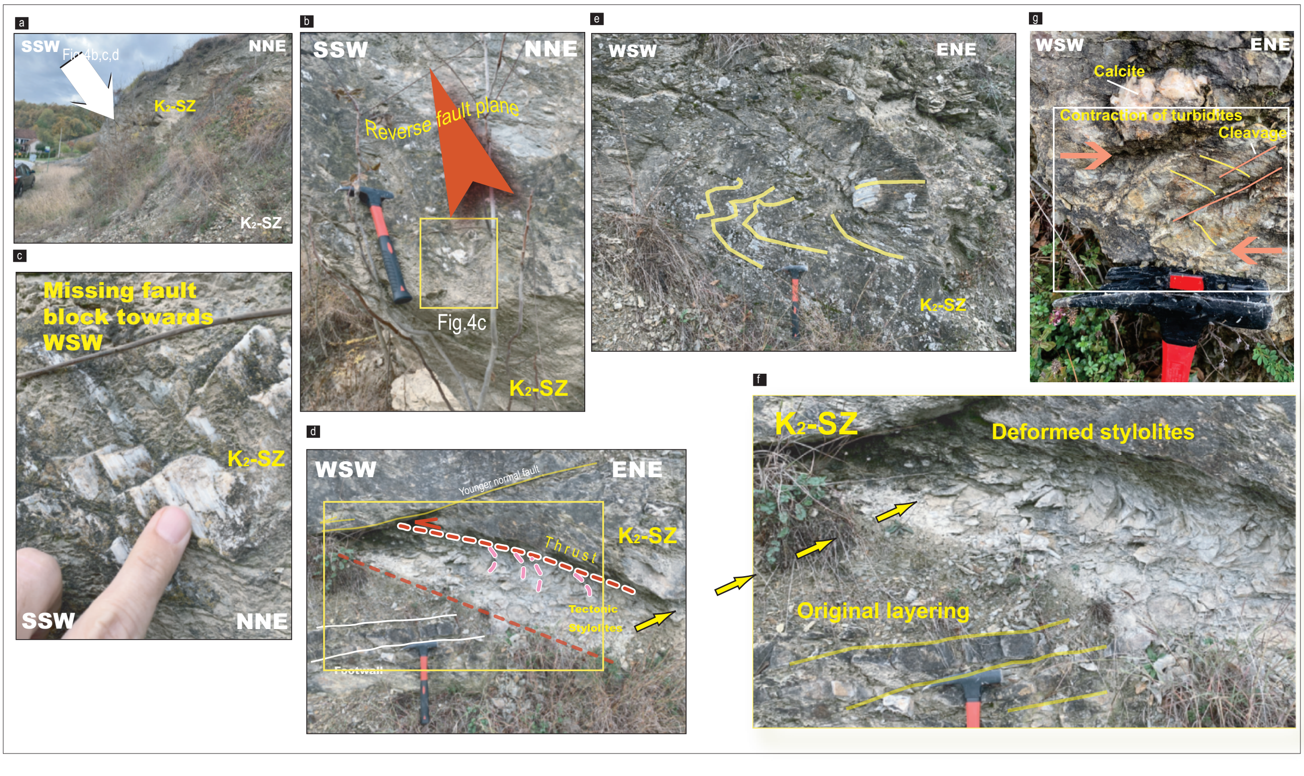


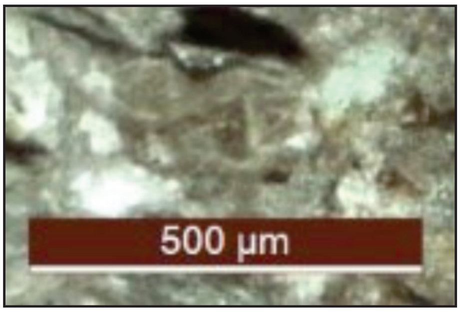
Fig. 4. a. The same outcrops near Guberevac village exposing highly deformed, previously unmapped deformations. b, c. The reverse fault, its hanging wall. Slickensides indicate reverse upwards-directed movement. d. The tectonic stylolite's confirming reverse kinematics, and proximity of thrust fault. e. Intensely folded isocline folds in the peculiar Sava Suture sediments. The fold hinge plunges towards NNE. f. Detail view of tectonic stylolite. g. Evidence of contraction and cleavage formation.

Structural analysis

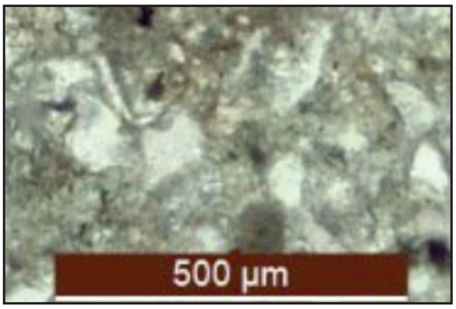
Preliminary field mapping of the critical outcrops yielded the presence of atypically complex folded turbidite sequences that, according to scarce available literature data, can be either of the latest Jurassic (Radulović, 1987) or the Upper Cretaceous age (Filipović et al., 1973). Observed deformations have not been mapped to date. To address these issues, we have applied the methods of lithostratigraphic and structural field mapping of the key outcrops, including the analysis of bedding data measured in a wider investigated area. The structural data (dip-direction/dip angle) are extracted from the Basic Geological Map of Yugoslavia on a scale of 1:100,000, sheets Obrenovac and Smederevo (Filipović et al., 1973; Pavlović et al., 1979; Fig. 6a, b, c). We additionally measured other field kinematic indicators, such as slickensides, striations, tectonic stylolites, and cleavage, to determine the displacement directions (Fig. 4a-g).

Results

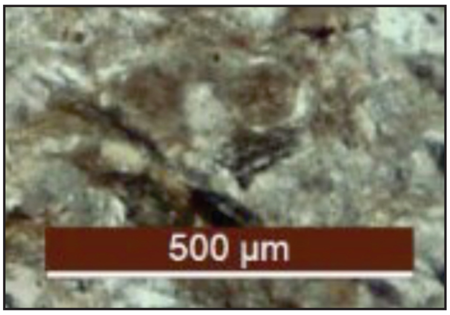
From the Guberevac area towards the Bela Reka fault, the mapped Upper Cretaceous turbidites turbidites are changing gradually changing (no sharp contact) into the heterogeneous sequence with dominant marlstone-type deposits (Anđelković, 1953; Fig. 7e-yellow-colored rocks, 8a, d). Such a change marks the transition from a shallower marine environment towards a deeper environment to the west of the Babe village. No sharp lithological change or tectonically displaced contact between the two turbidite belts is visible in the investigated area. There are no regional metamorphic changes, except in a few locations wherein small portions of Late Cretaceous turbidites are metamorphosed. According to the literature data, these spots were affected by the post-dating subvolcanic activity exposed at Stenička Bara, Babe village (Radulović, 1987; Fig. 7a, b, c, 8b).



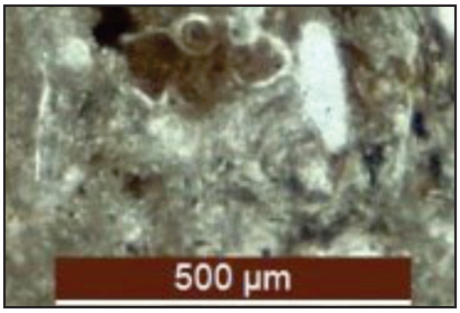
a. *Contusotruncana* cf. *C. fornicata* Plummer



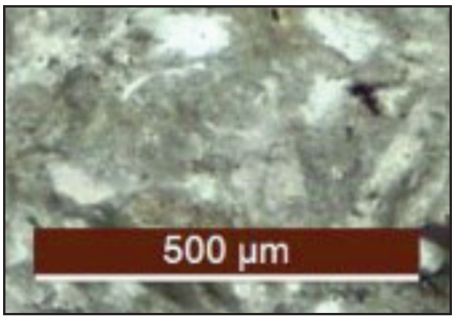
b. *Dicarinella* cf. *D. concavata* Brotzen



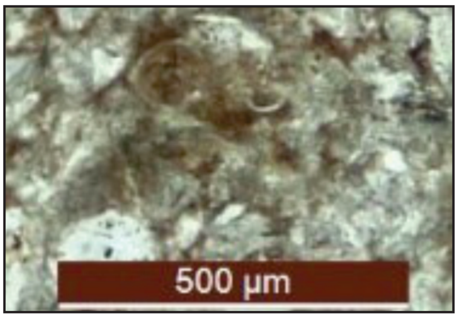
c. *Dicarinella* sp.



d. *Globotruncana hilli* Pessagno



e. *Globotruncana hilli* Pessagno



f. *Hedbergella* sp.

Fig. 5. Microfauna from the selected samples is define and is scarce, and some of them are deformed Foraminifera species from the deformed Guberevac turbidites: *Contusotruncana* cf. *C. fornicata* Plummer, *Dicarinella* cf. D. *concavata* Brotzen, *Dicarinella* sp., *Globotruncana hilli* Pessagno, *Hedbergella* sp.

Stratigraphic update: Cretaceous stratigraphic investigation regarding the age of Sava Suture Zone turbidites

As mentioned earlier, Toljić et al. (2018) proposed the distinction between the turbidite deposits: (i) in the hanging wall East Vardar Coniacian-Maastrichtian (lowermost Paleogene) turbidites *vs*. (ii) overriding Campanian (lowermost Paleogene) SSZ turbidites (divided by the Bela Reka fault; Fig. 2b). This study on the Upper Cretaceous turbidite sequences yielded (ii) the new stratigraphic data, whereby sequence positioned to the east of Bela Reka fault represents a subsystem of the Coniacian-Maastrichtian (-lowermost Paleogene) turbidites. The latter flysch belongs to the Upper Cretaceous foreland system of the East Vardar Zone/former south European foreland (separated by the Bela Rela fault; Toljić et al., 2018; see Spahić et al., 2023, for tectonic inheritance) (Fig. 2b). At the same time, the here presented new fossil content collected from the deformed SSZ(K_2-SZ) turbidites indicated that the observed structures are of the Santonian (late Santonian) age "likely of syn-contractional origin".

The new micropaleontological data of the rocks at the Guberevac locality has demonstrated the presence of identifiable pelagic foraminifera and some foraminifera species that cannot be determined. Microfauna is scarce and difficult to determine, mainly because samples were collected from highly deformed rocks. The presence of foraminifera species indicates deeper, calmer, and cooler water with an average salinity (pelagic, open sea environment). The following species were identified: *Contusotruncana* cf. *C. fornicata* Plummer, *Dicarinella* cf. *D. concavata* Brotzen, *Dicarinella* sp., *Globotruncana hilli* Pessagno, *Hedbergella* sp. (Fig. 5). The new biostratigraphic assembly pinpoints the exact Santonian age of the highly deformed Guberevac turbidites (lower plate), thus being the key information for dating of the observed structural elements embedded therein. This Santonian turbidite sequence should connect with the tuffs and andesite embedded into a thick succession of Santonian marlstones (according to Toljić et al., 2018). However, during this field mapping campaign, we observed no such Upper Cretaceous magmatic equivalents across the investigated area.

Structural analysis

Analysis of bedding planes

Field mapping of faults and folds, including the statistical analysis of the previously mapped turbidite layers (Fig. 6a) taken from the Basic Geological Map of Yugoslavia on a scale of 1:100,000 yielded the two distinctive directions among mapped deformations, E-W and NE-SW (Fig. 6b). The S_1 and S_2 diagrams (Fig. 6b) are depicting the bedding data from the sheets Obrenovac and Smederevo, respectively (Fig. 6a). The Basic Geological Map has no distinction of the Sava Suture Zone and East Vardar Zone turbidites. Thus, the measured dip direction/dip angle of the strata represents the bulk Upper Cretaceous measurements (Filipović et al., 1973; Pavlović et al., 1979; Fig. 6a). Nevertheless, to obtain the best results, we separated the Upper Cretaceous sediments into the SSZ and the East Vardar Zone (S_2) (Fig. 2b). The S_1 and S_2 diagrams are representing the manually subdivided trends of the same deformation age deducted from the bulk data (Fig. 6a-c). The S_1 has a bedding trend with dip directions orientation to the NE and SW, exposing the two π belts with the maximum of 047/68 and 214/77. The majority of the measurements have a SW-directed dipping of strata (Fig. 6b). From these statistical poles (maxima), we have extracted the two statistically calculated fold limbs (represented by the traces). The limb one has a dip direction/dip angle of 227/22, whereas the limb two has 030/13. The statistical axial plane has a dip direction/dip angle of 040/86, whereas the statically calculated b-axis/fold axis has a trend/plunge of 310/03 (aligned with the Alpine trend in the area; see Đoković 1985, for the explanation of the folding and associated b-axis/fold axis trends). The S_2 diagram has the statistical bedding with the principal dip directions of E-W, clustering the two π belts or a statistical maximum of the poles that have the maxima of 089/62 and 270/62 (with the majority of the measurements dipping towards the west). From these π belts/pole data, we have further extracted the two statistically calculated fold limbs, which are entirely in line with the observed cluster of field data: dip-direction/dip of the bedding, spatial position of west-divergent fault planes, including the important fold axes. Other rather subordinate maxima likely represent the clustering of the structural elements adjacent to the brittle faults (strata are allocated and shifted by the subsequent post-Cretaceous fault activity). Limb one has a dip direction/dip angle of 270/27, and limb two has measurements of 091/28. The statistical axial plane has a dip direction/dip angle of 270/89, whereas the b-axis/fold axis has a trend/plunge angle of 180/01. The two trends are exposed in Figs. 6b, c, showing that the Upper Cretaceous *s.l.* bedding (Fig. 6a) can be subdivided into the two principal shortening trends – NE-SW and E-W-directed (Fig. 6b).

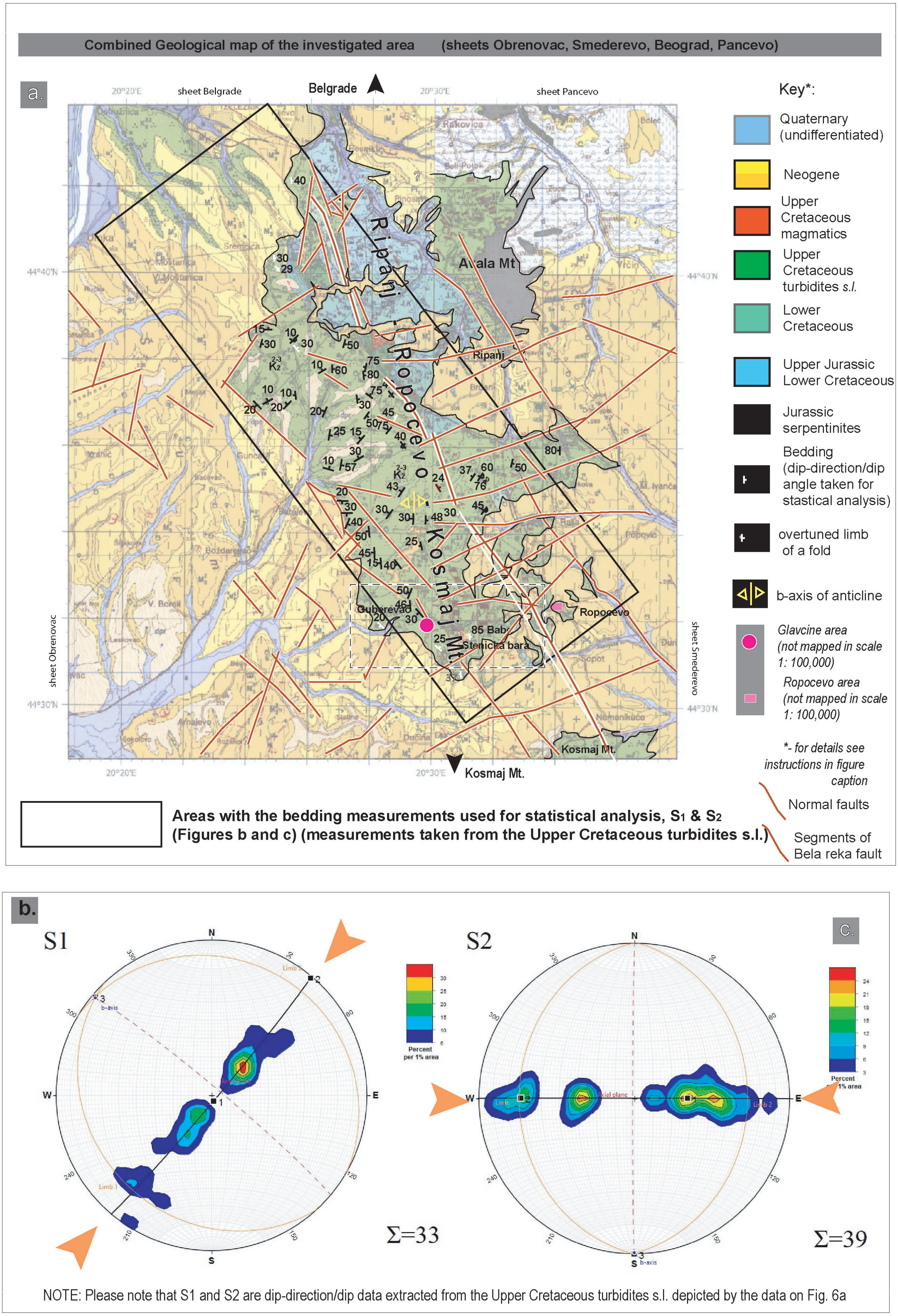


Fig. 6. a. Combined geological map of the investigated area. b. S_1 and S_2 diagrams present bedding data from segments of sheets Obrenovac and Smederevo. See text for details.

Results of key-area structural analysis

Observing compressional field kinematic indicators, such as slickensides, striations, tectonic stylolites, and cleavage, allowed us to determine the displacement directions (Fig. 4a-g). The outcrops expose a reverse fault plane, exposing its footwall domain and missing hangingwall. The plane is dipping towards the ENE with a dip of 55-60 and the azimuth of ca. 80, whereby the slickensides corroborate reverse upwards-directed movement towards the WSW (Fig. 4b, c, d). Intensely folded isocline folds in the peculiar Sava Suture sediments (Fig. 4e) are located slightly east of the slickensides (Fig. 4f). The fold hinge plunges towards NNE. In addition, the Guberevac outcrop exposes compressional cleavages observed earlier (Sajić, 1987).

Farther to the east (Fig.6a), away from the Guberevac site, between the Babe and Ropočevo areas (Fig. 2b, 3c, d, 7a-d), measurements show a significant change from the highly deformed into steeply inclined thin layered sequence (Fig. 3d). The latter sequence is represented by steeply inclined turbiditic layers that are disturbed by the emplacement of the Glavčine granitoid body. As mentioned, the measurements show steeper dip angles (Radulović, 1987). At the Babe village, the marlstones have sharp yet largely diluvium-covered contact with the older Albian limestone of the East Vardar Zone. This lithostratigraphic change presumably marks the covered thrust-type contact (as per Toljić et al., 2018; also in Spahić & Gaudenyi, 2022; Fig. 2b, 7e). Despite the widespread Quaternary cover, the subsurface lineament or Bela Reka fault is also inferred by the presence of the Albian sequence of the overriding East Vardar Zone (just a few meters from the presumed fault; Fig. 2b, 7d-f). The nearby “Ropočevo breccia” and the Albian sandy limestone sequence/calcareous-arenitic units are lithostratigraphic members of the “paraflysch” sequences (latest Tithonian-earliest Berriasian, Albian-Cenomanian; Dimitrijević & Dimitrijević, 2009; Spahić et al., 2023). The "paraflysch" is the clastic-carbonates sequence of Lower Cretaceous deposited on the reacivated and subsided European foreland (Dimitrijević & Dimitrijević, 2009; Spahić et al., 2023).

Discussion: Late Cretaceous convergence onset, post-collisional magmatic reactivation, and suture kinematics

In the wider Belgrade area Guberevac-Babe -Glavčine-Ropočevo area (Figs. 2a,b, 7, 8), the exact age of the onset of the regional lithospheric-scale contraction has not been previously constrained by field deformations. Nevertheless, a few recent reports proposed a similar Cretaceous onset of the convergence-related compressional deformations related to Apulia/Adria/Dinarides collision with the former south European foreland (Schmid et al., 2008; Toljić et al., 2018, Marton et al., 2022). Reports mainly highlight a tectonic connection of flysch deposits, describing the investigated Upper Cretaceous sequence as syn-contractional turbidites (Pamić, 2002).

Constraints on the Upper Cretaceous (Paleogene) regional compressional event (Cleavage patterns, folding and reverse faults)

The collected field data and constraints on deformation stages (Fig. 9), coupled together with previous papers published from the studied area, point to the presence of two cleavage trends: first, older NE-dipping cleavage (Sajić, 1987) overprinted by cleavage trending depicted during fieldwork (developed within west-vergent folds; Fig. 4e). The older stage fits with the precursory latest Jurassic mild collision (Spahić et al., 2023, 2024), frequently interpreted as an obduction-related event (hereinafter **Stage#0**; Maleš et al., 2023; Fig. 9). This pre-Cretaceous Tethyan convergent configuration is characterized by an intra-oceanic magmatic response of the latest Jurassic age (documented within the central East Vardar Zone; Resimić-Šarić et al., 2005; Šarić et al., 2009). Thus, we interpret this older cleavage pattern as a remnant of an earlier compressional stage related to the latest Jurassic closure of Neotethys (see also Spahić et al., 2023).

The second cleavage pattern fits into the N-S- (in Cretaceous reference) or today, E-W-directed shortening and development of folds (hereinafter **Stage#2;** Fig. 9). This second or younger N-S cleavage trend (Fig. 4g) and the observed folds are consistent with the investigated Late Cretaceous compressional event (**Stage#1**). **Stage#1** represents the onset of late Alpine Upper Cretaceous contraction, locally indicated by the observed folds (Fig. 4e). The observed folds have a west-northwest-vergence being of syn-contractional origin (b-axis or fold axis 12/9). Such combined fold–cleavage patterns may suggest the presence of a progressive Upper Cretaceous deformation (Stage 1 and Stage 2; Fig. 4g). According to the collected stratigraphic and structural data, it appears that the investigated late Mesozoic deformation was initiated already during the (late) Santonian.

During **Stage#3** (Fig. 9), the ongoing late Cretaceous shortening and collision produced the observed thrust faults (note that the thrust faults and folds are in a confined place; Fig. 4). The presence of reverse faults attests to the continuity of the Upper Cretaceous shortening (also indicated by the curved geometry of tectonic stylolites; Fig. 4d, f). The progressive thrusting contributed to a further narrowing the remaining marine Upper Cretaceous corridor (deep sea). Eventually, the Upper Cretaceous - Paleogene shortening reached the (micro)continent-continent collision stage. The investigated reverse fault planes measured within the "Upper SSZ" are cropping at a distance from the area of the Bela Reka fault (Guberevac section; Fig. 2b, 4). Such a distance from the main deformation front could suggest the presence of the oblique motion of the two crustal domains documented to the south in North Macedonia (Köpping et al., 2019; see later in the text).

Stage#4 exhibit evidence of the Stage 4 exhibit evidence of much younger regional extension (Fig. 9). The statistical results extracted from the Cretaceous layers show that the observed Late Cretaceous compressional trends (bedding; Fig. 6) are affected by the emplacement of the younger magmatic bodies or doming (e.g., the layering in the vicinity of the Glavčine ring structure; Radulović, 1987; Figs. 6a, 7a). In addition, the younger extensional-type brittle faults have the strike values dissipating towards the north (10-20°) and NNW (ca. 310°) (Fig. 6a). The statistical fault strike data are consistent with the younger extensional episodes (see Marović et al., 2007b; Marinović & Rundić, 2020, for details). Such a configuration suggests the latest Oligocene-Miocene extensional interference followed by the fault reactivation. In addition,

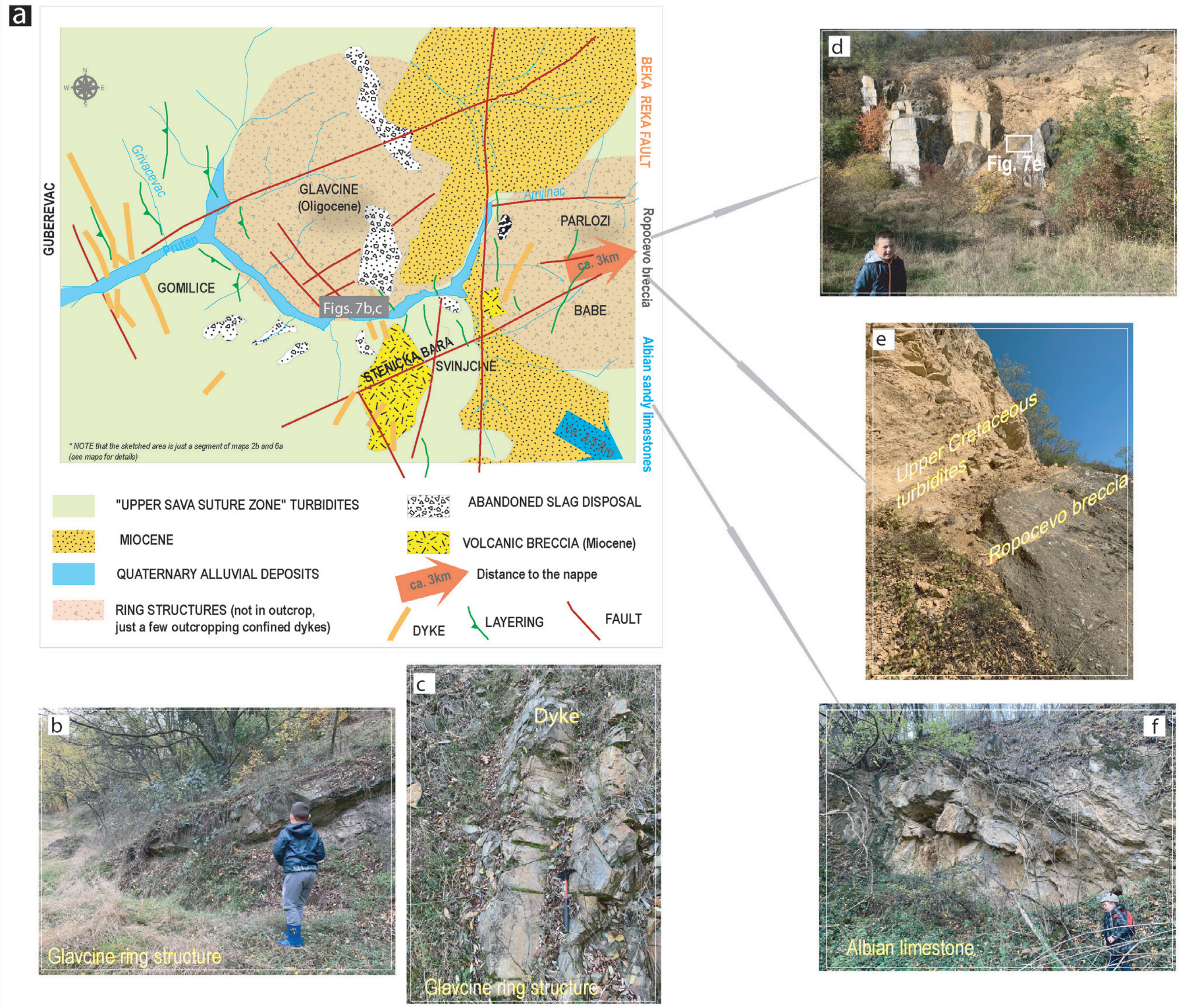


Fig. 7. a. Geological sketch-map of the Babe ore-baring Glavčine-Parlozi structure (inset from Radulović, 1987, modified). b, c. The emplacement of the magmatic body explains the post-depositional tilting near across Glavčine-Parlozi area. The entire area is abundant with the ancient Roman-time abandoned slag deposits, spread all over the mapped ring structures (Spahić et al., 2007; Tančić et al., 2009). d, e. Ropočevo abandoned quarry, East Vardar Zone turbidite segment as carrier of complex brecciated body (Fig. 2b; see Kurešević et al., 2022, Spahić et al., submitted, for details). f. Albian sandstones (also in Pavlović et al., 1979), according to Toljić et al. (2018) it is of East Vardar inheritance (see Fig. 2b).

literature data show that the investigated area experienced a two-staged post-collisional magmatic interference during the Tertiary (e.g., Pamić et al., 2002; Cvetković et al., 2004; Palinkaš et al., 2008).

Tertiary magmatic stages, evidence of extensional (post-orogenic) suture reactivation

Distribution of the Oligocene-Miocene magmatic entities implies that the late Paleogene igneous activity is clustered along the major NNW-SSE striking deep-crustal subsurface remnant lineament (Guberevac-Babe-Ropočevo segment). This NNE-SSW fault or subsurface geophysical lineament extends further to the south, striking across the Rudnik- Topola area and further in North Macedonia (Vukašinović, 1973b; Kostić, 2021; Toljić et al., 2021; Fig. 1, 2a). The emplacement of the subvolcanic bodies was also guided by the local faults, likely reactivated strike-slip fault near the Babe area (Spahić & Gaudenyi, 2022; Fig. 7a, red bold lines). Such a position could indicate the location of the overprinted former restraining band (compression) and releasing band (extension).

The post-collisional extension-type reactivation and the emplacement of magmatic bodies occurred mainly in both the SSZ- and East Vardar turbidites (Fig. 9). However, within the investigated area, its former overriding plate (Albian sandstone, "Ropočevo breccia" of the East Vardar Zone) carries no magmatic entities except for the kersantite body in the Ripanj area (Sokol et al., 2020). The former descending plate and SSZ turbidites are accommodation places of both (i) the Oligocene subvolcanic Glavčine-Parlozi ring structure (Fig. 8a,b) and (ii) the second Miocene igneous body exposed at the Stenička bara (Fig. 7a,b,c). The exposed pyroclastic rocks outline the youngest Miocene volcanic episode (25.12-23.27 Ma; Vasković, 1987). The presence of a suture-related

Fig. 8. The outcrops showing the "Upper Sava Zone" turbidite sequence at the top of Parlozi ring structure. b. "Pyroclastic bomb" found in the Parlozi area (also in Radulović, 1987), c. Thermally affected turbidites in the area of the principal Babe fault indicate proximity of the magmatic levels, d. Typical marlstone of the area.

post-collisional subvolcanic magmatic body could further be inferred by the occurrence of the rarely exposed eruptive igneous breccias (Fig. 8b). There, the underlying Glavčine-Parlozi magmatic body has thermally and chemically affected the surrounding cap-rocks, altering the investigated turbidites at their base (silification and turmalinization observed in the Babe village; Zrnić et al., 1998; Fig. 8c). The subsurface conditions are characterized with high temperature and lower pressure, typical for a subvolcanic level or shallow crust depths (Radulović, 1987; Zrnić et al., 1998; Logar et al., 1998). The sulfidic mineralizations are associated with quartz-latite, riolite, and explosive igneous breccias (Zrnić et al., 1998). Such an assembly indicated a protracted magma-related near-suture activity (Radulović, 1987).

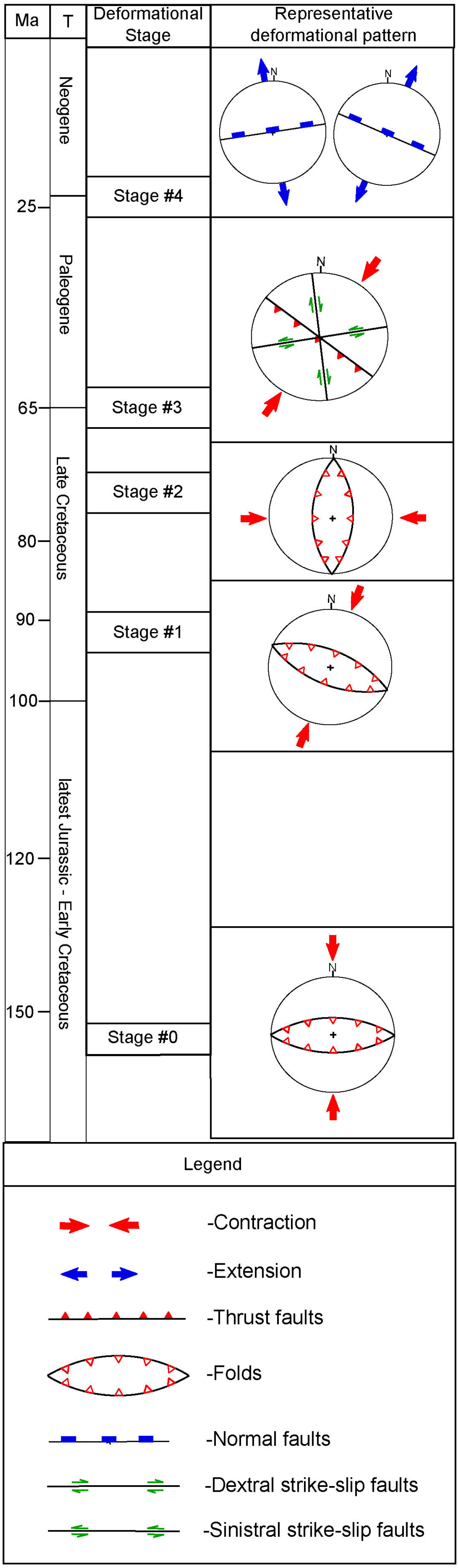
The Guberevac-Glavčine-Stenička bara igneous sub-province is additionally depicted by the subsurface aeromagnetic anomaly (Vukašinović, 1973b). The subsurface data delineate the geometry of the emplaced entities beneath the ring structures (Fig. 2b, 7a). According to the geophysical record, the subsurface igneous bodies have a NNW-SSE direction or towards the Avala Mt. and slightly southward, towards the nearby Kosmaj Mt. (Fig. 2b). The maximum values of ΔT intensity reaching 1000-1200 nT are positioned precisely at the aforementioned ring structures, the Babe-Glavčine and Kosmaj Mt., including the anomaly beneath the Venčane igneous area north of Bukulja and Rudnik Mts. (Vukašinović, 1973b; Fig. 1, 2a). Further to the south, the SSZ can be traced by this Oligocene magmatic reactivation (e.g., at Rudnik Mt., Kostić, 2021; Kostić et al., 2021; Fig. 1).

Orthogonal vs. oblique underplating?

Recent papers dealing with the investigated Belgrade area mainly explain the orthogonal subduction (relative to stable Europe), resulting initially in a fore-arc extension of its upper plate (Toljić et al., 2018, 2021). Accordingly, the presumed fore-arc extension provided the conditions further allowing the extrusion of bimodal magmas of the Upper Cretaceous age (e.g., Grubić et al., 2009; Ustaszewski et al., 2010; Cvetković et al., 2014, 2016; Sokol et al., 2019). However, a few earlier (Dimitrijević & Dimitrijević, 1975; Dimitrijević, 1997) and some more recent observations have indicated that this area or the area of NeoTethys Vardar Ocean underwent a multistage oblique lithospheric-scale collision starting in the latest Jurassic (Fig. 9). According to this scenario, after the oceanic closure occurred in the latest Jurassic, the narrowing of the remaining deep-sea Cretaceous strike-slip corridor stepped into the final stage of the continent-continent collision (see Farangitakis et al., 2020, for the kinematic modeling Köpping et al., 2019; Spahić & Gaudenyi, 2022).

The principal difference between these two (Upper) Cretaceous tectonic models is the lower plate configuration. Instead of the proposed orthogonal subduction, the oblique dextral underplating beneath the European plate occurred in the following two stages: (i) initially causing the Late Jurassic NeoTethyan Vardar closure and obduction; (ii) the terminal Late Cretaceous - Paleogene (micro-continent) collision (Dimitrijević & Dimitrijević, 1975; Grubić, 2002; Willingshofer et al., 1999; Pamić et al., 2002; Šarić et al., 2009; Bonev & Stampfli, 2008, 2011; Marroni et al., 2014; Köpping et al., 2019; Spahić & Gaudenyi, 2022; Spahić et al., 2023).

The Cretaceous lower plate remobilization of Jurassic oceanic crust contributed to the production of Cretaceous pull-apart basins and associated bimodal magmatism (Köpping et al., 2019; Spahić & Gaudenyi, 2022; Fig. 1, yellow-black rectangles). Once developed, pull-apart transtensional releasing bend segments allowed the deposition of turbidities and intrusion of the Upper Cretaceous (Coniacian) bimodal magmatism. This hypothesis of releasing and restraining bends could be verified by this study, which provides new constraints on a distant position of the Guberevac folds (restraining bend positioned away from the Bela Reka fault; Fig. 2). Such a strike-slip faulting mechanism is frequently associated with evidence of crustal “telescoping”. Telescoping allows the tectonic exposure of different crustal levels, further involving the exhumation of deeper lithosphere sections (Cao & Neubauer, 2015). The bimodal magmatic signal is documented across the entire Sava Suture Zone (former deep sea marine corridor; Fig. 1). These bimodal magmatic imprints can be found exclusively within the localized near-suture (thinned) lithospheric fragments (see different locations and their Upper Cretaceous magmatic imprints within the Sava Suture Zone: Ustaszewski et al., 2009; Cvetković et al., 2014; Prelević et al., 2017; Balen et al., 2020; Sokol et al., 2020; Toljić et al., 2021; Fig. 1). Accordingly, this Upper Cretaceous magmatism could serve as a marker of pull-apart mini-basins associated with strike-slip movements (releasing bend that was reactivated in Oligocene and Miocene, see earlier in text). Thus, the investigated Ripanj -Babe - Guberevac area could be described as a configurational crossover between the overprinted restraining and releasing bends



segments of the strike-slip Sava Suture Zone. Nevertheless, the complexity of the wider investigated area requires further study.

Conclusions

The study shows that the onset of the Late Alpine collision was during the (late) Santonian. A principal difference between the two almost identical, tectonically superimposed turbidites of the Upper Cretaceous age, can be attributed to observed different levels of the exposed compressional-type deformations. The "Upper Sava Suture Zone" positioned to the left of the Bela Reka fault experienced more intense compressive deformation, resulting in structural elements like folds, thrust faults, and tectonic stylolites. These structures are consistent with their foredeep-related depositional system, typical for turbidites. Second or the East Vardar Zone flysch (overriding plate) has no prominent Upper Cretaceous deformation observed across the investigated area. Thus, the entire Sava Suture Zone sector near Belgrade needs further study.

Based on field mapping and previously published geophysical and structural data (Filipović et al., 1973; Pavlović et al., 1979), the imprints of four tectono-deformational phases were interpreted since the end of the Jurassic. The interpretation yielded four tectono-deformational phases since the end of the shortening. The Santonian shortening marks the here-depicted onset of the contractional deformation. The Upper Cretaceous shortening led to the folding and progressive Upper Cretaceous–Paleogene contraction and thrust faulting. Progressive deformation led to the development of brittle structures, represented by the prominent reverse faults (Guberevac area). After the crustal thickening ceased in the early Paleogene, the area was reactivated by the Oligocene igneous intrusion (Glavčine-Parlozi) and Miocene volcanic episode (Stenička bara). Other main conclusions are:

The Guberevac-Babe SSZ sector holds evidence of the two-staged contractional events: the latest Jurassic closure of Neotethys Vardar ocean (Stage#0, not investigated in this study) and intense Santonian to post-Santonian tectonic events marking the late Alpine progressive compressional

Fig. 9. Deformation stages extracted from the study: Stage#0: latest Jurassic – Early Cretaceous compression; **Stage#1**: initial folding at the beginning of Upper Cretaceous with NNE-SSW tensors; **Stage#2:** folding at the end of Upper Cretaceous with E- W tensors; **Stage#3:** collision (transpression); **Stage#4:** post-orogenic extension and magmatic emplacement.

stage (Stages#1,2,3). This new insight resolves the previous conflicting lithostratigraphical interpretations by confirming the presence of the Santonian SSZ turbidites in Guberevac.

The intense initial post-Santonian (plastic) folding, including the observed vergence, suggests the presence of (late) Santonian syn-contractional deposition and progressive development of cleavage (Stages#1 and 2);

The observed thrust faults in the Guberevac area are marking the post-Santonian onset of the Adria-Europe collision (Stage#3). The reverse faults in the Guberevac-Babe SSZ segment are tectonically shifted several kilometers away from the main Bela Reka thrust interface;

The exhumed Guberevac-Babe-Kosmaj Mt. paleosuture segment has been interrupted by a few post-orogenic extensional episodes characterized by intense igneous activity (Stage#4): (i) initially during late Paleogene/Oligocene time by the emplacement of the subvolcanic Glavčine ore body, and (ii) during the Miocene, accounting for the widespread regional extension and the emplacement of the Stenička bara volcanic system. The study further shows that these suture-related intrusions may or may not penetrate the overlaying Upper Cretaceous turbidites in regional terms.

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