

The Zvornik “Suture” in the Internal Dinarides: A Key to Understanding Regional Strike-Slip Structures in the Balkans

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Abstract. Sedimentary basins that develop in convergent tectonic settings are excellent archives for evidence of the tectonic processes active during orogen formation. A representative example of this basin type occurs in the Internal Dinarides, at the boundary between the two most distal tectonic units of Adria – the Jadar–Kopaonik and Drina–Ivanjica units. This sedimentary basin possesses unique characteristics not described elsewhere in the Dinarides: it contains an “olistostrome mélange” formation, which Milorad Dimitrijević (1973) interpreted as a mélange produced by subduction and/or underthrusting of the Drina–Ivanjica element beneath the Jadar block. The type locality where this unit was first described is in the vicinity of town Zvornik, while the tectonic structure along which subduction was postulated was subsequently named the “Zvornik suture”. In this study we focus on another locality where the Upper Cretaceous “olistostrome mélange” has been mapped – the Jelica Mts. near the town of Čačak. By applying structural-geological mapping and detailed study of magmatic rocks and sedimentary successions across the broader Jelica Mts. area, we aimed to determine the principal properties of the tectonic structures related to activity along the Zvornik Fault, and to assess the potential geodynamic significance of this Upper Cretaceous “mélange”. Our results suggest that the volcano–sedimentary series of the Jelica Mts. represents deposition within a wedge-top basin that developed due to the oblique thrust of the Jadar–Kopaonik Unit. The pronounced dextral horizontal component along this thrust could have created transtensional domains in which partial melting of the upper mantle produced basalts which in this study are determined at 87.4 ± 0.96 Ma. Based on our findings, we conclude that the Zvornik Fault represents the front of the Jadar–Kopaonik thrust, which in recent stress field accommodate a significant dextral strike-slip component.

Key words:

Zvornik fault, Jadar–Kopaonik Unit, Drina–Ivanjica Unit, Jelica Mts., Senonian diabase-chert formation.

Апстракт. Седиментни басени, који се развијају у конвергентним тектонским режимима, представљају веома добре средине у којима се чувају докази о различитим процесима који су били активни током формирања орогена. Један од добрих примера оваквог типа басена развијен је у Интерним Динаридима, на граници између две најдисталније тектонске

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Кључне речи:

*Зворнички расед,
Јадарско-копаоничка јединица,
Дринско-ивањичка јединица,
планина Јелица, сенонска дијабаз-
ројска формација.*

јединице Јадранске микроплоче – Јадарско-копаоничке и Дринско-ивањичке. Овај седиментни басен одликује се јединственим карактеристикама, које нису описане у другим деловима Динарида – он садржи формацију „олистостромског меланжа“, коју је још 1973. године Милорад Димитријевић описао као меланж настао услед субдукције и/или подвлачења Дринско-ивањичког елемента под Јадарски блок. Типски локалитет где је ова јединица први пут описана била је у околини Зворника, па је тако и тектонска структура дуж које је претпостављена субдукција, названа – Зворнички шав. У овом раду, фокусирамо се на још један локалитет где је картиран горњокредни „олистостромски меланж“ – планину Јелицу код Чачка. Применом метода структурно-геолошког картирања и детаљног проучавања магматских стена и седиментних сукцесија на ширем подручју планине Јелице, покушали смо да одредимо основне карактеристике тектонских структура везаних за активност Зворничког раседа, као и геодинамички значај овог горњокредног „меланжа“. У складу са резултатима нашег истраживања, предложено је да вулканоседиментна серија планине Јелице представља резултат таложења у оквиру тзв. *wedge-top* басена, који је настао и развијао се услед активности косе навлаке Јадарско-копаоничке тектонске јединице. Управо хоризонтална десна компонента кретања дуж ове навлаке, могла је да створи услове за формирање транстензионог домена, у коме је могло доћи до парцијалног стапања горњег омотача и настанка базалта, чија је старост у овој студији одређена на 87.4 ± 0.96 Ма. На основу резултата наших истраживања, закључујемо да Зворнички расед представља фронт навлаке Јадарско-копаоничке јединице, са израженом десном хоризонталном компонентом кретања.

Introduction

The Dinarides represent part of the double-vergent Dinaric-Carpatho-Balkan orogenic chain that formed by convergence between the Adriatic microplate and the European continent since the Late Jurassic (e.g. SCHMID et al., 2020 and references therein). This tectonic convergence was initiated by widespread obduction of the Mesozoic Neotethys Ocean(s) onto the passive Adriatic margin during the latest Jurassic (DIMITRIJEVIĆ, 1995; ROBERTSON et al., 2013; SCHMID et al., 2020), and oceanic closure interpreted to have happened either during latest Jurassic - earliest Cretaceous (DIMITRIJEVIĆ, 1995; ROBERTSON et al., 2013) or the Late Cretaceous (SCHMID et al., 2020). Following these major tectonic events, the newly restructured boundary between Adria and Europe became the region where new sedimentary basin developed. The formation of the basins resulted from ophiolite obduction since as early as Late Jurassic (MIKES et al., 2008) and intense

nappe stacking of the internal and external Dinaric units from the Cretaceous until the Early Paleogene (SCHMID et al., 2020).

Traditionally, DIMITRIJEVIĆ & DIMITRIJEVIĆ (1973) and DIMITRIJEVIĆ (1995) interpreted the central Balkan tectonic framework through a two-ocean model. In this view, the Dinaride Ophiolitic Belt in the west and the Vardar Ophiolitic zone in the east represented separate oceanic domains divided by the Drina-Ivanjica Unit. In that view, the Zvornik Fault marked the final structural scar separating the distal Adriatic margin from the Vardar Zone to the east. Because of that, this fault was named the Zvornik suture. Shortly later, KARAMATA, DIMITRIJEVIĆ & DIMITRIJEVIĆ (1999) reinterpreted the Zvornik suture lineament as the direct northern extension of the Western Belt of the Vardar Zone (WB), which they considered a single oceanic channel that sat directly between the Drina-Ivanjica margin and the Jadar-Kopaonik block (Fig. 1). In both models for the Zvornik suture, an active oceanic domain, either

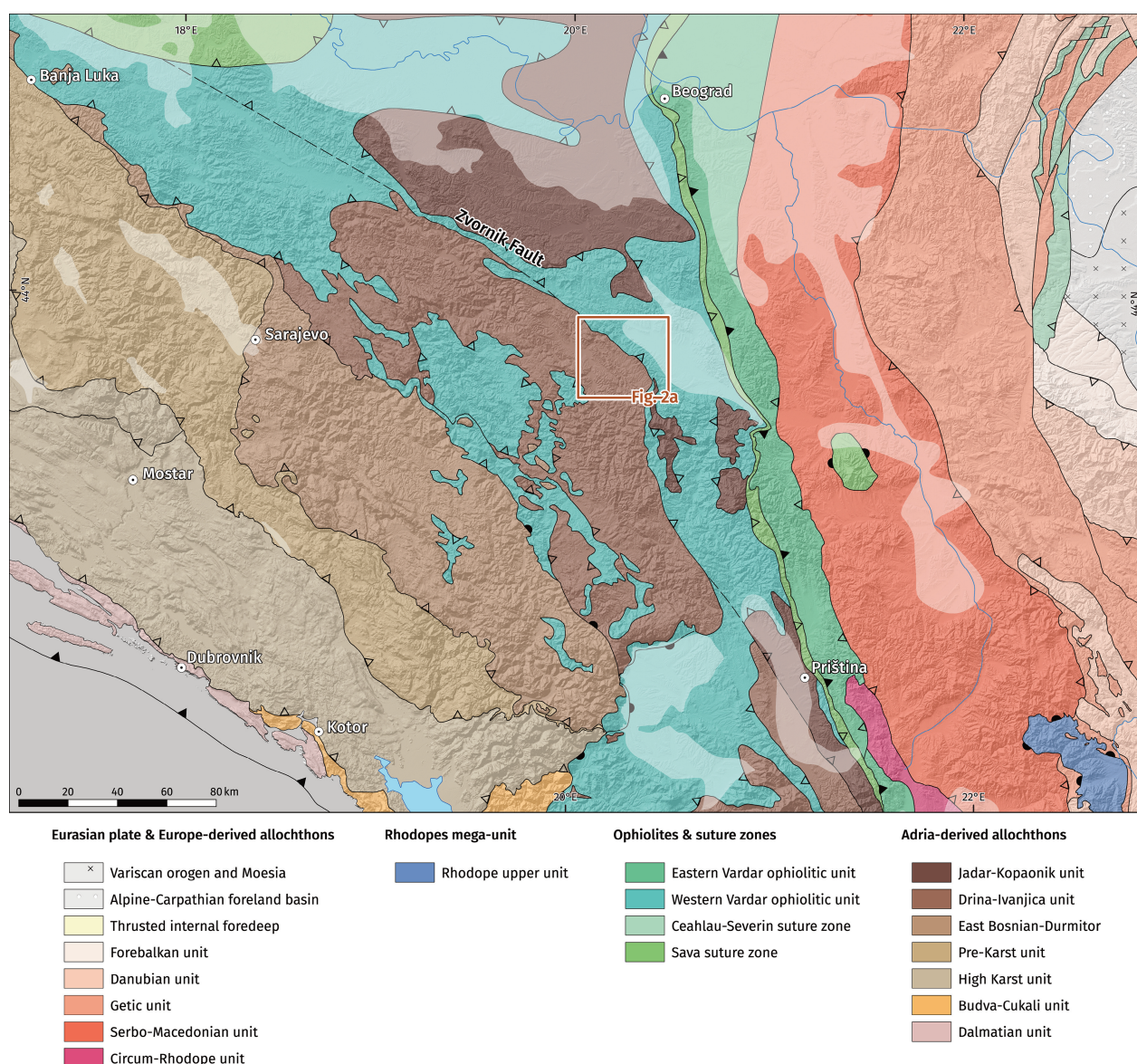


Fig. 1. Tectonic map of the central Balkan Peninsula, after SCHMID et al. (2020). The immediate research area is marked by red rectangle.

viewed as a separate basin or as part of the WB, persisted along this lineament well into the Late Cretaceous. Subsequent sedimentation was directly controlled by the tectonic processes active in this area. In order to organize the sedimentary successions, DIMITRIJEVIĆ (1995) classified the Cretaceous sediments of the domain between Europe and Adria into two large regional groups: (a) Cretaceous sediments of the Vardar zone and (b) Upper Cretaceous sediments of the Dinarides. As a sedimentary proof of an open oceanic domain within this system, DIMITRIJEVIĆ (1995) considered the "Senonian diabase-chert" olistostromes of the Jelica Mts. In parallel, KARAMATA et al. (1999) provided the complementary

magmatic evidence along the same WB strike, documenting ~80 Ma sheeted dykes interlayered with Campanian–Maastrichtian pelagic limestones at Kozara Mts. (KARAMATA et al., 2005), as well as Upper Cretaceous basalt flows entraining Campanian limestone blocks near Krupanj (FILIPOVIĆ, 2005).

Subsequent decades of research have largely converged toward a single-ocean hypotheses (e.g. SCHMID et al., 2008; CVETKOVIĆ et al., 2016; SCHMID et al., 2020; and references therein). In this view, the remnants of the Neotethys (or Vardar) Ocean were obducted onto the passive Adriatic margin during the Late Jurassic and were later affected by out-of-sequence thrusting during continental collision.

This post-obduction tectonics disrupted the original paleogeographic configuration, producing two geographically separated ophiolitic belts and exposing Adria-derived continental units as tectonic windows beneath the obducted ophiolites (Fig. 1).

Within this broadly accepted hypothesis, however, the precise configuration of the Adria – Europe boundary during the Late Cretaceous – particularly the role and significance of structures such as the Zvornik Fault – remains debated. This is especially evident in interpretations of Cretaceous sedimentary successions and their tectonic relationships, which form the basis for reconstructing the final stages of ocean closure and subsequent collision (TOLJIĆ et al., 2018; STOJADINOVIĆ et al., 2022).

In this study we focus on the immediate contact zone between the Jadar–Kopaonik and the Drina–Ivanjica units, along the southern prolongation of the original Zvornik Fault (Fig. 1). The investigated area is located in the Jelica Mts. near the town of Čačak, exposing a complex west-vergent thrust contact of the aforementioned tectonic units. This is one of the very few places in Serbia hosting the Upper Cretaceous “olistostrome mélange” (DIMITRIJEVIĆ & DIMITRIJEVIĆ, 1973; DIMITRIJEVIĆ & DIMITRIJEVIĆ, 1976; DIMITRIJEVIĆ, 1995). We study basement rocks, sedimentary units, magmatic rocks and deformation structures in all geological units, in order to reassess the geodynamic significance of the so-called “Senonian diabase–chert formation” as defined in the General Geological Map of the former SFRY (BRKOVIĆ et al., 1978; DIMITRIJEVIĆ, 1995). Our data suggest that significant dextral displacement along the Zvornik Fault was already active during the Late Cretaceous. Furthermore, we reinterpret this formation as the product of a wedge-top basin developed along the oblique Jadar–Kopaonik thrust front.

The problem of the Adria – Europe convergence in the Central Balkans

The issues outlined above reflect a broader and still unresolved problem: the timing and mechanism of the closure of the Mesozoic oceanic domain(s) between Adria and Europe (see STANKOVIĆ et al. (2026) for a comprehensive overview). Most recent hypo-

theses converge on the existence of a single Neotethyan (Vardar) Ocean (see SCHMID et al., 2020 for detailed discussion), whose remnants were obducted onto the passive Adriatic margin during the Late Jurassic and subsequently reworked by out-of-sequence thrusting. This obduction disrupted the original paleogeographic configuration and produced two ophiolitic belts. Within this tectonic setting, the Jadar–Kopaonik and the Drina–Ivanjica units represent two most distal continental domains of Adria, now exposed as tectonic windows below the obducted ophiolites of the Western Vardar Ophiolitic Unit (Fig. 1). Accordingly, the Zvornik Fault is regarded as a major tectonic boundary with a significant dextral component (e.g. SCHMID et al., 2008; GERZINA, 2010), separating these two tectonic units. By contrast, the final closure of the Neotethys Ocean is believed to have occurred along the Sava Suture Zone (see Fig. 1), defined as a narrow belt of Upper Cretaceous sedimentary, magmatic, and low-grade metamorphic rocks located between Adria- and Europe-derived units (Fig. 1) (SCHMID et al., 2020).

Despite this seemingly coherent architecture, several fundamental problems remain. These stem not only from the geological complexity, but also from the inconsistencies in the classification and interpretation of tectonic units. Two issues are particularly critical:

(1) Tectonic units in this region are frequently classified based on their geographic location rather than their geodynamic characteristics, leading to different interpretations of units that may share a common origin;

(2) Since the 1970s, various authors have not adhered to the original terminology for tectonic units and have often been inconsistent even with their own chosen terminology. Because of that, one can often find the same name for completely different tectonic units (e.g., the Central Vardar Zone *sensu* DIMITRIJEVIĆ (1995) and the Central Vardar Zone *sensu* TOLJIĆ et al. (2019) are different tectonic units with different geographical locations, formed in different geodynamic environments), or, albeit rarely, different names for the exactly same tectonic unit.

Similar ambiguities affect the interpretations of Cretaceous sedimentary successions located between Adria and Europe. They are commonly described in

terms of their present-day tectonic positions, neglecting their original depositional environment. Moreover, the Sava Suture Zone is axiomatically assumed to represent relicts of an Upper Cretaceous oceanic basin, with associated trench- or accretionary wedge deposits (SCHMID et al. 2020) (Fig. 1), regarding it as the final suture of the Upper Cretaceous (Sava/Neotethys) ocean. However, this interpretation has been increasingly challenged by recent studies (BALEN et al., 2020; SCHNEIDER et al., 2022, 2025; PRELEVIĆ et al., 2017; SOKOL et al., 2020, 2025; STANKOVIĆ et al., 2026; OLIĆ PECO et al., 2026; ŠUICA et al., 2026) that emphasized three main problems:

(1) clear evidence that Cretaceous ophiolites exist in the central Balkans is lacking; the mafic rocks from the Sava Zone previously interpreted as parts of an oceanic crust have been shown not to represent true ophiolitic sequences, but within-plate basaltic rocks (e.g. PRELEVIĆ et al., 2017; SOKOL et al., 2020, 2025; OLIĆ PECO et al., 2026; ŠUICA et al., 2026);

(2) undisputed ocean-floor sediments of Cretaceous age are lacking; for example, the *Scaglia Rossa*-type limestones from the Kozara and Klepa Mountains have been considered oceanic primarily due to their spatial association with basalts, rather than on the basis of independent sedimentological criteria (PRELEVIĆ et al., 2017; OLIĆ PECO et al., 2026);

(3) the origin of the Timok Magmatic Complex – often cited as unequivocal evidence for active subduction during the Late Cretaceous – can be explained by alternative geodynamic scenarios that do not require contemporaneous oceanic subduction (STANKOVIĆ et al., 2026).

In this context, sediments that can presently be found between the Serbo-Macedonian Unit (as part of the European continent) and the Jadar-Kopaonik Unit (as part of Adria), can be classified into three groups: (1) sediments deposited on the European margin, (2) sediments deposited on the Adriatic margin, and (3) central-zone sediments. The key question is if these domains represent originally separated basins later juxtaposed during Late Cretaceous–Paleogene collision (STOJADINOVIĆ et al., 2022), whether some of these tectonic contacts already formed during the Late Cretaceous (TOLJIĆ et al., 2018), or whether they were parts of a single de-

positional system that existed between Europe and Adria, subsequently dismembered by Paleogene shortening and out-of-sequence thrusting.

Geological setting

The Jelica Mts. represents an extremely complex area of thrust-faults that bring together portions of massive diabase and diabase breccia, serpentinites, mélangé and metamorphic rocks of the Jadar-Kopaonik Unit, over the Kosovska Mitrovica flysch, representing the cover of the Drina-Ivanjica Unit (Figs. 1, 2a,b). Geotectonically, DIMITRIJEVIĆ (1995) classifies this complex area into the so-called Studenica Slice, which he regarded as a separate tectonic unit located between the Drina-Ivanjica Unit and the Kopaonik block. There are two reasons for such classification: (1) it was not clear whether the metamorphic basement of the Studenica Slice corresponds to the Drina-Ivanjica Unit or to the Kopaonik block, and (2) DIMITRIJEVIĆ (1995) interpreted the peculiar "Senonian diabase-chert formation" as the olistostrome mélangé that he regarded the product of a Late Cretaceous subduction(?) / underthrusting of the Drina-Ivanjica Unit beneath the Vardar zone. However, SCHEFER et al. (2010) argued that the Studenica Slice is a metamorphic core complex exhumed during Miocene (~ 18 Ma), the metamorphic basement of which is analogous to the Kopaonik Metamorphic Series. Here, we adopted the tectonic division by SCHMID et al. (2020) (Fig. 1) according to which the Studenica Slice, and, hence, the Jelica Mts., is part of the Jadar-Kopaonik Unit, the most distal continental part of Adria.

The description of geological units follows the adopted tectonic division – first we describe the geological units belonging to the easterly positioned Jadar-Kopaonik Unit (Fig. 2) and then the geological units of the westerly positioned Drina-Ivanjica Unit (Fig. 2).

The Jadar-Kopaonik Unit

Metamorphic rocks of the Jelica Mts. represent the northern prolongation of the Studenica Series

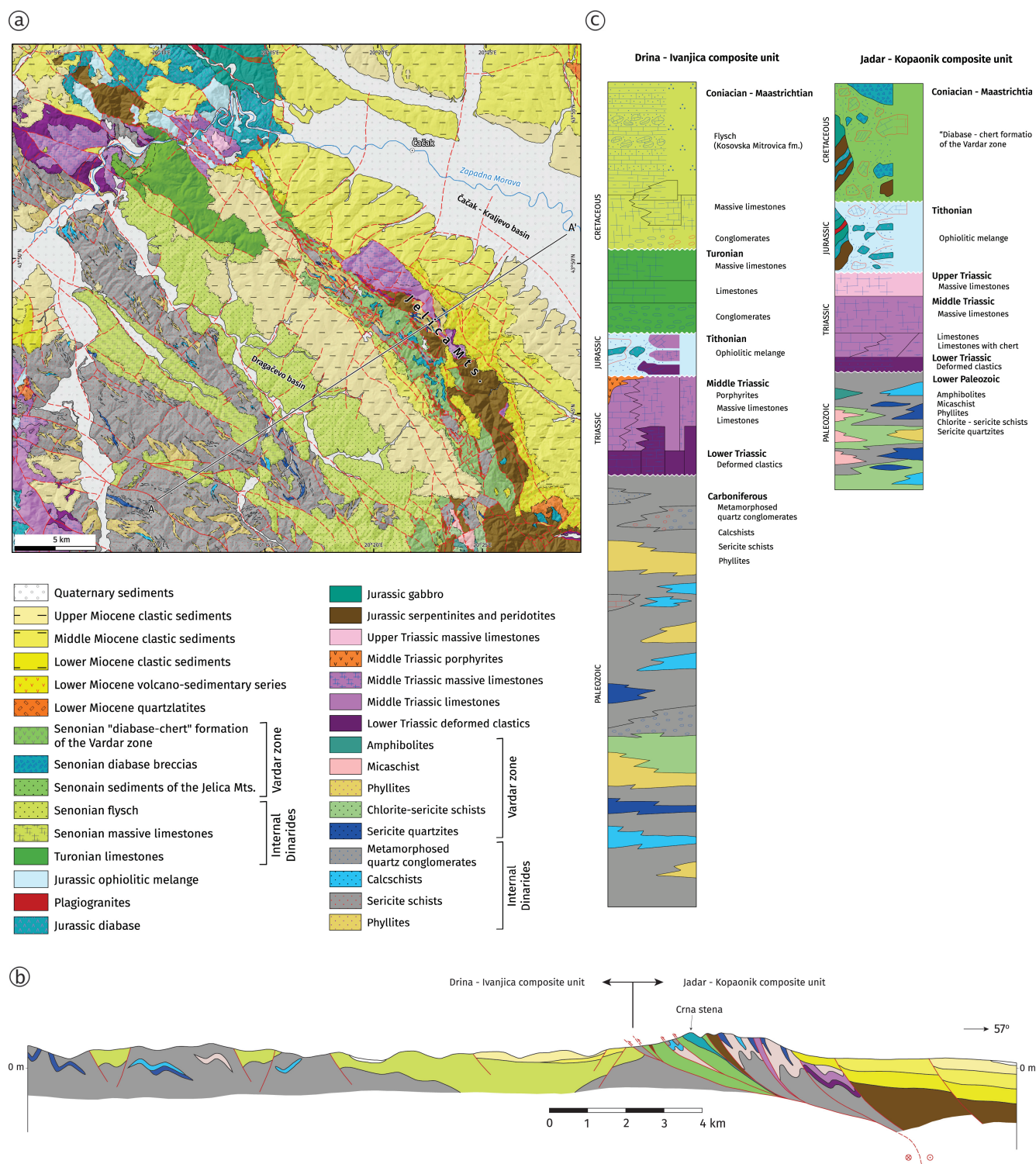


Fig. 2. a) Geological map of the research area, according to the General geological map of SFRY, sheets Titovo Užice (Mojsilović et al., 1978) and Čačak (Brković et al., 1978). The area shown on this map corresponds to the area marked by red rectangle in Fig. 1; **b)** Geological cross-section, marked as A–A' trace on the geological map in Fig. 2a; **c)** Lithological columns of the research area (Brković et al., 1978).

(Fig. 1). These rocks have been interpreted in several different ways. ĐOKOVIĆ (1985), for instance, argued that all four formations of the Drina–Ivanjica Unit have their analogues in the Studenica Slice. He considered the Studenica Slice as original part

of the Drina–Ivanjica Unit, separated from it during the final contraction within the Dinarides. On the other hand, SCHEFER et al. (2010) demonstrated evidence for similarities between the Studenica and Kopaonik Metamorphic Series, regarding them as

part of the Jadar–Kopaonik Unit. The metamorphic basement of the Jelica Mts. is represented by parashists of psammitic protoliths, with rare occurrence of pelitic sediments and meta-basic rocks (Fig. 2a,c). According to their metamorphic grade, they belong to albite–chlorite–muscovite subfacies of greenschist facies conditions. In most cases these rocks are cataclastic and retrograde metamorphosed and comprise meta-sandstones, phyllites, sericite–chlorite and chlorite–sericite schists, marbles and quartzites (Fig. 2a,c).

Triassic sediments belonging to the Jadar–Kopaonik Unit compose the main massif of the Jelica Mts. and can be found as a NW–SE-trending series of variable thickness. Lower Triassic sediments are represented by deformed sandstones with oriented grains of quartz, muscovite and rarely biotite. These are followed by clays and marls interbedded by thin sandstone layers overlain by stratified terrigenous limestones (Fig. 2c). Middle Triassic is represented exclusively by a thick carbonate rock complex. Its lowest part is made up of thin bedded limestones, that are continually followed by massive, dolomitized limestones and recrystallized dolomitic limestones with rarely preserved micritic structure (Fig. 2c). These sediments are covered by Upper Triassic massive limestone (Fig. 2c).

Jurassic rocks are represented by ophiolites and ophiolitic mélange, belonging to the Western Vardar Ophiolitic Unit (SCHMID et al., 2020). The ophiolites consist of peridotites, serpentinites, gabbro and diabase whereas the ophiolitic mélange is composed of both magmatic (diabase–spilite association) and sedimentary (sandstones, volcanoclastics, cherts, carbonates) rocks. The ophiolitic mélange has distinctive characteristics of an olistostrome formation, with km-sized olistoliths of Middle Triassic and Upper Triassic bedded limestones.

The Jelica Mts. is one of the very few places that host the peculiar Upper Cretaceous olistostrome mélange, referred to as the "Senonian diabase-chert formation" in the General geological map of SFRY, 1: 100 000 scale, sheet Čačak (BRKOVIĆ et al., 1978). According to the authors, this formation is similar to the Jurassic diabase-chert formation (=ophiolitic mélange) in all characteristics, except in the age of matrix and clasts. This geological unit is com-

posed of chaotically arranged clasts set in an arenite – alevrolite matrix and lacks clear stratification. The matrix is composed of arenite – alevrolite sediments. However, this formation does not have identical characteristics across the research area – it differs both in the clasts' dimensions and their composition as well as in the character of the matrix. The massif core of the Jelica Mts. is made up of monomict diabase breccia. Apart of that, diabase is also found along the ridge of the Jelica Mts. in the form of larger masses of predominantly coherent submarine lava, affected by pervasive spilitic alteration. Late Cretaceous age of this olistostrome mélange formation is determined based on microfauna found in matrix made up of terrigenous limestones, or in clasts of calcrudites and calcarenites. This microfauna is represented by globotruncanas: *G. lapparenti lapparenti*, *G. fornicata*, *G. cretacea*, and others.

The Drina–Ivanjica Unit

Metamorphic rocks belonging to this tectonic unit are Carboniferous in age. They are composed of metamorphosed clastic sediments, that show evidence of continuous deposition. The most important among them are alevritic, pelitic and psammitic sediments. All horizons contain quartz conglomerates, and some areas contain also marbles and green schists. In its upper parts, this geological unit show evidence of turbiditic characteristics. Paleontological analyses revealed presence of conodont association typical for Lower and Middle Carboniferous. The most common are *Gnathodus bilineatus*, *G. delicatus*, *G. texanus*, *Hindeodella bretonensis*, *Polygnathodella* sp., *Ozarkodina* sp., and others (BRKOVIĆ et al., 1978). Degrees of crystallinity and metamorphism differ across the whole unit. Three distinct zones striking NW–SE are determined, with degrees of metamorphism and crystallinity decreasing from east to west. It is important to note that these three zones are not parallel to the stratigraphic boundaries (DIMITRIJEVIĆ, 1995).

Triassic is represented by Lower and Middle Triassic sediments (Fig. 2a,c). Lower Triassic sediments transgressively cover Carboniferous metamorphic rocks and are composed of two facies:

deformed sandstones and deformed terrigenous limestones. These rocks are transgressively overlain by Middle Triassic sediments, represented by carbonates, mainly massive micrites, biomicrites and intra-biosparudites.

The Upper Cretaceous sediments that cover the Drina–Ivanjica Unit are known as the Kosovska Mitrovica Flysch formation in literature (e.g. DIMITRIJEVIĆ, 1995; SCHMID et al., 2020). This formation is interpreted as foreland sediments, deposited in the front of the propagating Jadar–Kopaonik thrust (SCHMID et al., 2008). In our research area, these sediments are deposited within the Dragačevo basin. It is important to note that this basin is asymmetric both spatially and temporally – its eastern side is older and steeper, whereas its western part is gentler and sedimentation started later (e.g. MOJSILOVIĆ et al., 1978; BRKOVIĆ et al., 1978). Sedimentation in this basin started with Cenomanian–Turonian transgression that produced shallow water quartz conglomerates and bedded limestones. Turonian sediments are mostly represented by massive limestones, deposited in shallow-water regions such as reefs and lagoons. These rocks are transgressively overlain by Maastrichtian sediments characterized by facies diversity. Along the coastal area, shallow-water sedimentation occurred during the whole Maastrichtian. The largest masses are made up of massive limestones, that are covered by sandstones via increased deposition of quartz material by the end of Upper Cretaceous. In the deeper parts of the Dragačevo basin depositional products are represented by bedded marly limestones, whereas the deepest parts contain very thin layers of marls, as products of pre-flysch sedimentation. The flysch formation has thickness of up to 570 m. It starts with basal unit made up of conglomerates that almost exclusively contain Paleozoic clasts. Continuously following these conglomerates, sediments are represented by microconglomerates, marly limestones and marls, and ultimately – typical flysch. Vertically, this unit can be divided into three parts. The lowest part, with thickness of 100–150 m, consists of carbonate sediments with very thin sequences and well-developed lamination intervals. The middle part is composed of turbiditic sequences, made of carbonate feldspar greywacke and sub-greywacke, and intervals of oli-

stostromes. The highest part of the unit is made of coarse-grained sequences, characterized by alternation of coarse-grained and fine-grained clayey greywacke and beds of calcrudites and calcarenites.

Neogene sediments

All older formations across the research area are transgressively covered by Neogene sediments deposited within the depocenters of the Čačak–Kraljevo basin, that existed in this area from Early to Late Miocene.

Materials and methods

The field mapping on the Jelica Mts. comprised several field campaigns from 2022–2025, including detailed mapping of all available outcrops in order to determine lithologies and their mutual relationships, as well as to study the deformation structures. Beside this, more than 150 samples have been collected aimed at constraining sedimentological characteristics and microfossils, petrography of magmatic rocks, and tectonic microstructures.

Structural geology

The area of the Jelica Mts. exposes an intensively deformed zone, which is already visible in map scale. Because of that, we focused our study along the regional-scale faults previously reported in the General geological map of SFRY (sheets Titovo Užice and Čačak). The field mapping consisted of analyzing the deformation structures, such as folding patterns, fault geometry and kinematics in order to determine tectonic transport directions and possible tectonic forces responsible for the observed deformations. Structural data, such as metamorphic foliations and lineations, and folds, brittle faults and the respective shear senses were also obtained.

Slip along the studied fault planes was determined using linear slip sense indicators, such as striations, slickenfibers, systematic elongation of mineral grains, and others (see DOBLAS, 1998 for details).



Fig. 3. An example of structural – geological mapping at observation point 23J002. **a)** Oriented photo of an outcrop; **b)** Photo of oriented sample for further microtectonic study, with a structural diagram showing the principal foliation plane; and **c)** photomicrograph of oriented sample 23J002.

Relative deformation chronology was determined based on cross-cutting relationships. The reconstruction of the tectonic regimes was done following the standard Andersonian regimes, with one vertical and two horizontal stress axes.

The kinematics of these tectonic structures have also been studied in thin sections. Microstructural investigations have been done on standard oriented thin-sections, and optical microscopy was used for evaluating metamorphic conditions and kinematic indicators. An example on how the measurements and sampling for further microtectonic study have been performed is illustrated in Fig. 3, where an observation point 23J002 is shown. All observation points and sampling locations can be accessed in the Supplementary Dataset 1.

Sedimentology and micropaleontology

In order to study primarily the “Senonian diabase–chert formation” or the “olistostrome mélange” but also other sedimentary successions in the study area, we sampled a total of 104 samples. The rock petrography and composition were determined through the analysis of thin-sections under transmitted-light

microscopy, using standard optical methods in mineralogical–petrographic investigations. The analyses were conducted with a Zeiss polarizing microscope, equipped with a Zeiss Axiocam 208 digital camera.

Carbonate rock classification was performed in accordance with the DUNHAM (1962) scheme, based on depositional textures and component relationships, as well as following the FOLK (1959, 1962) classification, which is based on the nature of allochems and the characteristics of the orthochem (matrix).

Micropaleontological analysis was likewise carried out on thin-sections by transmitted-light observations, using the same polarizing microscope. The study included the identification of planktonic foraminifera (globotruncanids) and other microfossil assemblages, along with their basic taxonomic characterization and paleoecological interpretation.

Petrography and U-Pb geochronology of magmatic rocks

To determine the age of magmatic rocks in the study area, LA-ICP-MS U-Pb zircon geochronology was conducted on two samples at the University of Mainz, Germany. The samples of basalts, 22J031 and 23J031, were taken from the quarry located at the top ridge of the Jelica Mts. (for sampling localities please refer to the Supplementary Dataset 1). A complete dataset, including detailed results of the zircon analyses for each site, can be accessed in the electronic appendices (Supplementary Dataset 2).

Samples were crushed to grain sizes below 500 µm and elutriated to remove small particles (< 63 µm). Zircon grains were separated from the bulk samples using standard techniques (jaw crusher, heavy liquids, Frantz isodynamic magnetic separator). Individual zircon grains were handpicked under UV light, using a binocular. Zircon grains were mounted in epoxy resin, polished to their centres, carbon coated and imaged by cathodoluminescence (CL) and back-scattered electron (BSE) using a scanning electron microscope (SEM; JEOL JSM-6610LV with an EDS analytical system) at the University of Belgrade.

Zircon U-Pb age determination was performed using the LA-ICP-MS at the Department of Geosciences, University of Mainz, with an ESI Nwr193

ArF 193 nm excimer laser system equipped with a TwoVol2 ablation cell coupled to an Agilent 7500ce quadrupole ICP-MS. Ion intensities for the following isotopes were measured by LA-ICP-MS applying a pulse repetition rate of 10Hz and an energy density of about 3 J cm⁻²: ²⁰²Hg, ²⁰⁴(Pb, Hg), ²⁰⁶Pb, ²⁰⁷Pb, ²⁰⁸Pb, ²³²Th and ²³⁸U. Background measurements of 15s were followed by 30s ablation and 20s wash-out time. The laser was operated at a repetition rate of 10Hz and a nominal energy output of 40 %, corresponding to a laser energy of 0.006mJ and a laser fluency of 0.8 J cm⁻². Helium gas was used for flushing the sample cell and was mixed downstream with the Ar sample gas of the mass spectrometer. The washout time for this configuration is 15s. The total acquisition time for each analysis was 60s, with the first 30s used to measure the gas blank. The instrument was tuned to give large, stable signals for the ²⁰⁶Pb and ²³⁸U peaks, low background count rates (typically around 150 counts per second for ²⁰⁷Pb), and low oxide production rates (²³⁸U¹⁶O/²³⁸U generally below 0.2 %). Single spot measurements with a diameter of 20–30 µm were arranged along transects through the zircon crystals, emphasizing sampling rim and core regions spot locations are marked in Supplementary Dataset 2. Ablation locations were selected based on CL images. For calibration of the LA-ICP-MS measurements, either 91,500 or GJ1 zircon was used, while Plešovice zircons were used as standards to monitor the accuracy and precision of the measurements. Data reduction was performed using Iolite (PATON et al., 2011) in combination with the Isoplot (4.15) add-in for Excel (LUDWIG, 2003) and IsoplotR (VERMEESCH, 2018). Data obtained for the zircon age standard 91,500 and GJ1 agree with published ages.

Results

Petrography of the magmatic, sedimentary and volcano-sedimentary successions

Basalts

In the Jelica Mts., the basement rock of the Jadarko Unit (comprising para-schists, marbles,

metabasites) are overlain by Upper Cretaceous volcano-sedimentary formations. Subalkaline to tholeiitic basalts occur interbedded with hemipelagic limestones and clastic sediments (Fig. 4). Dykes and pillow lavas (Fig. 4) are spatially associated with Coniacian–Santonian clastic deposits.

The basalts are strongly hydrothermally altered and typically display porphyritic textures with intersertal to locally skeletal and aphanitic groundmass (Fig. 4b,c). Primary mineral phases, plagioclase, clinopyroxene, Fe-oxides, and volcanic glass, are variably preserved but commonly overprinted by secondary assemblages. Alteration products include albite, chlorite, epidote, calcite, quartz, and titanite, suggesting zeolite to greenschist facies conditions.

The basalts contain abundant amygdalae that are predominantly filled with calcite, more rarely hematite. Plagioclase phenocrysts (labradorite to andesine) are commonly sericitized and albitized, whereas clinopyroxene is largely replaced by chlorite and epidote, with only rarely preserved relics of augite compositions. Locally, dendritic augite and skeletal plagioclase textures are observed, pointing to rapid crystallization under disequilibrium conditions. Rare olivine phenocrysts occur as altered relics only. The overall mineral assemblage, together with the preservation of primary basaltic textures despite pervasive alteration, supports classification of these rocks as spilites (CANN, 1969), reflecting extensive seawater – rock interaction.

Hyaloclastite has also been identified in thin section (Fig. 6) in close association with the basaltic rocks (see also below). It contains secondary mineral phases and altered volcanic glass fragments, including palagonite. Notably, radiolarian remains have been observed within this material (Fig. 6), although they have not yet been taxonomically determined. The presence of hyaloclastite and Radiolarians further supports submarine volcanic emplacement and contemporaneous sedimentation.

Micritic carbonates

Sedimentary successions closely associated with the volcanic units are represented by micritic car-

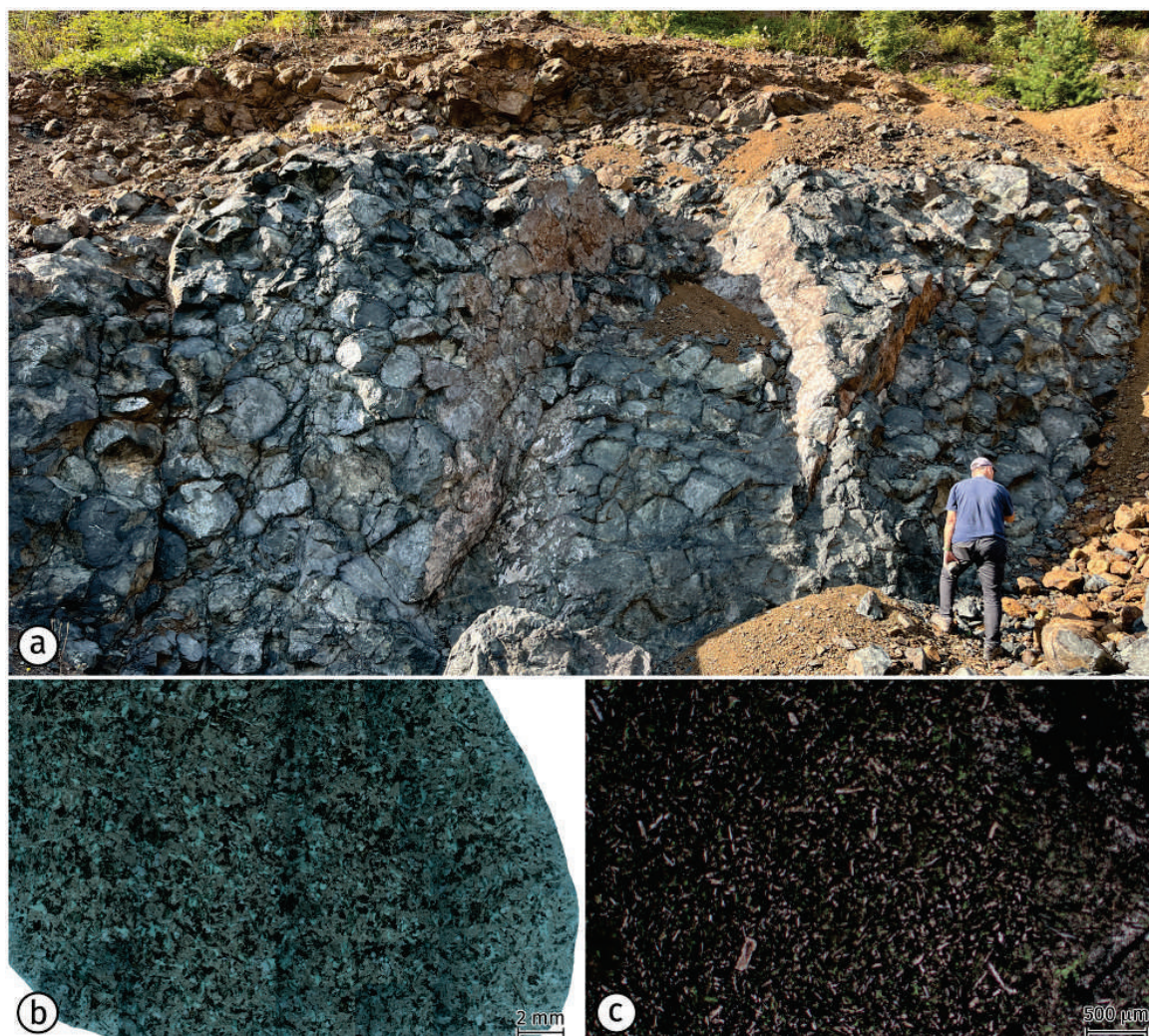


Fig. 4. Field photos of Jelica Mts. **a)** pillow basalts at Crna stena quarry; **b, c)** petrography of basalts.

bonate rocks displaying pronounced compositional and textural heterogeneity, reflecting mixed carbonate–siliciclastic sedimentation. The rock matrix consists predominantly of micritic calcite, locally impregnated with finely dispersed iron oxides that impart a reddish coloration. Subhorizontal, discontinuous laminae enriched in siliciclastic material are a characteristic feature. These laminae contain a silt-sized fraction dominated by quartz, sericite, and plagioclase, with subordinate lithoclasts, and exhibit a weak to moderate preferred orientation, giving them a more distinctly clastic character compared to the surrounding matrix. Intergranular spaces are filled by micritic calcite cement, likely with minor clay mineral contributions (Figs. 3, 5).

Outside these siliciclastic-rich laminae, the rocks are more homogeneous and carbonate-dominated, consisting of a micritic matrix with dispersed bio-

clasts. Planktonic foraminifera, particularly globotruncanids (e.g., *Globotruncana*), are the most abundant components, while occasional prismatic fragments attributable to *Inoceramus* shells are also observed. The fabric is generally poorly oriented, consistent with low-energy depositional conditions, although subtle alignment may reflect primary lamination or minor early diagenetic reorganization.

Texturally, the rocks correspond to foraminiferal wackestone to packstone (DUNHAM (1962) classification), with local transitions toward siliciclastic, mud-supported lithotypes. In terms of compositional classification, the carbonate-dominated portions can be described as foraminiferal biomicrites *sensu* FOLK (1959, 1962), whereas siliciclastic-enriched intervals represent hybrid micritic lithologies with significant terrigenous input, approaching marly compositions. Some samples are distinctively more

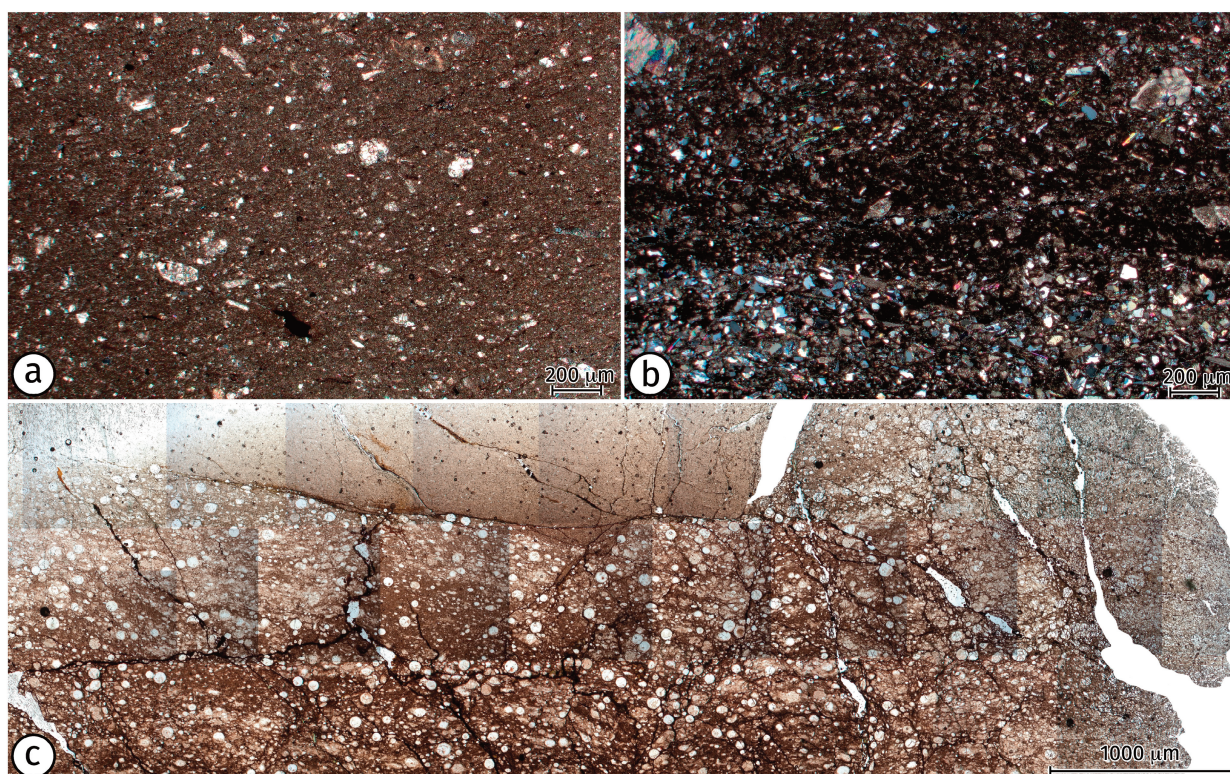


Fig. 5. Petrography of sedimentary succession.

carbonate-rich, characterized by a homogeneous micritic (orthochem) matrix with dispersed Fe-oxide pigment and abundant small bioclasts. In these varieties, the siliciclastic component is subordinate and occurs as isolated grains of quartz and feldspar, lacking the organization seen in laminated facies.

The microfossil assemblage is dominated by planktonic foraminifera, including globotruncanids (e.g., *Contusotruncana fornicata* and *Globotruncana* sp.), accompanied by smaller hedbergelids and

globigerinelloids, while benthic forms (e.g., rotalids) are rare. Radiolarian remains are also present, although not taxonomically determined.

Volcano-sedimentary succession

Volcano-sedimentary succession is comprised of polymict, matrix-supported conglomeratic rocks characterized by a poorly sorted and highly heterogeneous clastic assemblage (Fig. 6). Clasts range in

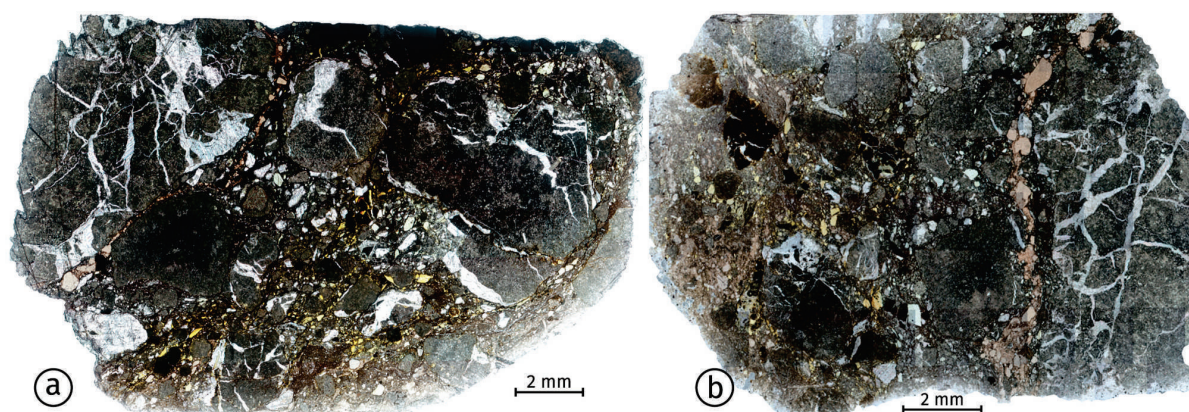


Fig. 6. Petrography of volcano-sedimentary succession. Photomicrograph of a thin section of sample (a) from observation point 24J010, and (b) from observation point 22J008.

size from fine sand-sized particles to those several millimeters in diameter, with a predominance of subrounded to rounded grains embedded within a mostly volcanoclastic matrix. The clast population is compositionally diverse and dominated by mafic and felsic lithologies. Basaltic clasts commonly display micro-ophitic textures, indicating a doleritic to basaltic protolith (Figs. 6, 8). The grains show plastic behavior visible by lobate grain boundaries (Fig. 6). These clasts are variably altered and locally contain domains of palagonite, reflecting the transformation of primary volcanic glass under low-temperature aqueous conditions (Figs. 7, 8). The presence of palagonite suggests that the original volcanic material was at least partly glass-rich, consistent with rapid cooling in subaqueous emplacement. In addition to volcanic components, the rock contains abundant radiolarite clastites with the presence of recrystallized radiolarians preserved as ghost structures, carbonate clasts (similar to micritic carbonates from the sedimentary succession) recognizable by their microcrystalline carbonate matrix. These clasts are typically reddish.

Syn-eruptive and post-depositional features are prominent and include pervasive fracturing and cementation. The clasts are crosscut by calcite veins, which locally form dense networks and indicate multiple episodes of fluid infiltration. While many fractures are confined to individual clasts suggesting brecciation prior to final transport, calcite veins also crosscut the surrounding matrix (Fig. 6). This distribution

indicates that fracturing, plastic deformation and hydrothermal calcitisation were generally synchronous processes driven by the rapid cooling of hot basaltic fragments and subsequent fluid release within the wet, largely unconsolidated sediment. In addition, Fe-rich alteration products are locally present, reflecting fluid-rock interaction under oxidizing conditions.

The rounded morphology of the clasts indicates transport and reworking rather than *in situ* fragmentation, supporting interpretation as a resedimented deposit. The matrix is fine-grained and heterogeneous, comprising altered volcanic material, fine lithic fragments, and mineral grains (likely quartz and feldspar). The overall fabric is matrix-supported, with no preferred clast orientation and no evidence of sorting or grading, consistent with deposition from a high-density debris flow.

New age constraints based on U-Pb geochronology

Zircon grains from the Jelica samples are mostly subhedral, displaying prismatic to short-prismatic habits, and range from 50 to 120 μm in length with aspect ratios between 1:1 and 2:1. Cathodoluminescence (CL) imaging reveals medium luminescence with characteristic oscillatory zoning. For sample 22J031, 45 analyses were conducted on 29 grains; for 23J031, 8 analyses were performed

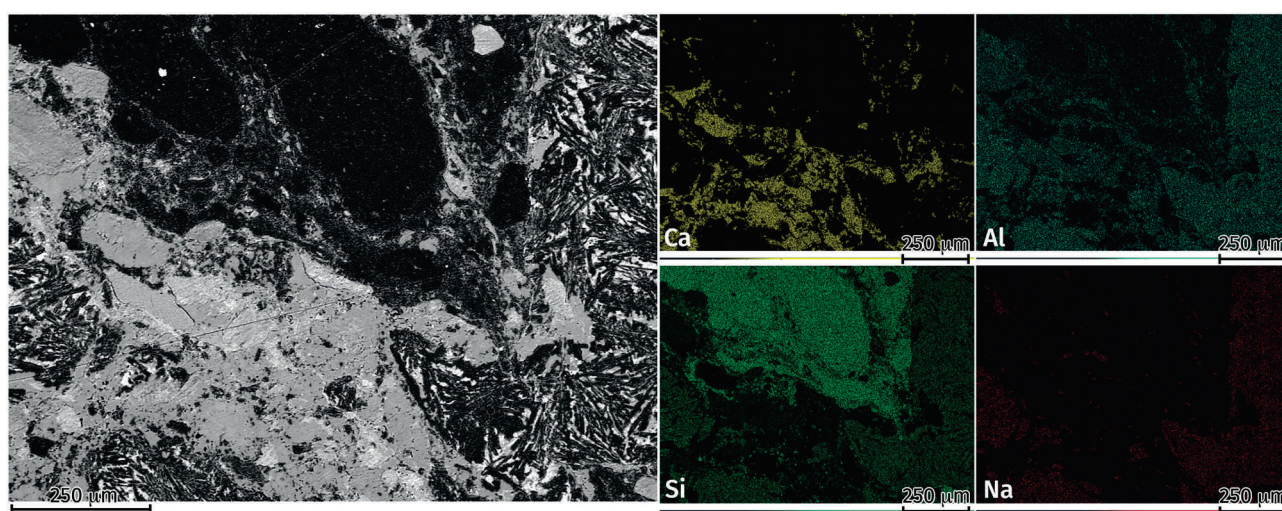


Fig. 7. Details of the petrography of volcano-sedimentary succession; left – BSE image of the matrix, showing clear plastic behavior of basaltic magma at the contact with a clast of clastic sediment; right – element map of the same detail, showing Si-rich clastite and carbonate matrix.

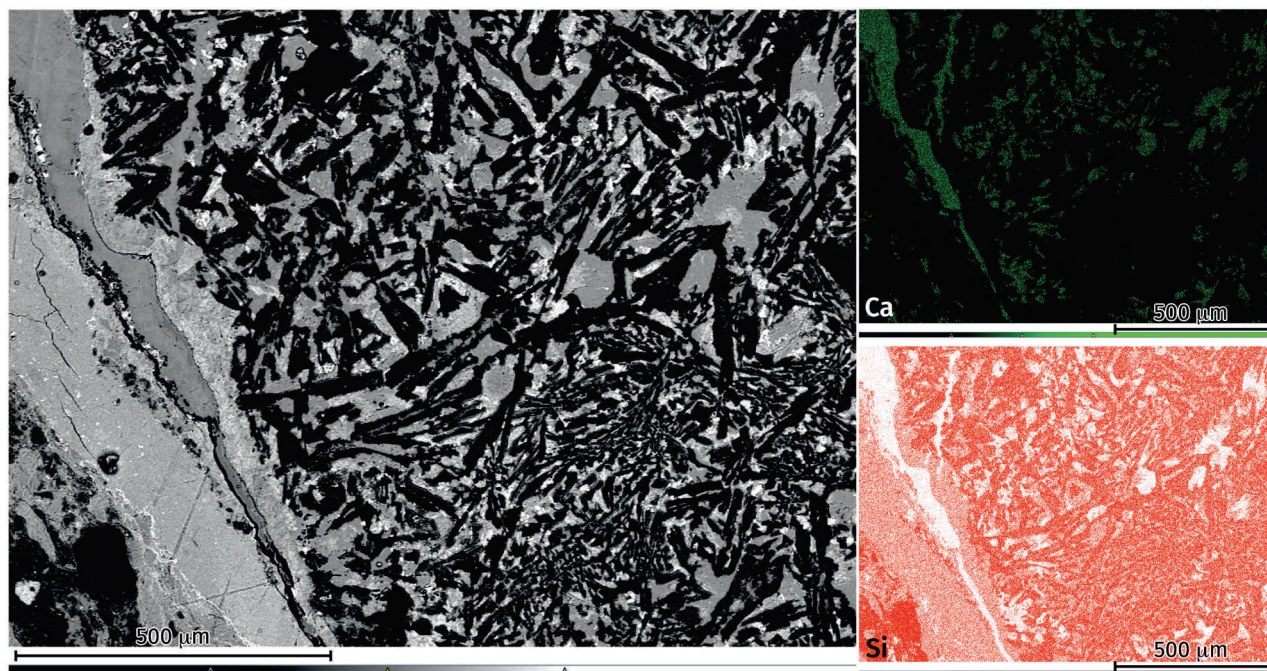


Fig. 8. Details of the petrography of volcano-sedimentary succession; left – BSE image of the volcanic clast, showing preserved basaltic glass (palagonite) at the edge of the clast; right – element map of the same detail, showing Si-rich composition of the glass, and nearby carbonate matrix.

on 2 grains (see Supplementary Dataset 2). Th and U contents range between 173 and 568 ppm and 346–965 ppm (see Supplementary Dataset 2), respectively, yielding high Th/U ratios (0.36–0.59).

Laser ablation ICP–MS U–Pb analyses of zircons reveal a complex dataset characterized by variable

initial common lead incorporation. The dataset was evaluated utilizing a combination of Wetherill $^{206}\text{Pb}/^{238}\text{U}$ vs. $^{207}\text{Pb}/^{235}\text{U}$ and Tera–Wasserburg $^{207}\text{Pb}/^{206}\text{Pb}$ vs. $^{238}\text{U}/^{206}\text{Pb}$ concordia diagrams processed via IsoplotR (Fig. 9) (VERMESCH, 2018). A subset of eleven analyses exhibited negligible common

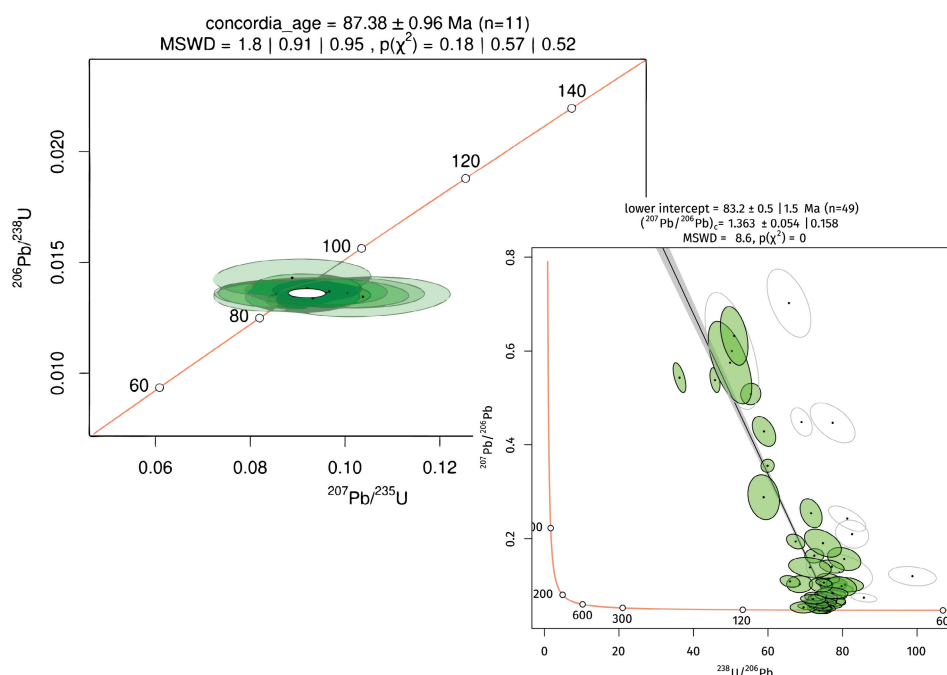


Fig. 9. Diagram of zircon Pb analyses for sample 23J031 – Jelica. Eleven analyses plot concordantly on the Wetherill space, yielding concordance age of 87.4 ± 0.96 Ma, MSWD = 1.8, which is interpreted as the crystallization age. Inset: a 2D SemiTotal Ludwig linear regression through the whole but filtered population (analyses demonstrating radiogenic lead loss characterized) yields a lower intercept age of 83.2 ± 0.5 Ma, MSWD = 8.6 ($n=49$).

lead signals, with raw ^{204}Pb counts (CPS = ~ 0) resting at the instrument detection limit. In Wetherill space, these grains form statistically relatively unified, and concentric cluster yielding concordance age of 87.4 ± 0.96 Ma, MSWD = 1.8, which is interpreted as the crystallization age. Conversely, the remaining zircons display low but measurable common lead signals, with raw ^{204}Pb counts CPS = ~ 150 . These analyses show a distinct, steep linear mixing array in Tera–Wasserburg space, pulling vertically toward elevated $^{207}\text{Pb}/^{206}\text{Pb}$ values. We interpret this as a variable incorporation of magmatic common lead. A 2D SemiTotal Ludwig linear regression through the filtered population (analyses demonstrating localized, recent radiogenic lead loss characterized by lateral flaring to the right of the main cluster) yields a lower intercept age of 83.2 ± 0.5 Ma, MSWD = 8.6 ($n=49$). Several older concordant analyses yielded Permian–Triassic, Carboniferous and Paleoproterozoic ages, implying restricted assimilation of older crustal material (see Supplementary Dataset 2).

The structural data and petrology of deformed lithologies

The Jelica Mts. is characterized by ductile deformation that resulted in a prominent NW–SE-striking bedding planes S_0 (Fig. 10a) and main foliation S_1 (Fig. 10b). It is notable that S_0 data group into one maximum and one sub-maximum (Fig. 10a), statistically defining an isoclinal fold with NW-plunging statistical axis. The main foliation S_1 is subparallel to the bedding planes and dips towards NE (Fig. 10b). However, as is evident from the statistical diagram in Fig. 10b and the detailed structural map shown in the Supplementary Dataset 4, foliation S_1 varies across the study area.

This deformation pattern is consistently observed at the mesoscale structures along the numerous outcrops, examples of which are shown in Fig. 11 and Fig. 12. This structural continuity embraces the metamorphic successions of the Jadar–Kopaonik Unit, mylonitized Lower Triassic limestones, Middle Triassic clastic–carbonate sequences, the Upper Cretaceous volcano–sedimentary unit, and the strongly de-

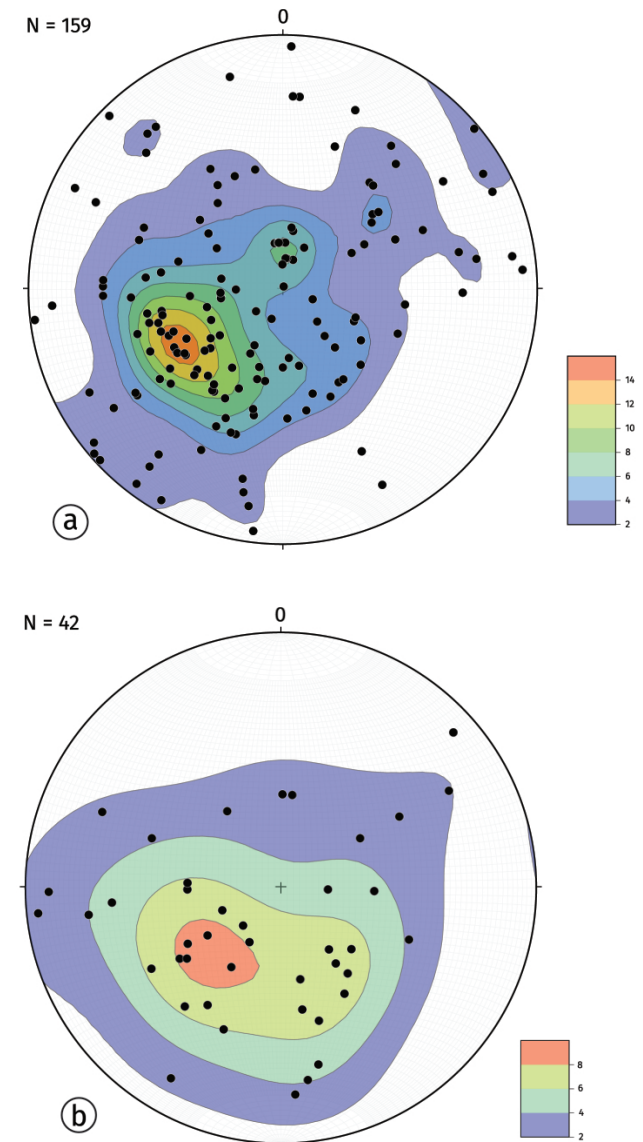


Fig. 10. Statistical structural diagrams of (a) bedding planes S_0 , and (b) main foliation S_1 . Measured orientations of bedding planes and foliations are illustrated by poles.

formed Jurassic ophiolitic mélange (Figs. 11, 12). Across all these lithologies, the dominant NE-dipping foliation S_1 is associated with kinematic indicators recording top-SW tectonic transport (Fig. 11). This is especially evident based on S-planes transposition forming boudinage of more competent (carbonate) material in Middle Triassic clastic–carbonate sediments (Fig. 11a), and sigma clasts of competent material within the Upper Cretaceous volcano–sedimentary unit (Fig. 11b). Metamorphic series of the Jelica Mts. exposes intensive folding also in the outcrop-scale (Fig. 11e), represented by isoclinal folds with axial planes dipping towards NE, and

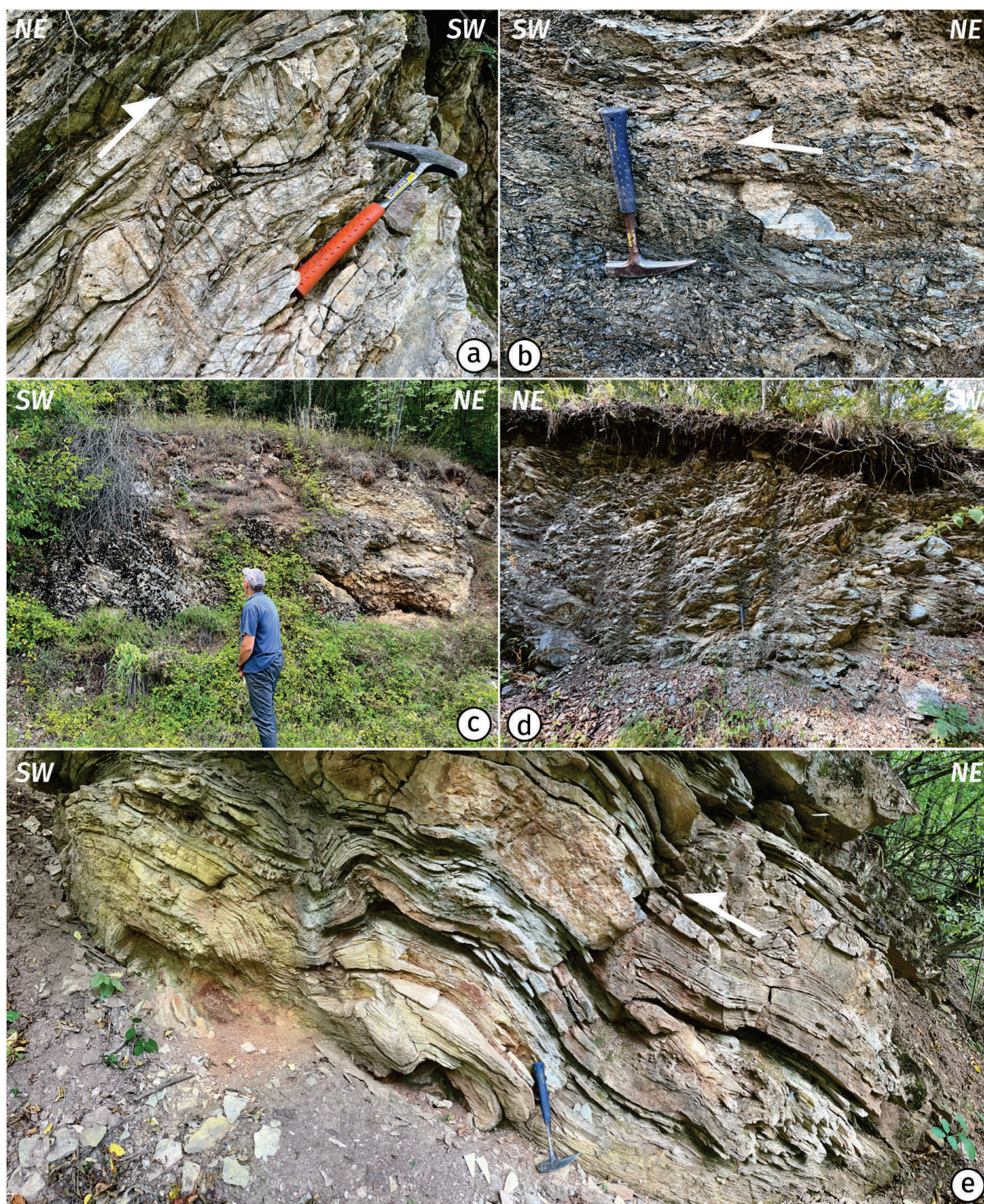


Fig. 11. Outcrop-scale structures within different lithologies on the Jelica Mts. **a)** Foliation in Middle Triassic clastic-carbonate unit, with boudinaged carbonate beds, indicating top-SW tectonic transport, observation point 23J005; **b)** Kinematic indicators within the Upper Cretaceous volcano-sedimentary unit in the form of a pseudo-sigma clast of carbonate rock within the matrix made of diabase breccia, observation point 23J045; **c)** Deformed Upper Cretaceous volcano-sedimentary unit, with clear NE-dipping foliation at the observation point 23J035; **d)** Intensely deformed Upper Cretaceous volcano-sedimentary unit at the observation point 23J043, here dominated by mixed blocks of clastic sediments and Jurassic serpentinites, with kinematic indicators for top-W tectonic transport; **e)** Metamorphic series of the Jadar-Kopaonik Unit at the observation point 23J034, exposing tight isoclinal folds with NE-dipping axial planes, and boudinaged hinge zones indicating top-S tectonic transport.



Fig. 12. Outcrop-scale structures at the main ridge of the Jelica Mts., in the most intensive deformation zone. **a)** N–S-striking subvertical fault in the Upper Cretaceous volcano-sedimentary unit at the observation point 24J009, here mainly mixed up of clastic sediments and serpentinites; **b)** Upper Cretaceous volcano-sedimentary unit at the observation point 24J010 exposing NW-striking main foliation in the narrow zone of the main Jadar–Kopaonik thrust (thin section from the same observation point is shown in Fig. 6a); **c)** Tectonic contact between the Jurassic serpentinites and Upper Cretaceous volcano-sedimentary unit, in the form of a subvertical reverse fault with top-NW tectonic transport, at the observation point 24J012 located in the narrow zone of the main Jadar–Kopaonik thrust front.

NW-plunging subhorizontal fold axes. Transposition of S_1 -planes can be clearly observed within the metamorphic unit. Axial plane cleavage is parallel to S_1 planes and dips towards NE.

Structural data from the narrow zone of the main Jadar–Kopaonik thrust front (Fig. 12) show the existence of subvertical tectonic structures, as also interpreted in the geological cross-section shown in Fig. 2b. It is notable that tectonic transport along these faults is spatially heterogeneous, with kinematic indicators showing displacement towards west, south–west and north–west. Such deformation is localized along the main thrust fronts, mapped in localities 24J012 and 23J046.

A key observation is provided by an outcrop of strongly deformed Jurassic ophiolitic *mélange* ex-

posed on the southeastern flanks of Jelica (Monastery Stjenik, locality 23J046; Fig. 13), located at the contact with mylonitized Lower Triassic limestones. The measured foliation (S_1 034/44) and associated kinematic indicators consistently indicate a top-SW transport, identical to that observed in all deformed lithologies, including the Upper Cretaceous volcano-sedimentary unit. The continuity of deformation style across this contact suggests that the *mélange* was affected by the same deformation event and that its present structure is largely post-depositional.

The *mélange* is composed of lens-shaped blocks of serpentinite embedded in a strongly foliated, schistose matrix. The blocks range from decimeter to meter scale and consist of serpentinitized ultra-

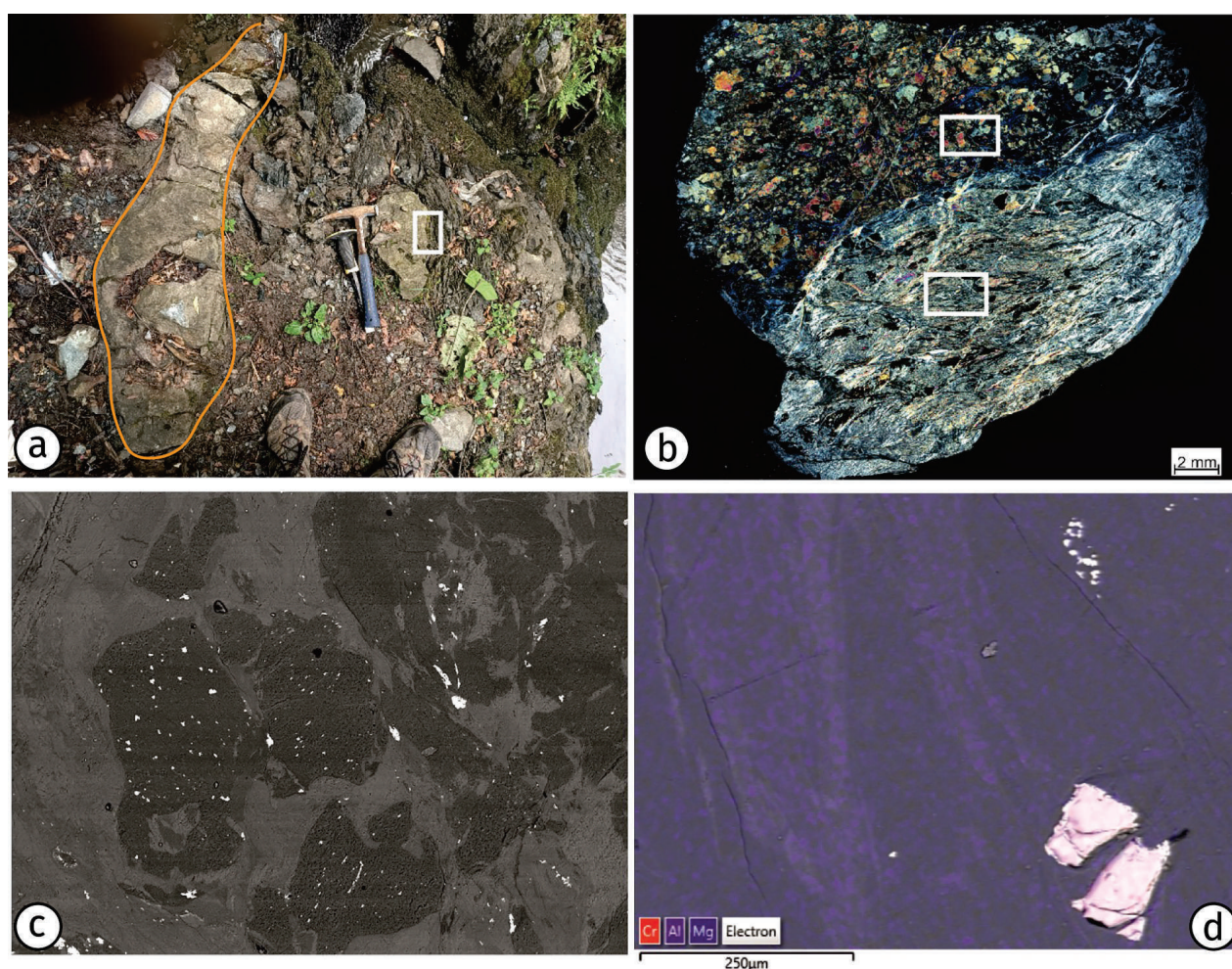


Fig. 13. Deformed ophiolitic *mélange* at the observation point 23J046; the view at different scales. **a)** Outcrop-scale structures showing S_1 034/44 and associated kinematic indicators for top-SW tectonic transport; **b)** Thin section (crossed polars) of the very contact between deformed serpentinite and the serpentinite–chlorite schist from the matrix (see the white rectangle at (a)); **c)** BSE image of serpentinite (see the white rectangle at (b)); **d)** Element map of matrix section, showing distribution of clinoclhor (pale pink, Al-rich), antigorite (dark pink, Al-poor) and chromite grains.

mafic rocks, locally preserving relict orthopyroxene grains pseudomorphed by serpentine minerals (Supplementary Dataset 3). The relicts of Cr-spinel are also observed, intensely altered (Fig. 13, Supplementary Dataset 3). The matrix is dominated by low-density ultramafic material, forming a serpentinite-chlorite schist composed of antigorite, clinochlore, and accessory chromite (Fig. 13, Supplementary Dataset 3). Mineralogical and chemical characteristics indicate that the matrix derives from an ultramafic protolith.

The coexistence of antigorite and Mg-rich chlorite (clinochlore) constrains metamorphic conditions to the greenschist facies. This mineral assemblage is stable over a relatively restricted pressure-temperature range, typically corresponding to temperatures of $\sim 300\text{--}350^\circ\text{C}$ (with empirical chlorite thermometry yielding 308°C) and pressures of ~ 3 kBar, consistent with the lower parts of the upper crust (detailed P-T modeling parameters are provided in Supplementary Dataset 3). The stability of antigorite in these conditions, combined with the absence of low-temperature serpentine polymorphs (e.g. lizardite, chrysotile), further supports this interpretation. These estimates are consistent with microstructural observations from other lithologies in the study area, where quartz exhibits dynamic recrystallization by subgrain rotation recrystallization, indicating deformation temperatures of as high as $400\text{--}450^\circ\text{C}$.

Taken together, geological relationships, structural data, and petrological constraints suggest that the studied *mélange* represents a fragment of Jurassic ophiolitic material that was incorporated into the Upper Cretaceous tectono-sedimentary system and subsequently deformed under greenschist-facies conditions during SW-directed tectonic transport.

Discussion

Interpretation of tectonic structures

Based on available structural data, at least two ductile deformation phases are evident within the study area, both characterized by general compression and tectonic transport to the southwest. Deformation

phase D1 is now preserved only as isoclinal folds that have been refolded during D2 deformation phase. Phase D1 is most likely of Upper Jurassic age, since it occurs in the metamorphic basement of Jelica, in Triassic sediments, and in the Jurassic ophiolitic *mélange*. Deformation phase D2 is expressed in all lithologies present on the Jelica Mts., except in the youngest Miocene, Pliocene and Quaternary sediments. Accordingly, the timing of phase D2 can be constrained to the interval between the Upper Cretaceous and the Oligocene. Considering the broader geodynamic context of the central Balkan region, the D1 deformational structures recorded on the Jelica Mts. can most plausibly be interpreted as representing the terminal stage of the Neotethys Ocean obduction onto the passive margin of Adria whereas the ductile phase D2 may be linked to the collision between Adria and Europe. However, taking into account all tectono-magmatic and tectono-stratigraphic characteristics of the area, it can be concluded that deformation phase D2 was active during the Late Cretaceous and likely into the early Paleogene, i.e., it occurred contemporaneously with deposition of the volcano-sedimentary formation of the Jelica Mts.

Although the overall tectonic transport during the deformation phase D2 was top-SW, significant deviations from that direction are observed – from top-NW, through top-W, to kinematic indicators pointing to top-S tectonic transport (see Fig. 12). In addition, the axes of mesoscopic folds (see detailed structural map in Supplementary Dataset 4) systematically plunge to N-NW. These features suggest that kinematic indicators across the entire study area are not consistent, despite the general top-SW tectonic transport. This inconsistency may indicate that a significant component of horizontal displacement occurred along the observed regional tectonic structure, i.e. along the thrust of the Jadar–Kopaonik Unit onto the Drina–Ivanjica Unit. Considering the strike of the entire Jelica Mts. structure and the described deformational features, this horizontal component must have been dextral, so the entire structure of the Jelica Mts. can be described as an oblique thrust with a pronounced dextral component.

From a geodynamic perspective, this interpretation of thrusting of the Jadar–Kopaonik Unit over

the Drina–Ivanjica Unit could imply that the entire convergence between Adria and Europe was probably oblique. Although our investigations are confined only to Jelica Mts. and therefore cannot provide unequivocal proof for such interpretation, it is consistent with data from other localities where the so-called Zvornik “suture” has been mapped (GERZINA, 2010; SCHMID et al., 2008), then with observations from the northeastern sector of the Internal Dinarides (MLADENOVIĆ & PRELEVIĆ, submitted for publication), and also with broader geodynamic models (LE BRETON et al., 2021) that propose dextral strike-slip movements already at the onset of the collision between the Adria and Europe.

This interpretation, which implies significant horizontal displacements along the front of the Jadar–Kopaonik Unit (first-order structure of the Dinarides), also allows for the possibility of contemporaneous activation of extensional/transensional domains in those areas. Given the importance of this first-order tectonic structure, extension generated in this manner could penetrate to deep lithospheric levels and potentially induce decompression, partial melting of upper-mantle and production of basic magmatic rocks. The feasibility of such a process is demonstrated by recent numerical geodynamical modeling (STANKOVIĆ et al., 2025). We propose that this tectonic scenario is able to explain conditions for the formation of Upper Cretaceous basalts (see also below), contemporaneously with the development of a sedimentary depocenter in the tectonically active (oblique) thrust.

Magmatism in the study area

The Upper Cretaceous magmatism in the Jelica Mts. forms part of a broader magmatic episode developed along the Sava Zone (SOKOL et al., 2025; and references therein). Recent studies distinguish two geochemically and tectonically distinct groups within this system: (1) European-side (upper plate) occurrences and (2) Adria-side (Dinaric, lower plate) occurrences (SOKOL et al., 2025); the Jelica Mts., and Rujevac near Krupanj (SOKOL et al., 2025; and references therein) localities represent key examples of the Cretaceous magmatic activities along the Zvornik

fault on the Adria-side. At the scale of the Sava Zone, Upper Cretaceous magmatism displays a marked geochemical asymmetry between the Adria- and European-side domains. The Adria-side volcanic rocks are dominated by basaltic compositions with MORB- to E-MORB-like signatures, modest LREE enrichment, and trace-element patterns indicative of melting within a depleted to mildly enriched mantle source or higher degrees of melting. By contrast, the European-side occurrences commonly exhibit stronger HFSE- and LREE enrichment and more pronounced within-plate (OIB-like) affinities, often interpreted to reflect contributions from more enriched and deeper, garnet-bearing mantle sources, in combination with smaller degrees of melting.

The Jelica basalts can be regarded as a typical representative of the Dinaridic magmatic domain. Their rare earth element (REE) patterns show moderate LREE enrichment ($\text{LaN/YbN} = 0.81\text{--}1.65$; $\text{LaN/SmN} = 0.61\text{--}1.00$) and only limited HREE fractionation. Overall, they are more enriched than N-MORB, broadly comparable to E-MORB, and significantly less enriched than typical OIB, consistent with other Dinaridic localities (CVETKOVIĆ et al., 2014; OLIĆ PECO et al., 2026). Such geochemical characteristics indicate melt generation within the spinel stability field, pointing to a relatively shallow mantle melting. The absence of strong HREE depletion suggests that garnet was not a major residual phase, consistent with melting of a relatively shallow, lithospheric to sublithospheric mantle source (SOKOL et al., 2025). This interpretation implies comparatively thin lithosphere and typical upper-mantle conditions beneath the Adria-derived units.

The geochemical contrast between the European and Dinaridic domains does not necessarily require fundamentally different tectonic settings. Instead, it can be more consistently explained within a common geodynamics operating across the wider Sava Zone (SOKOL et al., 2020). In this interpretation, Late Cretaceous magmatism developed in a broadly transensional regime, likely related to slab rollback and associated extensional deformation. Magmas were generated by decompression melting but sampled compositionally heterogeneous mantle domains. The observed variability therefore primarily reflects lateral heterogeneity of the lithospheric mantle,

with relatively depleted to mildly enriched sources beneath the Dinarides and more strongly metasomatized mantle beneath the European margin, likely modified during earlier subduction events (PRELEVIĆ et al., 2017; STANKOVIĆ et al., 2026).

The Jelica basalts provide important constraints on this model. Their E-MORB-like affinity, moderate enrichment, and spinel-field melting signatures are consistent with derivation from a relatively shallow and only mildly enriched mantle source (SOKOL et al., 2025). At the same time, structural observations from the basement units point to significant transcurrent deformation, suggesting that magma emplacement was closely linked to localized zones of extension developed along major strike-slip structures. Accordingly, the Jelica magmatism is best interpreted as the product of tectonically controlled, localized decompression melting within a transtensional regime, where strike-slip kinematics along the Zvornik suture facilitated the formation of short-lived extensional domains and focused magma ascent.

Sedimentary processes of the study area

The sedimentary lithologies exposed across Jelica Mts. indicate deposition under relatively low-energy pelagic to hemipelagic conditions, characterized by the gradual settling of fine carbonate mud and planktonic debris, with intermittent contributions from terrigenous sources.

The microfossil assemblage dominated by planktonic foraminifera, notably globotruncanids accompanied by subordinate hedbergelids and globigerinelloids dominate, whereas benthic taxa are rare. This assemblage is indicative of open-marine conditions and suggests sedimentation in relatively deep-water settings. Globotruncanids are interpreted as representing a bathypelagic component, while hedbergelids and globigerinelloids are associated with comparatively shallower planktonic habitats. Radiolarian remains are also present, although they have not been taxonomically resolved.

Taken together, the sedimentological and micropaleontological characteristics point to deposition in a hemipelagic to pelagic marine environment, pe-

riodically influenced by the input of terrigenous material. Such input was most likely delivered via distal turbiditic processes or suspension settling. The presence of *Globotruncana* constrains the age of the deposits to the Upper Cretaceous (Senonian). The occurrence of siliciclastic laminae reflects fluctuations in sediment supply and depositional dynamics within the basin, potentially linked to tectonic activity along a major fault zone.

In many respects, these deposits exhibit strong similarities to the *Scaglia Rossa* facies, particularly in their micritic composition, the abundance of planktonic foraminifera (e.g., *Globotruncana*), the occasional presence of *Inoceramus* fragments, and the reddish coloration imparted by dispersed iron oxides. The observed microfacies and textures are also consistent with those described from classical *Scaglia Rossa* successions. However, the Jelica carbonates contain a significantly greater and more systematically organized siliciclastic component, as well as the presence of lithoclasts. These features indicate a more substantial and episodic influx of terrigenous material that is atypical for the classical *Scaglia Rossa*, which is generally characterized by minimal siliciclastic input, representing a relatively pure pelagic carbonate system (KUHN, 1990; KAMINSKI & GRADSTEIN, 2005).

Volcano-sedimentary successions, and particularly the presence of pelagic *Scaglia*-type limestones as a diagnostic and widespread lithology, are often interpreted as evidence of deep-ocean sedimentation and, by extension, the oceanic nature of the lithosphere in which the associated volcanism developed. However, global studies of *Scaglia*-type limestones (KUHN, 1990; KAMINSKI & GRADSTEIN, 2005) demonstrate that they are not reliable palaeogeodynamic indicators. Such deposits typically form above the carbonate compensation depth, under conditions of minimal detrital input, low organic productivity, and well-oxygenated bottom waters, with hematite locally imparting their characteristic red coloration. Even the occurrence of abyssal agglutinated foraminifera does not unequivocally indicate abyssal depths but rather reflects oligotrophic conditions. Consequently, the presence of *Scaglia*-type deposits within the Jelica Mts. succession alone is insufficient to determine whether

this Upper Cretaceous basin was truly oceanic in character.

Accordingly, although the studied deposits can be broadly compared to the *Scaglia Rossa* on the basis of their fossil assemblage, micritic fabric, and coloration, they are more appropriately interpreted as a proximal or tectonically influenced equivalent, representing a mixed carbonate–siliciclastic facies. This interpretation implies deposition within a basin located closer to a continental margin or within an active tectonic setting, where pelagic sedimentation was periodically overprinted by clastic input, in contrast to the more stable and distal conditions characteristic of the classical *Scaglia Rossa* of the Umbria–Marche domain (KUHN, 1990; KAMINSKI & GRADSTEIN, 2005).

The Zvornik Fault: implications for basin evolution in the central Balkans

Any attempt to define a unified model that integrates the diverse lithologies and deformation structures observed in the Jelica Mts. must be placed within the broader geodynamic architecture of the Late Cretaceous evolution of the Adria–Europe boundary. In this context, the key issue is the still unresolved geodynamic significance of the Zvornik Fault (traditionally termed the Zvornik “suture”) and its associated volcano–sedimentary unit mapped as the “Upper Cretaceous diabase–chert formation” on the General Geological Map of the former SFRY (DIMITRIJEVIĆ & DIMITRIJEVIĆ, 1973; DIMITRIJEVIĆ & DIMITRIJEVIĆ, 1976; DIMITRIJEVIĆ, 1995).

In his seminal studies, Milorad Dimitrijević (DIMITRIJEVIĆ & DIMITRIJEVIĆ, 1973, 1976; DIMITRIJEVIĆ, 1995) interpreted the Zvornik suture as the site of closure of a Cretaceous oceanic basin between the Drina–Ivanjica and Jadar units. Within this geodynamic context, the “Upper Cretaceous diabase–chert formation” (or “olistostrome mélange”) was regarded as a product of subduction-related processes accompanying the consumption of this oceanic domain. Importantly, Dimitrijević also recognized a significant dextral component along this structure, demonstrating an early appreciation of its kinematic complexity. Although this interpretation was for-

mulated on the basis of limited data available at the time, it represents a remarkably forward-looking attempt to explain the geological complexity of the central Balkans, remaining an important conceptual reference. However, more recent regional structural, sedimentological, and petrological data including one presented here suggest that the Jelica Mts. record does not require the existence of a Late Cretaceous oceanic basin (SCHMID et al., 2008; PRELEVIĆ et al., 2017; KÖPPING et al., 2019). Instead, the observed features are more consistent with a tectonically controlled depositional system developed within a continental collisional setting. In other words, this structural architecture represents an intracontinental nappe stacking setting that took place long after the complete disappearance of any Mesozoic oceanic domain, where one block of pre-existing continental crust tectonically overrode another.

At first glance, the association of basaltic rocks with micritic carbonates may suggest derivation from an oceanic crust–pelagic sediment system. Indeed, similar associations from Kozara Mts. have been used to argue for the existence of an Upper Cretaceous “Sava Ocean” (USTASZEWSKI et al., 2009). However, comparable lithological assemblages from the Klepa Mts. and the Belgrade area have been interpreted as products of within-plate magmatism emplaced in transtensional settings along a major strike-slip plate boundary (PRELEVIĆ et al., 2017; KÖPPING et al., 2019; SOKOL et al., 2020, 2025). This interpretation is also consistent with the geochemical characteristics of the Jelica basalts, which do not support an origin as fragments of typical oceanic lithosphere, comparable to Jurassic counterparts.

Moreover, the spatial distribution of these basaltic occurrences provides an additional constraint: they are systematically aligned along major tectonic structures, particularly first-order thrusts (e.g. SOKOL et al., 2025). This observation suggests a genetic link between deformation and magmatism. In such a tectonic setting, dextral oblique convergence along the Adria–Europe boundary would have generated localized transtensional domains within the evolving orogenic wedge, enabling partial melting of the upper mantle and rapid ascent of basaltic magmas into contemporaneously active sedimentary basins (e.g. STANKOVIĆ et al., 2025).

The interpretation of the “Upper Cretaceous diabase–chert formation” must therefore be consistent with this tectonically active setting (Fig. 14). The Jelica Mts. area lies directly adjacent to the Dragačevo Basin, which represents the sedimentary cover of the Drina–Ivanjica Unit and forms part of the Kosovska Mitrovica flysch formation. This flysch has been interpreted as a foreland basin developed in front of the advancing Jadar–Kopaonik thrust (SCHMID *et al.*, 2008).

Within this broader foreland system, we interpret the Jelica volcano–sedimentary unit as representing a more proximal depocenter developed directly on top of the advancing thrust wedge (Fig. 14). Such basins are widely known as wedge-top (or piggyback) basins (ORI & FRIEND, 1984). They form on actively deforming thrust sheets and are characterized by syn-tectonic sedimentation, rapid facies changes, and frequent mixing of sedimentary and volcanic material. Because they develop in structurally controlled depressions (e.g. synclines or local extensional zones), they commonly preserve evidence of contemporaneous deformation, including growth structures and progressive unconformities (DECELES & GILES, 1996; ORI & FRIEND, 1984).

The structural and sedimentological characteristics of the Jelica Mts. succession are consistent with this interpretation. The deposits record an active tectonic environment in which carbonate and siliciclastic sediments were intermixed, while submarine volcanism (pillow basalts, hyaloclastites) occurred within the basin. Furthermore, the pervasive deformation observed within the unit indicates that sedimentation and tectonic activity were broadly coeval. In this structural setting, two coeval and genetically linked depocenters can be distinguished in the vicinity of the Zvornik Fault (Fig. 14):

(i) the Dragačevo Basin, representing the main foredeep of the system, characterized by typical flysch sedimentation and formed in response to lithospheric flexure ahead of the advancing Jadar–Kopaonik thrust;

(ii) the Jelica basin, presumably representing a wedge-top (piggyback) basin developed on the thrust wedge itself, in close spatial and genetic association with the propagating thrust front.

These two depocenters formed parts of a single foreland system but occupied different structural positions and therefore recorded different sedimen-

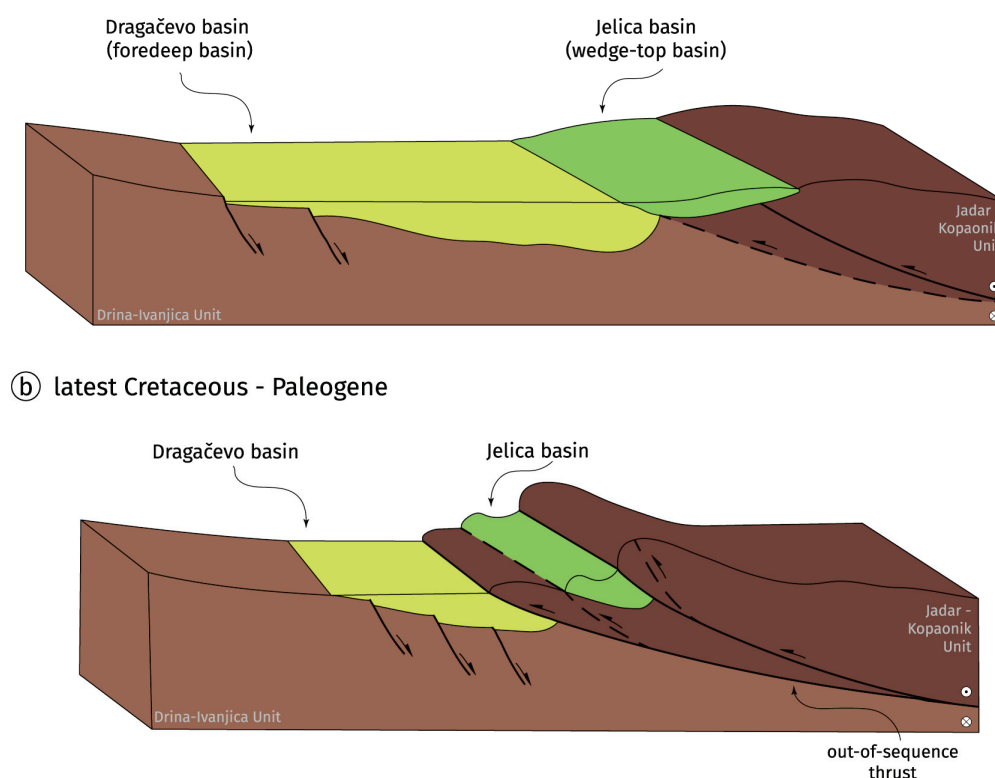


Fig. 14. Schematic evolution of Jelica wedge-top basin and Dragačevo foredeep basin in the collisional framework of the propagating Jadar–Kopaonik oblique thrust (modified and redrawn after STENDARDI *et al.*, 2023 and MUTTI *et al.*, 2003). Not to scale!

tary and tectonic processes. As thrusting progressed (Fig. 14b), both depocenters migrated and were subsequently overprinted and partly dismembered by later deformation, including out-of-sequence thrusting and Miocene rotations associated with the opening of the Pannonian Basin.

On this basis, we interpret the Zvornik Fault not as an oceanic suture (DIMITRIJEVIĆ & DIMITRIJEVIĆ, 1973; DIMITRIJEVIĆ & DIMITRIJEVIĆ, 1976; DIMITRIJEVIĆ, 1995), but as the frontal zone of the obliquely propagating Jadar–Kopaonik thrust system, characterized by a pronounced dextral component. Activity along this structure controlled the simultaneous development of the foreland Dragačevo Basin, the wedge-top Jelica basin, and associated transtensional domains in which basaltic magmatism was emplaced.

A potential difficulty in this interpretation arises from the occurrence of micritic limestones comparable to *Scaglia Rossa* - type deposits, which are commonly associated with relatively deep-marine, hemipelagic environments. However, previous studies suggest that the occurrence of hemipelagic carbonate facies comparable to *Scaglia Rossa* does not preclude deposition within a wedge-top basin; in the foreland basin systems, wedge-top and foredeep depozones may spatially and temporally overlap, and their distinction in ancient settings is commonly ambiguous (DECELLES & GILES, 1996). Accordingly, the Jelica succession may be interpreted as having formed within a structurally segmented, partly submarine wedge-top domain that locally evolved into deeper depocenters under the combined influence of tectonic subsidence and restricted sediment supply. In such settings, localized depressions may undergo enhanced subsidence and reduced clastic input, resulting in sediment-starved conditions that favor the accumulation of fine-grained hemipelagic carbonates (ORI & FRIEND, 1984). Consequently, the development of relatively deep-water facies, including *Scaglia Rossa* - type micrites, seems compatible with a wedge-top basin setting, particularly where sediment routing is restricted and subsidence temporarily outpaces sediment supply. In the Jelica Mts, the coexistence of micritic carbonates, basaltic rocks, and ophiolitic mélange (of Jurassic age but then reworked during Upper Cretaceous) may be explained by such a tectonically partitioned wedge-

top basin system, in which deeper, low-energy depocenters developed alongside structurally controlled zones of magmatism and mass transport. This interpretation not only reconciles the presence of hemipelagic facies with syn-tectonic sedimentation but also supports a model in which basin architecture was primarily governed by oblique convergence and associated strain partitioning along the Zvornik Fault.

Conclusions

Our integrated study of geological structures and volcano-sedimentary successions along the southern prolongation of the Zvornik Fault in the Jelica Mts. provides a new geodynamic perspective on the Late Cretaceous evolution of the Adria–Europe boundary in the central Balkans, leading to the following key conclusions:

An intracontinental setting of the Zvornik Fault:

The Upper Cretaceous volcano–sedimentary successions of the Jelica Mts. do not reflect an oceanic subduction zone (suture), as previously proposed by Milorad Dimitrijević (DIMITRIJEVIĆ & DIMITRIJEVIĆ, 1973; DIMITRIJEVIĆ & DIMITRIJEVIĆ, 1976; DIMITRIJEVIĆ, 1995). Instead, it represents the front of the Jadar–Kopaonik oblique thrust with pronounced dextral slip. We interpret this structural architecture as an intracontinental nappe stacking setting that took place long after the complete disappearance of any Mesozoic ocean, where the continental Jadar–Kopaonik Unit tectonically overrode the Adriatic continental margin.

Reinterpretation of the “Olistostrome mélange”:

Traditionally mapped as “Upper Cretaceous diabase–chert formation” or “Upper Cretaceous olistostrome mélange”, volcano-sedimentary formation of the Jelica Mts. likely represents a product of a wedge-top basin evolved during the activity of the Jadar–Kopaonik thrust system. The Jelica wedge-top basin was coeval with the Dragačevo basin, representing a part of the Kosovska Mitrovica flysch formation, previously interpreted (SCHMID et al., 2008) as a foreland basin developed in front of the propagating Jadar–Kopaonik thrust. These two depocenters formed parts of a single foreland system but occupied dif-

ferent structural positions and therefore recorded different sedimentary and tectonic processes.

Synchronous volcanism and sedimentation: Petrographic and microstructural data demonstrate that basaltic volcanism, hydrothermal alteration, and high-density debris-flow sedimentation were completely coeval. The basalts are Upper Cretaceous in age, with a zircon U–Pb age of 87.4 ± 0.96 Ma. Their E-MORB-like affinity, moderate enrichment, and spinel-field melting signatures are consistent with derivation from a relatively shallow and only mildly enriched mantle source. Within the tectonic framework of the Jelica Mts. tectonic structure, these basalts most likely originated within the trans-tensional domain formed due to the dextral displacement along the Jadar–Kopaonik main thrust.

This paper is entirely dedicated to the centenary of the births of Milorad Dimitrijević and Stevan Karamata. Their research on the geodynamic significance of the Zvornik "suture" and the Senonian diabase-chert formation (MD), and on the age of the "ophiolites" of the Kozara Mts. (SK), provided the basis for our ideas and guided the research presented here. Although a different view of the Upper Cretaceous geodynamics of the Internal Dinarides is offered here, the contribution of Milorad Dimitrijević and Stevan Karamata to this topic is enormous

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Supplementary data

Supplementary data to this article can be found online at the following link:

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Резиме

Зворнички шав у Унутрашњим Динаридима: кључ за разумевање регионалних транскурентних раседа на Балкану

Динариди представљају део двоструко-вергентног динарско–карапато–балканског орогеног ланца који је формиран конвергенцијом између Јадранске микроплоче и Европског континента од горње јуре. Ова тектонска конвергенција је иницирана широко распрострањеном обдукцијом мезозојског Неотетиса на пасивну јадранску маргину током најкасније јуре, док се сматра да се затварање океана догодило или током најкасније јуре – најраније креде или у горњој креди. Након ових значајних тектонских догађаја, реорганизована граница између Јадранске микроплоче и Европе постала је подручје где су се развили нови седиментни басени.

Формирање басена било је резултат обдукције офиолита још од горње јуре и интензивних навлачења интерних и екстерних динарских јединица током креде и палеогена.

Тектонски модел централног Балкана традиционално је тумачен кроз модел постојања два океана. Према том виђењу, Динаридски офиолитски појас на западу, и Вардарски офиолитски појас на истоку, представљали су одвојене океанске домene, раздвојене Дринско-ивањичким елементом. У том контексту, Зворнички расед представљао је коначну шавну зону која је одвајала дисталну Јадранску маргину од Вардарске зоне. Због тога је овај расед назван – Зворнички шав.

У овој студији фокусирамо се на непосредну контактну зону између Јадарско-копаоничке и Дринско-ивањичке јединице, дуж јужног продужетка оригиналног Зворничког шав. Истраживано подручје налази се на планини Јелици код Чачка, која представља западно-вергентни навлачни контакт између наведених тектонских јединица. Осим тога, ово је једно од ретких места у Србији где је картирана горњокредна "дијабаз-рожначка" формација. У овом раду проучаване су метаморфне стене подлоге, седиментне и магматске стене, као и деформационе структуре, у циљу дефинисања геодинамичког значаја ове "сенонске дијабаз-рожначке формације".

Наша интегрисана студија геолошких структура и вулканоседиментних формација дуж јужног продужетка Зворничког шав на планини Јелици пружа нову геодинамичку перспективу за еволуцију границе Јадранске микро-плоче и Европе у горњој креди, што води до следећих кључних закључака:

Интраконтинентална позиција Зворничког раседа: горњокредна вулканоседиментна формација Јелице не указује на океанску субдукциону зону. Уместо тога, она представља фронт Јадарско-копаоничке косе навлаке са израже-

ним десним кретањем. Према нашој интерпретацији, ове структуре настале су током интраконтиненталног навлачења, много након потпуног нестанка било каквог мезозојског океана, током процеса навлачења Јадарско-копаоничке јединице на Јадранску континенталну маргину.

Реинтерпретација "сенонске дијабаз-рожначке формације": ова вулканогено-седиментна формација планине Јелице највероватније представља продукт тзв. *wedge-top* басена који се развио током активности Јадарско-копаоничке навлаке. Јелички басен био је истовремен са Драгачевским басеном, који представља део формације флиша Косовске Митровице (претходно интерпретиран као *foreland* басен који се развио испред пропaгирајуће Јадарско-копаоничке навлаке). Ова два депоцентра била су део истог *foreland* басена, али на различитим структурним позицијама.

Синхроност вулканизма и седиментације: Петрографски и микроструктурни подаци указују на то да су базалтни вулканизам, хидротермалне промене и турбидитна седиментација били истовремени. Базалти су горњокредне старости, која је одређена на основу старости циркона, датираних на 87.4 ± 0.96 Ма. На основу њиховог Е-MORB афинитета, умереног обогаћења и података који указују на стапање у подручју спинела, закључено је да су настали стапањем релативно плитког и благо обогаћеног извора у омотачу. На основу комбинације петролошких и геохемијских података и структурно-геолошких података, закључено је да су ове стене највероватније настале у транстензионом домену насталог услед десног кретања по косој Јадарско-копаоничкој навлаци.

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