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Bi-directional extensional control of the Berane Basin formation, northern Montenegro

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Abstract. The Berane Basin is a Miocene, northeast-southwest oriented intramountain basin of the Dinarides, overlying the pre-neotectonic basement of the Drina–Ivanjica unit, the East Bosnian–Durmitor unit and the Western Vardar Zone. The structural evolution and the tectonic regimes that controlled the formation of the Berane Basin are not fully understood. In this paper, we conducted field kinematic analysis by applying fault-slip inversion to derive paleostress regimes and study the deformation phases that led to the formation of the Berane Basin. Observed deformation is related to the latest Oligocene-Miocene extension in two directions, perpendicular and parallel to the Dinarides orogen. Such bi-directional extension resulted in a complex fault pattern where, among observed normal, oblique and strike-slip faults, those with oblique-normal slip dominate. The observed faults likely form a system of mutually overprinting half-grabens, mainly driven by orogen-parallel extension associated with the large-scale regional Skadar–Peć Fault, while orogen-perpendicular extension has subordinate effects on the Berane Basin formation.

Key words:
bi-directional extension,
stress regime, strain partitioning,
Dinarides, Berane Basin.

Апстракт. Берански басен је миоценски унутарпланински басен Динарида, оријентисан правцем североисток-југозапад, који лежи на пренеотектонској основи Дрина–Ивањице, Источнобосанско–дурмиторске јединице и Западне вардарске зоне. Структурна еволуција и тектонски режими који су контролисали формирање Беранског басена нису у потпуности познати. У овом раду, примењена је кинематска анализа путем инверзије кретања по раседима да би се добили режими палеонапонског поља и проучиле деформационе фазе које су довеле до формирања Беранског басена. Опсервиране деформације су везане за најкасније олигоценску до миоценску екстензију по два правца, управну и паралелну на Динаридски ороген. Таква двосмерна екстензија резултирала је комплексним системом раседа, где међу опсервираним гравитационим, косим и транскурентним раседима, доминирају коси

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Кључне речи:
двосмерна екстензија,
напонски режим,
расподела деформација,
Динариди, Берански басен.

гравитациони. Опсервирани раседи формирају системе полу-ровова који се међусобно преклапају, а генерално су контролисани екстензијом паралелном орогену асоцираном са смицањима по великом регионалном Скадар–Пећ раседу, док је екстензија управна на ороген имала подређене ефекте у формирању Беранског басена.

Introduction

The Berane Basin represents a Miocene intra-mountain basin located in the Internal Dinarides of northern Montenegro (Fig. 1, Schmid et al., 2008, 2020, and references therein). Processes that caused its formation, the kinematics of the structures controlling its opening and subsidence and its general position in the overall Dinarides structure, are not yet fully understood. The longer Berane Basin axis is northeast-southwest oriented, which differs from other Cenozoic intra-mountain basins of the Dinarides orogen formed by an orogen-perpendicular extension (Andrić et al., 2017; van Unen et al., 2019a, 2019b, and references therein). Potentially, a very large influence on the development of the Berane Basin was the deformation along the nearby large-scale orogen-perpendicular Skadar–Peć Fault (Handy et al., 2019; Marović et al., 2007). The Skadar–Peć Fault offset has two components, an orogen-parallel normal and a dextral strike-slip component (Handy et al., 2019).

The aim of this study is to determine the kinematics of the Berane Basin-controlling faults and to link the basin formation and its present-day geometry to large-scale regional processes controlling deformations in the Dinarides during the Miocene times. We conducted the paleostress analysis of fault kinematics along the Berane Basin margins taking into account faults' superposition to constrain tectonic regimes and phases that controlled the basin subsidence and deformation.

Geological settings

The study area is located in the northwest-southeast oriented southwest-vergent Dinarides orogen, connecting the Alps, Albanides and Hellenides (Fig. 1, van Unen et al., 2019a, b). The tectonic evolution of the Dinarides and the processes that determined their present-day geometry and the formation of sedimentary basins were manifested in different deformation phases and tectonic regimes. The most significant events are related to the middle Triassic, Jurassic, Cretaceous–Paleogene, Eocene, early Miocene and Plio–Quaternary periods (Schmid et al., 2008, 2020, and references therein; see also Gawlick et al., 2017, and Gawlick & Missoni, 2019).

The first significant tectonic event in the evolution of the Dinarides was continental rifting during the Middle Triassic, which was accompanied by extensive magmatism and the development of the Adriatic passive continental margin. This rifting ultimately resulted in the opening of the Neotethys Ocean between the Adria microcontinent and Europe-derived tectonic units (Schmid et al., 2008, 2020; van Hinsbergen et al., 2020 and references therein). Subsequently, the Neotethys Ocean started to close by subduction during the Middle Jurassic, which was followed by the Late Jurassic obduction and the emplacement of ophiolites over the Adriatic passive margin (i.e., the Western Vardar ophiolitic unit of Schmid et al., 2008, 2020 and references therein). For slightly different timing and interpretations of the Triassic passive margin formation and subsequent Middle-Late Jurassic intra-oceanic subduction and obduction see Gawlick et al. (2017) and Gawlick & Missoni (2019) and references therein. Following the closure of the Neotethys Ocean, during the Cretaceous-Paleogene collision, a composite nappe-stack system formed in the Adriatic passive margin, creating the Dinarides orogen (Schmid et al., 2008, 2020, and references therein). The uppermost nappe in the composite nappe-system is the Jadar-Kopaonik unit in the Internal Dinarides, which is thrust over the Drina–Ivanjica unit, which is further thrust over the East Bosnian–Durmitor unit, the most external of the Internal Dinarides units. The East Bosnian-Durmitor unit is thrust towards south-

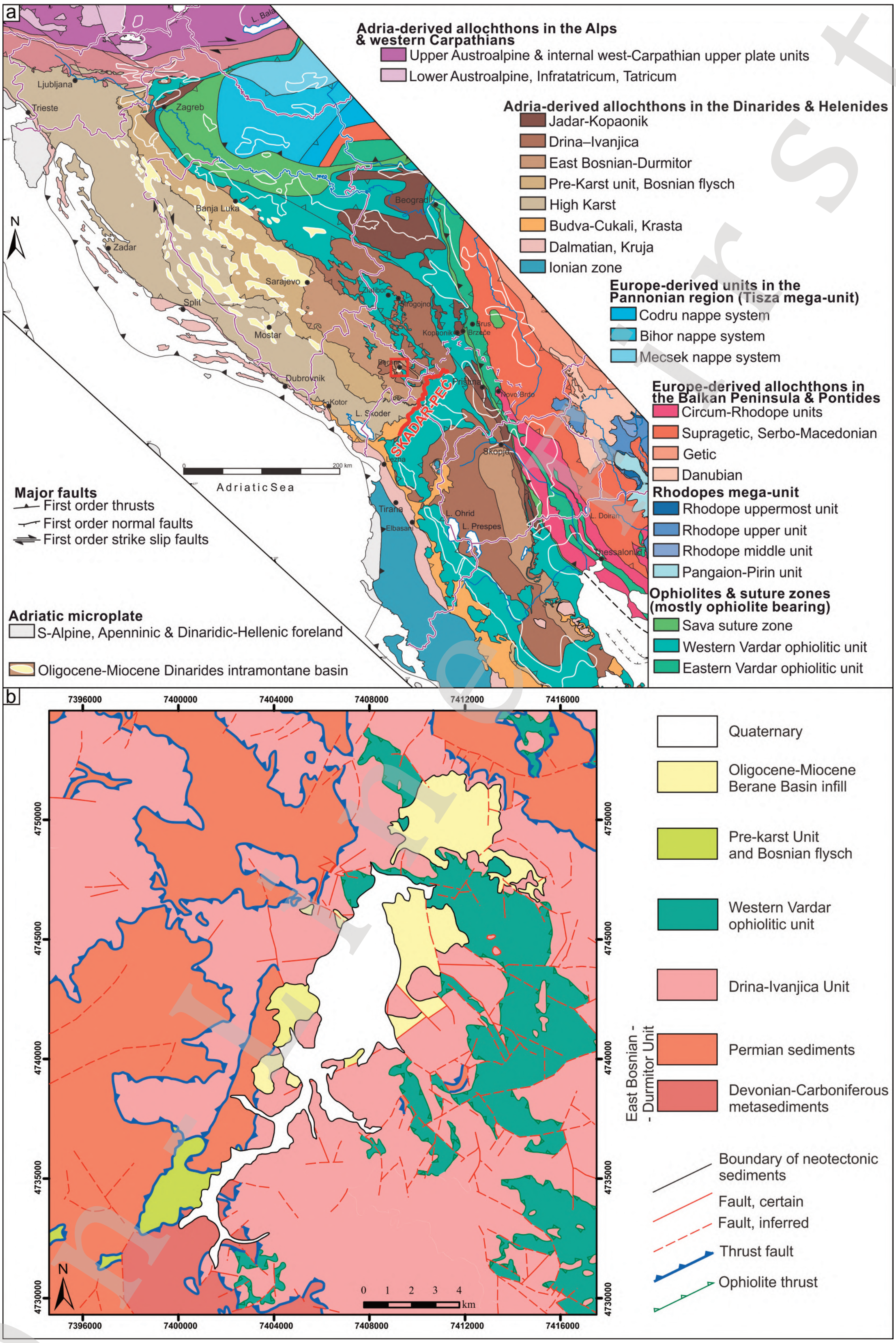

Fig. 1. a) *Tectonic map of the Dinarides orogen, with a wider area shown that includes units of Adriatic and European affinity (modified after* van Unen *et al., 2019b and* Schmid *et al., 2020). The red rectangle indicates the position of the study area shown in Figs. 1b, 2, 5 and 6.* ***b)*** *Tectonic map of the study area (modified after the Basic Geological Map of Socialist Federal Republic of Yugoslavia 1:100 000, sheet Ivangrad;* Živaljević *et al., 1981;* van Unen *et al., 2019b and* Schmid *et al., 2020).*

west over the External Dinarides units, consisting of nappe sequence of Pre-karst unit and Bosnian flysh, the High Karst unit, the Budva–Cukali unit and the external-most Dalmatian unit (Fig. 1). Ultimately, the collision caused the formation of the Sava zone, a suture zone between units of Adriatic and European affinity (e.g., Pamić, 2002; Schmid et al., 2008, 2020). Following the collision, during the Oligocene-Miocene, the regional tectonic regime changed to an extensional one, controlled by the interplay of the two subducting slabs, the Dinaridic and the Carpathians slabs, which resulted in the formation of the back-arc Pannonian Basin north of the Dinarides (Bada et al 2007; Schmid et al., 2008, 2020; Matenco & Radivojević, 2012; Stojadinović et al., 2013, and references therein). The final process, still active today, is the Pliocene-Quaternary indentation of the Adriatic microplate causing the inversion of the Pannonian Basin associated with a compressional stress field in the Dinarides (Bada et al., 2007; Schmid et al., 2008, 2020; van Unen et al., 2019b and references therein).

The Berane Basin is located in the transition zone between the Dinarides and Hellenides (Fig. 1a). According to the traditional tectonic divisions, the Berane Basin overlies the East Bosnian–Durmitor Unit which is to the south-southwest of the basin thrust over the Pre-Karst Unit and is farther to the north thrust by the Drina-Ivanjica Unit (Fig. 1b; Živaljević et al., 1981, 1982; Dimitrijević, 1997; Schmid et al., 2008). Additionally, a structural subdivision in the Berane Basin vicinity is further complicated by unclear internal relationships of several potential tectonic windows and klippen. Živaljević et al. (1981, 1982) interpret Triassic units to the west of the basin as the Bjelasica window of the Pre-Karst Unit outcropping beneath the East Bosnian–Durmitor Unit, while Triassic-Jurassic sedimentary and magmatic rocks overlain by ophiolitic melange (traditionally known as the Diabase-chert formation) located eastward of the basin are attributed to the Lim sub-unit of the East Bosnian – Durmitor Unit (Dimitrijević, 1997). Recently, different interpretations of the area have been proposed in which both Bjelasica and Lim are actually tectonic klippen of the Drina-Ivanjica Unit overlying the East Bosnian–Durmitor Unit (Fig. 1b; e.g., see Fig. 1 of van Unen et al, 2019a). We note that the internal tectonic subdivision of the Mesozoic rocks in the Cretaceous-Paleogene nappe-stack is of lesser importance for the structural evolution of the Berane Basin and adopt the recent-most tectonic units division of van Unen et al. (2019a).

According to van Unen et al. (2019a), the main regional structures in the Berane Basin vicinity are the nappe contacts between the Drina–Ivanjica, East Bosnian–Durmitor and Pre-Karst units (Fig. 1b). Additionally, the large-scale southeast-dipping orogen-perpendicular Skadar–Peć Fault (note alternative names in publications such as Scutari–Peć, Shkoder–Peć, Scutari–Peja or Shkoder–Peja; e.g., Kissel et al., 1995; Handy et al., 2019; Grund et al., 2023) is located to the southeast of the Berane Basin, offsets the orogenic structure and marks the transition between the Dinarides and Helenides (Fig. 1). The Skadar–Peć Fault is divided into two segments, the Skadar-Peć Transverse Zone (SPTZ) and the Skadar–Peć Normal Fault (SPNF), which differ in terms of kinematics and the direction of extension to which their origin is related (Handy et al., 2019). The Skadar-Peć Transverse Zone has a pronounced dextral offset, while the SPNF, the Skadar-Peć Normal Fault, is related to the orogen-parallel extension (Handy et al., 2019). The strike-slip domain of the fault, SPTZ, was active sometime between the Late Cretaceous and middle Eocene, while SPNF has two normal faulting phases (Grund et al., 2023). The early phase of normal faulting was associated with mylonitic shearing, where the age of metamorphism is older than Eocene. The later phase is set in the middle to late Miocene times and is related to syn-rift sedimentation during the tectonic subsidence of the Metohija Basin on the fault hanging wall (WKB of Grund et al., 2023).

The Dinarides nappes, overlain by the Berane Basin, are made of Devonian–Carboniferous, Permian, Triassic, Jurassic and Cretaceous-Paleogene rocks, while the basin's infill is built of uppermost Oligocene to Miocene sediments (Figs. 2, 3; Živaljević et al., 1982; Đorđević Milutinović & Ćufalić, 2010; Đorđević Milutinović et al., 2018 and references therein).

The East Bosnian–Durmitor unit consists of the oldest rocks in the research area, represented by chlorite-sericite schists with lenses of weakly meta-

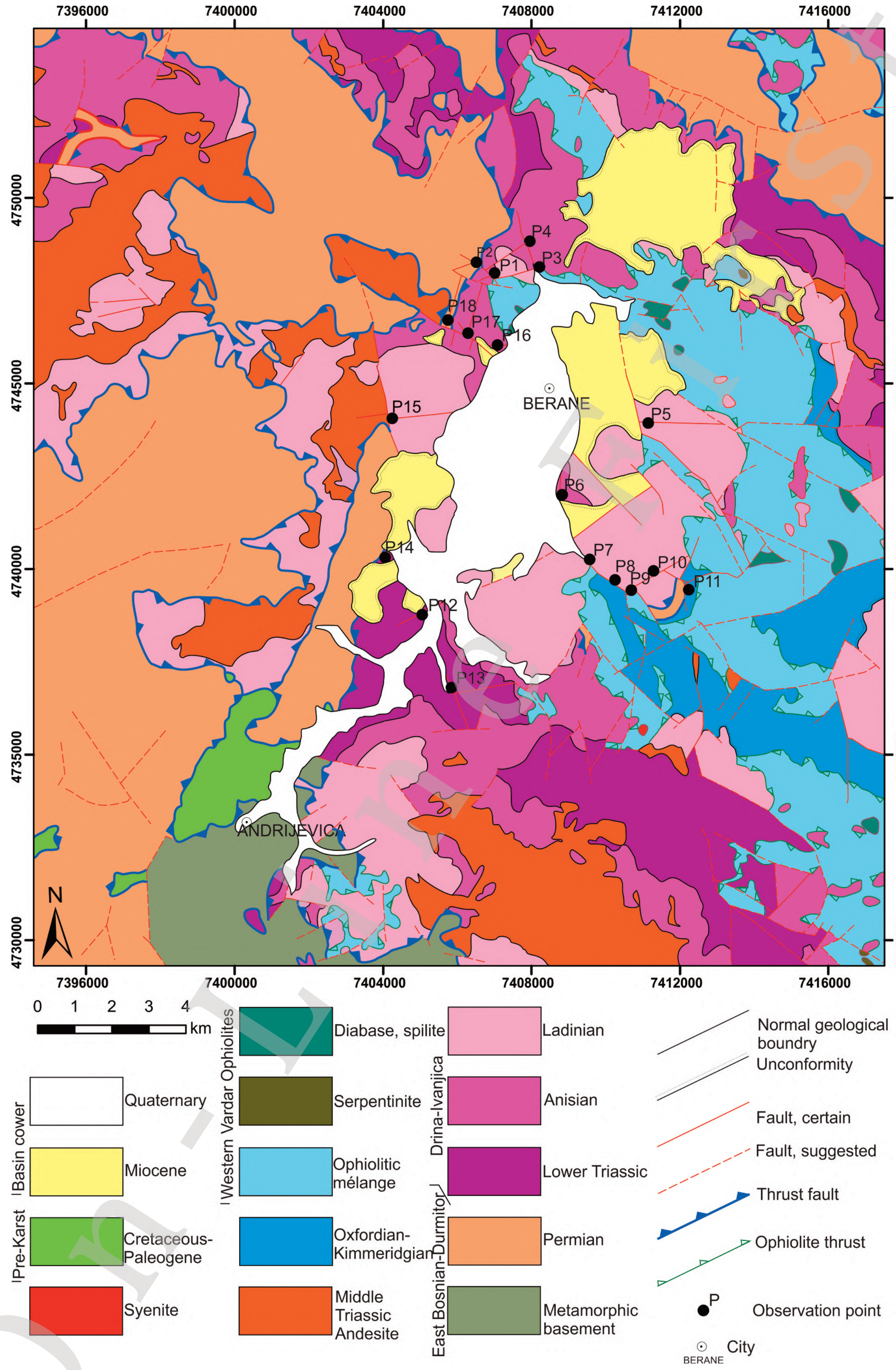

***Fig. 2.** Geological map of the study area with observation points (modified after the Basic Geological Map of Socialist Federal Republic of Yugoslavia 1:100 000, sheet Ivangrad; Živaljević et al., 1981 and Schmid et al., 2020).*

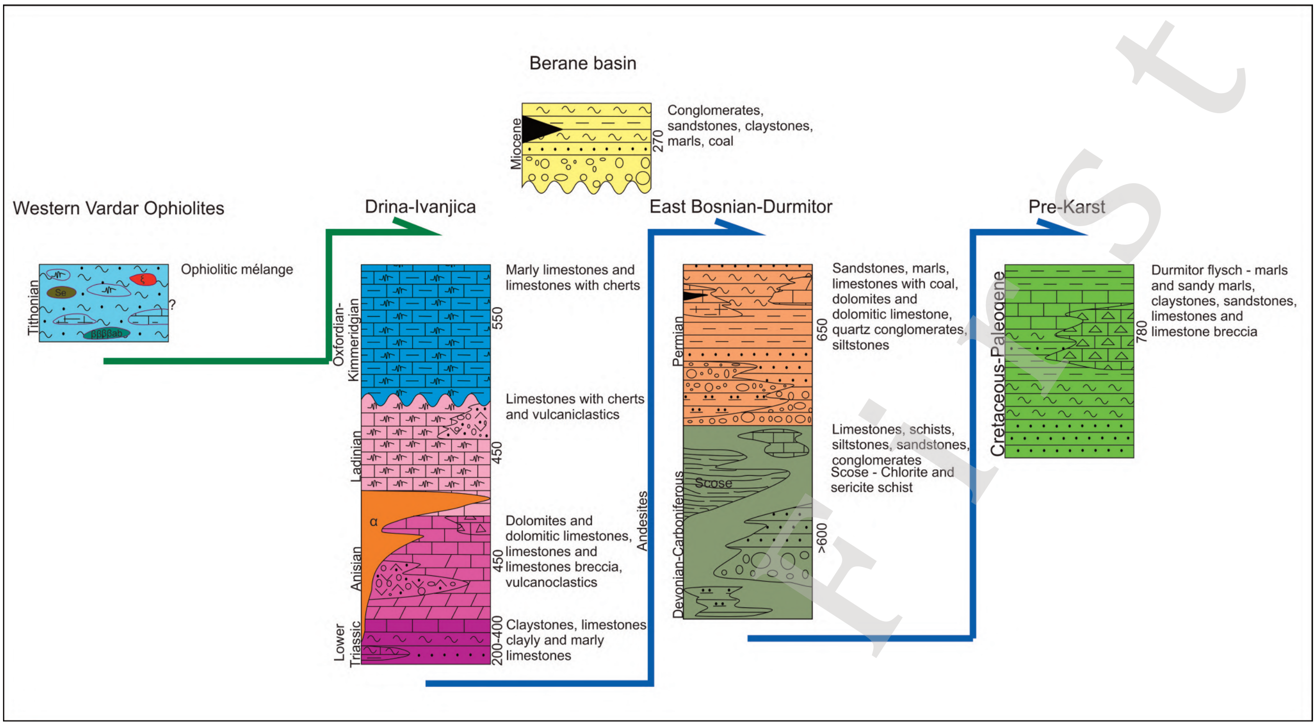

Fig. 3. *Geological columns of tectonic units and the Berane Basin in the study area (modified after Živaljević et al., 1982). The green line indicates obduction-related trusting and the blue lines indicate Cretaceous-Paleogene thrusting.*

morphosed sandstones, siltstones, limestones, conglomerates and schists metamorphosed in the very low- to low-greenschist facies, while the age of the protoliths is estimated as Devonian-Carboniferous (Živaljević et al., 1982). The Permian rocks were deposited continuously on the Devonian–Carboniferous assemblage and are made of semi-metamorphosed marly sandstones and schists, conglomerates and carbonate platform rocks (Živaljević et al., 1982).

The Mesozoic rocks are mostly located within the Drina-Ivanjica tectonic klippen tectonically overlying the East Bosnian-Durmitor unit (van Unen et al., 2019a). They are represented by the Triassic and Oxfordian to Kimmeridgian formations, overlain by the Tithonian ophiolitic melange of the Western Vardar Zone (traditionally termed Diabase-chert formation; Živaljević et al., 1982). The Lower Triassic formations are the oldest rocks of the Drina–Ivanjica unit in the area, lithologically represented by argillaceous nodular limestones and quartz mica sandstones and shales (Živaljević et al., 1982). Sedimentation continues with the Anisian and Ladinian association of carbonates and volcaniclastic rocks related to rifting and the opening of the Neotethys in this area (Živaljević et al., 1982). Unconformably overlying the Triassic sediments and magmatics, the Oxfordian and Kimmeridgian formations are represented by layered marly limestones with cherts and were deposited in a deeper water environment (Živaljević et al., 1982). The western Vardar zone is represented by a lithologically chaotic sandy-clay ophiolitic melange associated with olistoliths of oceanic lithosphere rocks (Živaljević et al., 1982).

Late Cretaceous-Paleogene turbidites of the Prekarst & Bosnian flysch outcrop in tectonic windows southwest of the Berane Basin. Flysch, known in this area as Durmitor flysch, is represented by marls, clays, sandstones and limestones, which contain lenses of limestone breccias (Živaljević et al., 1982).

The Neogene sediments in the study area are restricted to the Berane Basin, while the Quaternary cover is related to various recent or active geomorphic processes (Živaljević et al., 1982). Lithological members of the basin infill are marls, clays, sands, gravels, conglomerates and coal. The age of the sediments has been determined as Miocene, based on the paleoflora of the *Nelumbo* genus (Živaljević et al., 1982; Đorđević Milutinović et al., 2018). However, the earliest deposition in the basin started already in the latest Oligocene (Đorđević Milutinović & Ćufalić, 2010; Đorđević Milutinović et al., 2018 and references therein). Quaternary formations related to the basin itself are generally represented by fluvial deposits as a result of the activity of the river Lim, while the other Quaternary sediments in the study area consist of glacial, lacustrine and deluvial deposits (Živaljević et al., 1982).

Methodology

In this study, we conducted a field mapping of faults kinematics, their geometry and superposition along the Berane Basin margins. The mapping of brittle faults and shear zones was done in various chronostratigraphic and tectonic units and included observations and dip-direction/dip measurements of faults, slickenside kinematic indicators (e.g., Doblas, 1998) such as mineral growth fibres and grooves and Riedel shears, taking into account slip directions, confidence criteria (after Sperner & Zweigel, 2010) and fault cross-cutting and truncating relationships to derive deformation superposition.

The one or several nearby outcrops where structures were observed are shown on the geological map as an observation point (Fig. 2). At each outcrop, we carefully analysed fault superposition based on available data and observations to derive a local sequence of faulting. Subsequently, all local observations were integrated into a relative faulting sequence in the studied area. Based on the faults' superposition and correlation with existing observations elsewhere (e.g., van Unen et al., 2019a, b; Grund et al., 2023), in this study, we further analysed only deformation superpositionally located between the two compressional phases. More precisely, we analysed structures post-dating Cretaceous-Paleogene collision (i.e., older contraction-related structures) and pre-dating late Miocene-Quaternary indentation (thrusting and associated strike-slip, *sensu* van Unen et al., 2019a). Given the relatively small study area, we conducted fault-slip data inversion to calculate reduced paleostress tensors to derive tectonic regimes driving the Berane Basin opening. In the first step, fault-slip data from nearby observation points belonging to the same chronostratigraphic and tectonic units were grouped in different sets based on the similarity of their kinematics. Then, we used standardized inversion procedures for calculation and optimization of reduced paleostress tensor (e.g., Angelier & Mechler, 1977; Angelier & Goguel, 1979; Angelier, 1994) implemented in WinTensor software (Delvaux & Sperner, 2003; Delvaux, 2011). Following the consistency of obtained reduced paleostress tensors in the studied area, the two main deformation phases were distinguished, extension parallel to the orogen (Dpar) and extension perpendicular to the orogen (Dperp). Note that the resulting paleostress axes within these two phases do not show strong orientation in a certain direction, but vary significantly. In that sense, in this paper, we consider orogen-parallel extension when the smallest stress axis ($\sigma3$) is located in the NW or SE stereonet quadrant, while orogen-perpendicular extension is associated with $\sigma3$ located in the NE or SW stereonet quadrant. The limitations of the paleostress method in this area are related to a large number of strike-slip or oblique-slip faults that locally accommodate different amounts of extension, and are synchronous with normal faults. Such strain partitioning between coval faults of different kinematics is a known methodological limitation (e.g, van Unen et al., 2019b, Krstekanić et al ., 2020, 2022 and references therein) and has to be taken into account in data interpretation.

Results

Most of the observed structures related to the extensional processes that resulted in the formation of the Berane Basin are purely brittle and are documented in various Triassic to Jurassic sedimentary rocks along the basin margins. In most cases, these structures are represented by individual discrete brittle faults or systems of subparallel fault planes (Fig. 4a–d), occasionally associated with brecciated material or fault gouge within the fault zone.

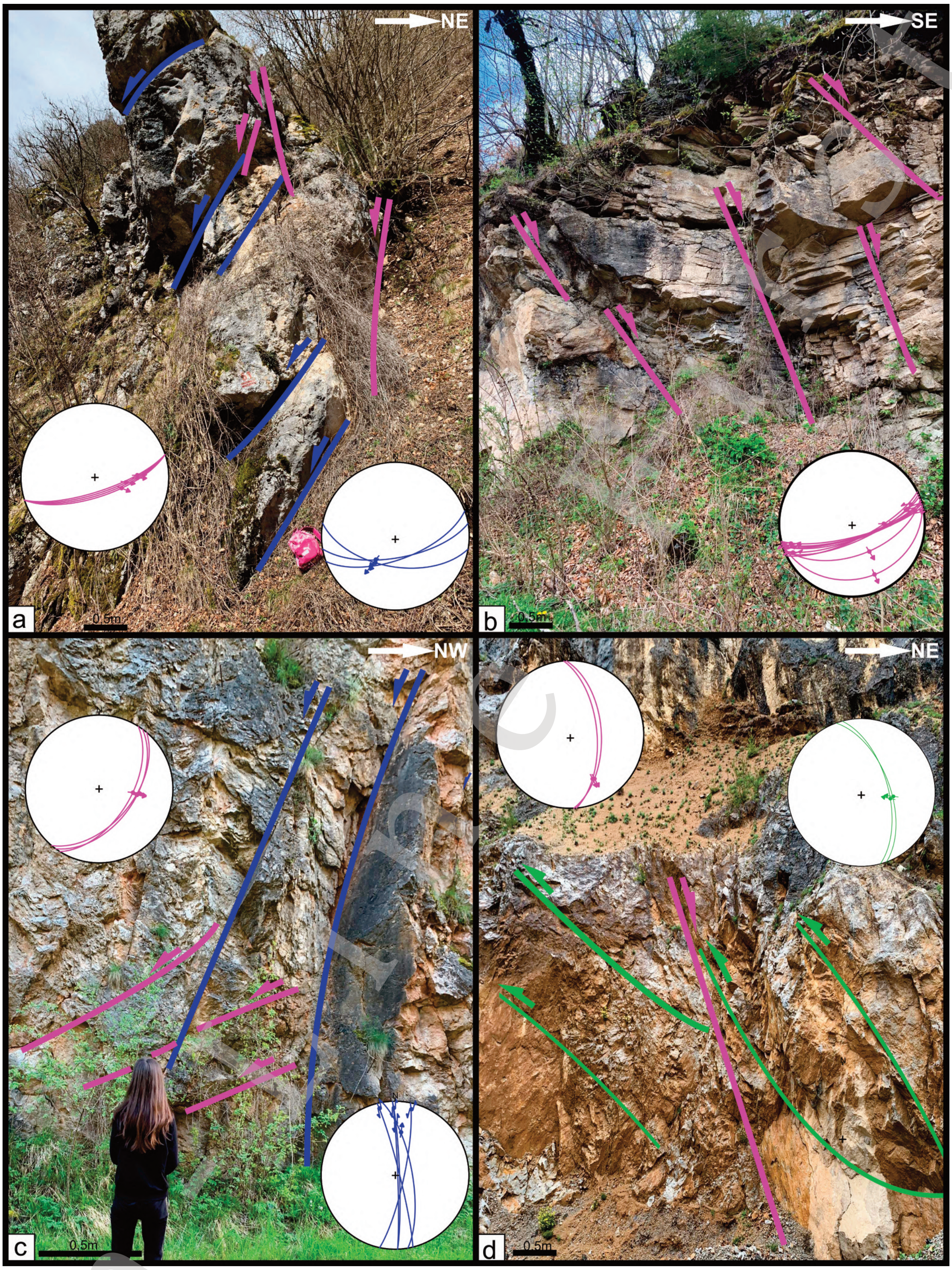

Fig. 4. *Geological structures related to the bi-directional latest Oligocene-Miocene extension and their mutual relations. Faults related to extension parallel to the orogen are shown in purple, faults related to extension perpendicular to the orogen in dark blue, and faults related to Cretaceous-Paleogene northeast-southwest compression in green.* ***a)*** *Faults from the observation point P1, faults created in the extension parallel to the orogen cross-cut the orogen-perpendicular extension faults.* ***b)*** *Normal faults formed by NW–SE oriented orogen-parallel extension, located in Upper Jurassic sediments at point P11.* ***c)*** *Strike-slip to highly oblique-normal faults formed by orogen-perpendicular extension cross-cut faults formed by orogen-parallel extension at point P4.* ***d)*** *The relationship between Cretaceous-Paleogene reverse faults and normal faults of orogen-parallel NW-SE extension, located on observation point P15.*

The first group of structures related to the orogen-parallel extension were observed along both basin margins, in the northwest and south-southeast. These are dominantly NE–SW oriented moderate-high angle normal and oblique-normal faults that have a more dominant dip-slip component (Fig. 5). Additionally, numerous high-angle to sub-vertical highly oblique-slip and strike-slip faults were also associated with orogen-parallel extension. These faults have variable orientations, from WSW–ENE to NW–SE and rarely N–S (Fig. 5). All the structures related to orogen-parallel extension are well distributed along the basin margins, with both normal and strike-slip faults present along both margins. The paleostress directions resulting from the inversion of the fault-slip data show dominant extensional to transtensional regime, and locally strike-slip (Table 1). In all the situations the minimal stress axis is sub-horizontal to low-angle and oriented in WNW–ESE to NNW–SSE directions (Fig. 5, Table 1).

The second group of structures, related to orogen-perpendicular extension, consists dominantly of high-angle to sub-vertical strike-slip and oblique-slip faults, while normal faults with dominant dip-slip component were less common. Strike-slip faults have varying orientations, dominantly from NW–SE to NE–SW and sometimes E–W and are more numerous along south-western margin of the basin (Fig. 6). Contrastingly, rare normal faults are more often observed along north-western basin margin where they have moderate to high dip angle and are oriented in NW–SE to N–S direction (Fig. 6). Calculated reduced paleostress tensors demonstrate that these faults were active under strike-slip and extensional regimes (Table 2).

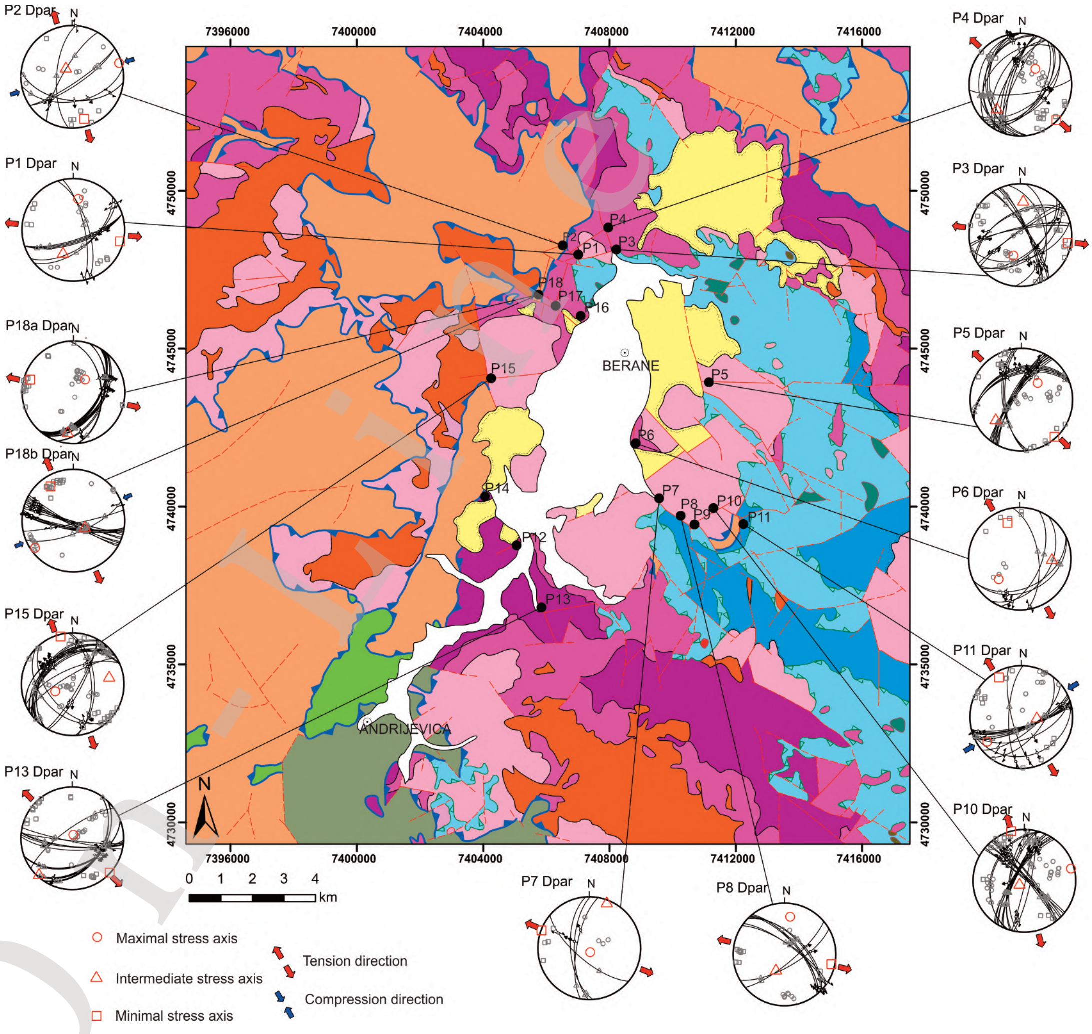

__Fig. 5.__ Stereoplots with faults related to orogen-parallel extension with calculated paleostress axes. The legend is the same as in Fig. 2.

Table 1. *Results of the paleostress analysis of faults related to extension parallel to orogen. Legend: Point – observation point on which the faults were measured; DI – Drina–Ivanjica unit, EBD – East Bosnian–Durmitor unit, WVO – West Vardar Ophiolites; P – Permian,* T_1 *– Lower Triassic,* T_1^2 *– Anisian,* T_2^2 *– Ladinian;* J_3^{1+2} *– Oxfrodian – Kimmeridgian,* J_3^3 *– Titonian; n – number of faults in the set; α – arithmetic mean of angles between measured and theoretical slip direction; R – stress ratio (σ2–σ3)/(σ1–σ3); Q – quality of results (after* DELVAUX & SPERNER*, 2003); NF – extension, NS – transtension, SS – strike-slip.*

	Point	Tectonic unit	Rock age	σ_1	σ_2	σ_3	n	α	R	Q	Regime
Orogen-parallel extension	P1	DI	T_2^1	006/40	193/50	102/2	8	9,2	0,08	D	NS
	P2	EBD	P	74/4	326/76	165/14	6	16,1	0,78	D	SS
	P3	WVO	J_3^3	195/50	353/38	92/11	17	16,3	0,33	D	NS
	P4	DI	T_2^1	44/56	223/34	313/1	20	11,1	0,29	C	NF
	P5	DI	T_2^2	42/50	230/40	137/4	18	11,9	0,41	C	NF
	P6	DI	T_2^1	229/41	95/39	343/25	5	4,7	0,44	E	NS
	P7	DI	T_2^2	196/78	022/12	292/1	4	7	0,5	E	NF
	P8	DI	T_2^2	006/34	213/53	105/13	9	11,8	0,77	D	NS
	P10	DI	T_2^2	278/81	063/8	153/5	23	13,2	0,45	C	NF
	P11	DI	J_3^{1+2}	237/18	100/66	332/16	14	9,9	0,63	C	SS
	P13	DI	T_1	357/85	224/3	134/4	17	16,1	0,5	D	NF
	P15	DI	T_2^2	251/54	72/36	341/1	21	13,2	0,5	C	NS
	P18a	EBD	P	26/71	191/18	282/5	16	7,7	0,54	C	NF
	P18b	EBD	P	242/12	123/67	337/20	16	3,1	0,83	C	SS

Table 2. *Results of the paleostress analysis of normal faults related to extension perpendicular to orogen. Legend: Point – observation point on which the faults were measured; DI - Drina-Ivanjica unit, EBD – East Bosnian–Durmitor unit; P – Permian,* T_1 *– Lower Triassic,* T_2^1*– Anisian,* T_2^2 *– Ladinian,* J_3^{1+2} *– Oxfrodian – Kimmeridgian; n – number of faults in the set; α – arithmetic mean of angles between measured and theoretical slip direction; R – stress ratio (σ2–σ3)/(σ1–σ3); Q – quality of results (after* DELVAUX & SPERNER*, 2003); NF – extension, NS – transtension, SS – strike-slip.*

	Point	Tectonic unit	Rock age	$?_1$	$?_2$	$?_3$	n	α	R	Q	Regime
Orogen-perpendicular extension	P1	DI	T_2^1	262/81	014/8	023/5	6	6,8	0,33	D	NF
	P2	EBD	P	157/15	272/57	59/29	2	2	0,5	E	SS
	P4	DI	T_2^1	241/84	130/2	40/5	10	6,7	0,86	C	NF
	P5	DI	T_2^2	130/52	245/32	244/18	9	1,2	0,91	D	NF
	P7	DI	T_2^2	253/63	122/18	025/19	5	4,7	0,28	E	NF
	P8	DI	T_2^2	99/25	255/63	005/10	19	9,8	0,81	C	SS
	P9	DI	J_3^{1+2}	293/28	130/61	027/7	6	1,4	0,26	D	SS
	P10	DI	T_2^2	100/3	359/73	191/17	23	17,7	0,53	D	SS
	P11	DI	J_3^{1+2}	145/75	325/15	55/1	4	18,9	0,73	E	NF
	P13a	DI	T_1	283/7	153/79	014/8	12	17,2	0,43	D	SS
	P13b	DI	T_1	350/29	165/61	259/2	7	10,3	0,51	D	SS
	P15	DI	T_2^2	110/18	322/69	203/10	6	2	0,24	D	SS
	P16	DI	T_2^1	349/31	186/57	84/8	15	8,6	0,8	C	SS
	P17	DI	T_2^1	281/23	146/59	20/20	6	8	0,94	D	SS

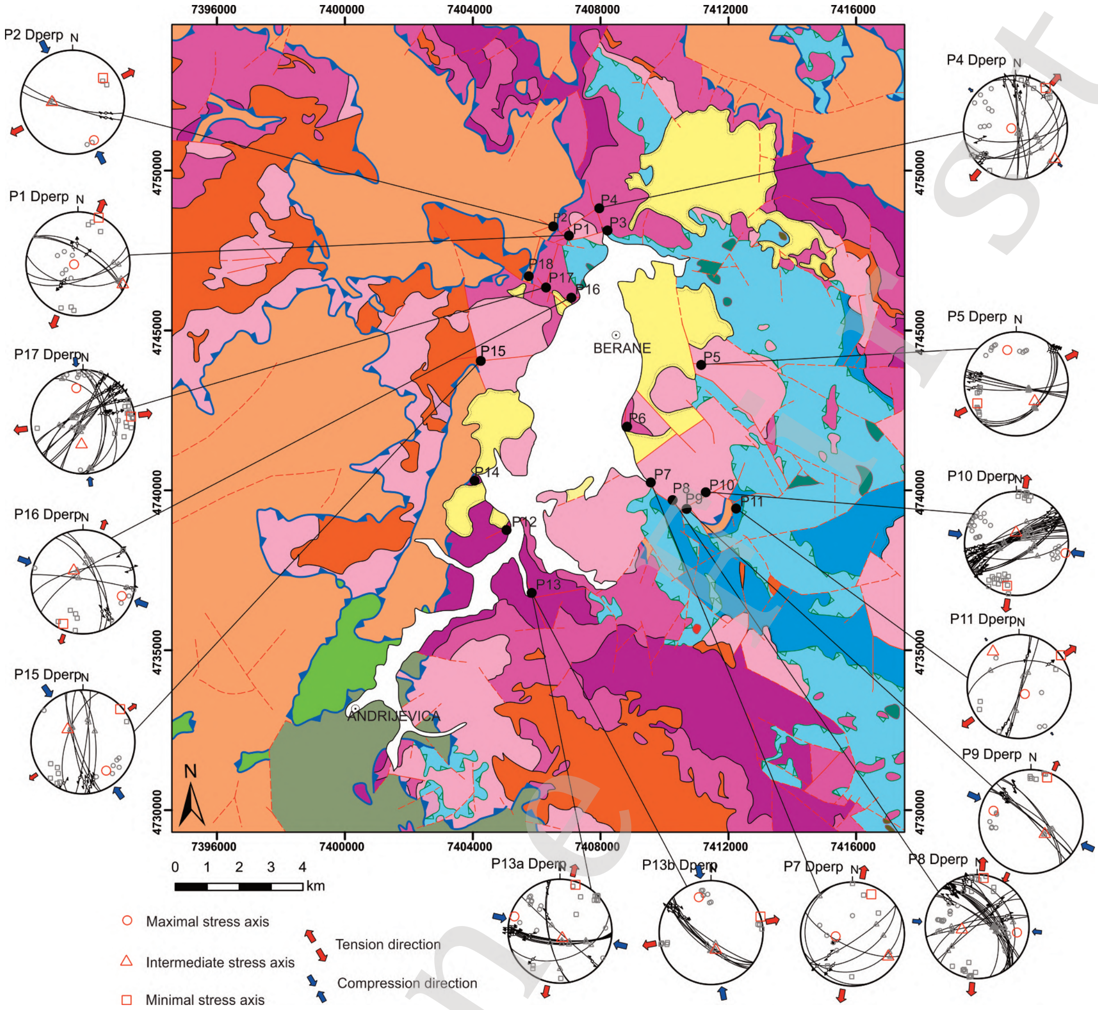

Fig. 6. *Stereoplots with faults related to orogen-perpendicular extension with calculated paleostress axes. The legend is the same as in Fig. 2.*

In all cases, the minimal stress axis is sub-horizontal and oriented in NNE–SSW to ENE–WSW direction, with the most dominant direction being NE–SW (Fig. 6, Table 2), which is parallel to the Berane Basin's longer axis and perpendicular to the Dinarides orogen. Accordingly, the maximal stress axis was in strike-slip sets sub-horizontal and oriented in WNW–ESE to NNW–SSE direction.

In a superpositional sense, these two fault groups cross-cut each other (Fig. 4a, c), while they cut older reverse faults also observed in the study area (Fig. 4d) and are cut by the youngest Plio–Quaternary N–S compression. Therefore, we assume that these two groups of faults are synchronous, belonging to the same deformation phase.

Discussion

The results of the kinematic analysis conducted in this study have shown that two coeval tectonic regimes were active during the formation of the Berane Basin. These two regimes were dominantly NW-SE oriented orogen-parallel extension and a more complex strike-slip to extensional regime with extension oriented in NE–SW (i.e., perpendicular to the Dinarides orogen; Figs. 5, 6). Considering their mutual cross-cutting relationship, as well as their superposition with Cretaceous–Paleogene NE–SW compression and late Miocene to Quaternary N–S compression (observed in our study area as well as elsewhere in the Dinarides (e.g., van Unen et al., 2019a, b) we suggest that both groups of structures presented above are formed by a complex bi-directional extension, which was controlling the deposition in the Berane Basin. Given the uppermost Oligocene–lower Miocene age of the oldest basin infill (Živaljević et al., 1982; Đorđević Milutinović & Ćufalić, 2010; Đorđević Milutinović et al., 2018), the observed bi-directional extension likely started during the latest Oligocene–earliest Miocene. However, because of the strong initial effects of the Triassic rifting associated with similar extension directions (e.g., van Unen et al., 2019a, b), without the absolute dating of faults, we cannot exclude that some of the observed structures are of Triassic age. Nonetheless, the facts that the faults were also observed in the Upper Jurassic sediments and the overprint of earlier compressional structures support the interpretation of the post-Cretaceous Paleogene age of the majority of observed deformation. However, the reported strike-slip to transpressional regime during Paleogene in the internal Dinarides (e.g., Ilić & Neubauer, 2005; Mladenović et al., 2015; Porkoláb et al., 2019), likely the continuation and part of the same Cretaceous–Paleogene convergence and shortening (Porkoláb et al., 2019), resulted in strike-slip and oblique-slip faults with similar orientations and kinematics as some of the faults formed during the Miocene extension. Therefore, taking into account the significant similarity of the strike-slip tear and transfer faulting during Cretaceous-Paleogene shortening (van Unen et al., 2019b; Porkoláb et al., 2019), Miocene bi-directional extension and late Miocene-Quaternary compression (van Unen et al., 2019a), inferences on the strike-slip faulting age(s) in the Berane Basin area should be taken with caution. However, the superposition of reverse and normal faulting in the studied area, and their interaction with the strike-slip faults infer the change in post-Cretaceous times from contractional deformation to bi-directional extension and finally again to contractional deformation followed by significant strain partitioning.

The large variability in fault orientation and their kinematics, in particular, the change between coeval normal, oblique-normal and strike-slip faults controlled by distinct paleostress regimes, indicate a significant strain partitioning during the Miocene extension in the study area. We suggest that both directions of deformation formed a series of half grabens (Fig. 7a, b) that typically form with normal faulting in the centre of the fault system which change along the fault strike to more oblique or strike-slip displacements towards the fault tips as the offset dissipates or is transferred to another normal fault along strike-slip transfer faults. Due to being formed under two coeval extension directions, half grabens superpose, while faults overprint each other (Fig. 7c). However, these two tectonic regimes likely didn't have the same effect on the basin subsidence. The more numerous normal faults formed by orogen-parallel extension imply that this extensional direction was more responsible for the basin subsidence, while the orogen-perpendicular extension had less effect on the basin geometry and likely contributed to its segmentation. This is somewhat different from the rest of the Dinarides farther to the NW of our studied area, where the orogen-perpendicular extension was more dominant than the orogen-parallel one (van Unen et al., 2019b).

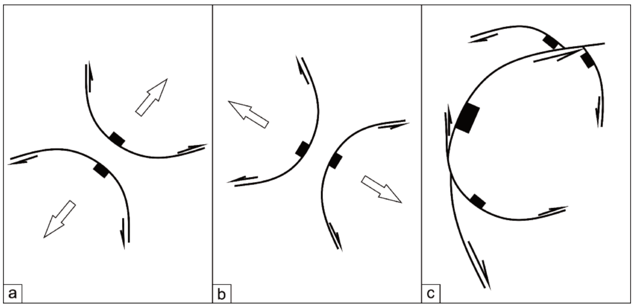

Fig. 7. Sketch of the mechanism of strain partitioning between coeval faults with different kinematics. ***a)*** *Half grabens formed by NE–SW extension.* ***b)*** *Half grabens formed by NW-SE extension.* ***c)*** *Interplay of mutually overprinting half grabens resulting in a complex fault pattern.*

Two potential drivers of extensions that led to the formation of Oligocene-Miocene basins in the Dinarides are the extension in the Pannonian Basin (e.g., Matenco & Radivojević, 2012; van Unen et al., 2019b and references therein) and the roll-back of the Aegean slab (i.e, Aegean collapse; e.g., Handy et al., 2019). For the majority of the Dinarides intramontane basins located farther away to the NW (Fig 1a), the orogen-perpendicular, Panonnian Basin-related extension, was more dominant (van Unen et al., 2019b). However, the Berane Basin is located more closely to the Hellenides and the Aegean slab than to the Pannonian Basin suggesting that it could have been influenced more by the Aegean slab roll-back. Furthermore, most of the orogen-perpendicular extension could have been accommodated along the reactivated East Bosnian–Durmitor thrust (van Unen et al., 2019a,b), leading to the more dominant effect of the orogen-parallel extension in its hanging wall. This all implies that the shift from orogen-perpendicular- to orogen-parallel-dominated extension in the Dinarides takes place in a larger vicinity of our studied area, which leads to a significant strain partitioning. Previously, the influence of the Aegean slab-driven extension was inferred to be limited to the Hellenides and taken up mostly by the Skadar–Peć Fault that controls the oroclinal bending and extensions parallel and perpendicular to the orogen in the upper plate above the Hellenic slab segment of the Adriatic plate (Handy et al., 2019; Grund et al., 2023). However, the results of this study suggest that the gravitational, fault-controlled collapse behind the Hellenides island arc likely resulted in local subsidence also farther to the north-west and beyond the Dinarides-Hellenides boundary (i.e., the Skadar–Peć Fault), in an area of the Dinarides that includes the Berane Basin (Marović et al., 2007).

Conclusions

In this study, we conducted a field kinematic analysis of structures along the Berane Basin margins, which were controlling its formation and subsidence. The results of fault-slip data inversion and observed fault superposition have shown that the two distinct tectonic regimes were coeval and active during the latest Oligocene-Miocene basin formation. These two regimes and associated complex fault pattern were the result of the interplay of two directions of extension, one parallel to the Dinarides orogen and one perpendicular to it. We suggest that the basin formed as a complex system of mutually overprinting half grabens, where normal faults change their kinematics to strike-slip along strike, or otherwise strike-slip faults accommodate the transfer of extension between different normal faults. Furthermore, observations suggest that the orogen-parallel extension contributed more to the subsidence and geometry of the Berane Basin compared to the one perpendicular to the orogen, while both were more likely driven by the extension associated with the Skadar-Peć Fault, rather than the Pannonian extension.

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Резиме

Двосмерна екстензиона контрола формирања Беранског басена, северна Црна Гора

Берански басен ситуиран је у домену граничног подручја Динарида и Хеленида, на пренеотектонској основи Дрина-Ивањице и Источнобосанско-дурмиторске јединице. Значај басена огледа се у могућности разумевања узајамног дејства процеса везаних за Динаридски ороген и утицај Егејеског колапса који је резултирао настанком басена на овом подручју. Формирање басена у овом подручју, последица је деловања раседа Скадар–Пећ, који контролише ороклино повијање и екстензије паралелне орогену и управне на њега на горњој плочи југозападно повлачећег хеленидског сегмента адријске плоче (Handy et al., 2019; Grund et al., 2023). Гравитациони колапс, који је контролисан раседом, иза хеленидског острвског лука, резултирао је стварањем басена северно од границе Динарида–Хеленида, у подручју које захвата и Берански басен (Marović et al., 2007). Циљ овог истраживања јесте да објасни узајамно дејство и последице истовременог дејства екстензија на овом подручју. Теренска структурна истраживања су у овом раду била усмерена на проучавање геометрије и кинематике раседа који контролишу отварање Беранског басена по ободу самог басена. На основу опсервиране суперпозиције раседних структура, одрађена је палонапонска анализа анализа раседа млађих од кредно-палеогене компресионе фазе и старијих од горњомиоценско-квартарне компресије. Резултати су показали да, почевши од најкаснијег олигоцена и током миоцена, двосмерна екстензија, праћена снажном расподелом деформација и често косим смицањима, контролише формирање Беранског басена. Екстензија паралелна Динаридском орогену, испољена генералним правцем СЗ–ЈИ, показује доминантније утицаје на субсиденцију и настанак самог басена, док је екстензија управна на Динаридски ороген, генералног правца СИ–ЈЗ, имала утицај на сегментацију басена. Басен показује грађу система полу-ровова, при чему се осим гравитационих раседа, присутни и системи транскурентних раседа који акомодирају разлике у износима екстензије и преносе деформацију између суседних гравитационих раседа.

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