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Paleogene–Early Miocene deformations of Bukulja–Venčac crystalline (Vardar Zone, Serbia)

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Abstract. Low-grade metamorphic rocks of the crystalline of Mts. Bukulja and Venčac, which are integral parts of the Vardar Zone, are of Late Cretaceous age. From the Middle Paleogene to the beginning of the Miocene, they were subjected to three phases of intensive deformations. In the first phase, during the Middle Paleogene, these rocks were subjected to intense shortening (approximately in the E–W direction), regional metamorphism and deformations in the ductile and brittle domains, when first-generation folds with NNE–SSW striking fold hinges were formed. In the second phase, during the Late Oligocene and up to the Early Miocene, extensional unroofing and exhumation of the crystalline occurred, which was followed by intrusion of the granitoid of Bukulja and refolding of the previously formed folds in a simple brachial form of Bukulja and Venčac with an ESE–WNW striking B-axis. The third phase was expressed in the Early lowermost Miocene (before the Ottnanghian), under conditions of NE–SW compression and NW–SE tension. It was characterized by wrench-tectonic activity, particularly by dextral movements along NNW–SSE striking faults.

Key words: Serbia, Vardar Zone, Bukulja–Venčac crystalline, structural analysis, tectonics, metamorphic core-complex.

Апстракт. Ниско метаморфне стене кристалина Букуље и Венчаца, које су саставни део Вардарске зоне Србије, су горњокредне старости. Оне су од средине палеогена до почетка миоцена биле захваћене интензивним деформацијама током три фазе обликовања. У првој фази, током средњег палеогена, биле су изложене јаком сужењу (приближно правцем И–З), регионалном метаморфизму и деформацијама у дуктилном и brittle домену, када су формирани набори прве генерације са Б-осама пружања ССИ–ЈЈЗ. У другој фази, током горњег олигоцена, до у доњи миоцен дошло је до екстензионог откривања и ексхумације кристалина, што је било праћено утискивањем гранитоида Букуље и пренабирањем претходно формираних набора у једноставну брахиформу Букуље и Венчаца са Б-осом пружања ИЈИ–ЗСЗ. Трећу фазу, која се испољила у раном доњем миоцену (пре отнанга) у условима СИ–ЈЗ компресије и СЗ–ЈИ, тензије карактерише wrench-тектонска активност, посебно декстрална кретања дуж раседа пружања ССЗ–ЈЈИ.

Кључне речи: Србија, Вардарска зона, букуљско-венчачки кристалин, структурна анализа, тектоника, метаморфни core-complex.

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Introduction

Crystalline of Bukulja and Venčac, with its non-metamorphosed Mesozoic–Cenozoic cover and Oligocene–Miocene granitoid, spatially belongs to the Vardar Zone (Fig. 1). These are terrains with complex geological compositions which have been discussed many times, often with controversial explanations.

There are dilemmas about the age of the crystalline in the first place, which directly influenced different explanations of the tectonics of these terrains. The crystalline has most often been considered to be of Paleozoic age (SIMIĆ 1938; FILIPOVIĆ 1973; FILIPOVIĆ & RODIN 1980; ĐOKOVIĆ *et al* 1995; TRIVIĆ 1998). Such an opinion is mostly based on the fact that these are rocks of different metamorphic grade, while there are no reliable paleontological proofs or even paleontological proofs of any kind. However, according to findings of globotruncana and other fauna and on the base of palynologic data from low-metamorphic rocks of Venčac, BRKOVIĆ *et al*. (1980) and MAROVIĆ *et al*. (2005), respectively, concluded that the Bukulja–Venčac crystalline is of Late Cretaceous age.

According to its age, folding of the area has also been explained in different ways. ĐOKOVIĆ & MAROVIĆ (1985, 1986) separated three generations of folds in these terrains. These authors related the first fold generation to Hercynian deformation, which is marked by NE–SW striking fold axes. In the second phase, during older Alpine tectogenetic events, the Hercynian fold structures were refolded into E–W striking folds. The third generation of folds is the consequence of a pluton intrusion and further refolding of all the existing folds into large domes and brachial synclines.

TRIVIĆ (1998) separated three (? four) generations of folds. According to this author, axes of the oldest, Hercynian structures are oriented in the WNW–ESE direction. These structures were refolded into folds with NNW–SSE striking axes during the first phase of Alpine deformation in the Mesozoic. Later, during the later Alpine phases, the geometry of such folds became more complex due to a pluton intrusion and strike-slip movements along E–W striking faults.

MAROVIĆ *et al*. (2005) considered the metamorphic rocks of Bukulja and Venčac to be of Late Cretaceous age and the authors are of the opinion that there are only Alpine and no Hercynian folds in these rocks.

The relationship between the crystalline and the non-metamorphosed Cretaceous (prevailingly Late Cretaceous) deposits, including tectonically incorporated slices of serpentinite, is unclear and has been explained in different ways. Sedimentary deposits are widespread on the surface, mostly north, east and southeast of the Bukulja–Venčac crystalline, and they were also drilled out under Neogene deposits of the Aranđelovac and Belanovica Basin. There are also isolated and disconnected portions of Cretaceous sediments on the southern rim of the crystalline. All this points to the possibility that the crystalline was completely covered by Cretaceous sediments. The majority of authors is of the opinion that the Cretaceous sediments transgressively overlie the crystalline. According to TRIVIĆ (1998), metamorphic rocks were thrust over Cretaceous sediments in certain parts of the terrain in the South. BRKOVIĆ *et al*. (1980) and ĐOKOVIĆ & MAROVIĆ (1986) mentioned sections where metamorphic rocks gradually transit into non-metamorphosed Upper Cretaceous deposits.

Finally, in accordance with different interpretations of the geologic composition, the geotectonic position of the Bukulja–Venčac crystalline unit is also controversial. Its metamorphic content resembles the Drina–Ivanjica crystalline (ĐOKOVIĆ *et al*. 1995). The Bukulja–Venčac crystalline is located on the eastward extension of the Jadar Block, which is made of Paleozoic rocks. This fact led FILIPOVIĆ (1995), FILIPOVIĆ & JOVANOVIĆ (1998) and FILIPOVIĆ (2005) to include at least a part of it (western part of Bukulja) into the Jadar entity. There is also the opinion that Bukulja–Venčac crystalline is completely different from the metamorphic rocks of both the Drina–Ivanjica and Jadar developments and that it is made of metamorphosed Cretaceous deposits belonging to the Vardar Zone (BRKOVIĆ *et al*. 1980; MAROVIĆ *et al*. 2005).

The above-cited problems concerning the geologic composition of the Bukulja–Venčac crystalline are a challenge for further investigations directed toward new and better documented solutions. The results of one of these studies, which represent a contribution to a better understanding of the Paleogene–Early Miocene tectonics of these regions, are presented in this paper.

Short Review of The Lithostratigraphic Characteristics of the Terrain

A wider area of the Bukulja–Venčac crystalline is made of rocks of different composition and age (Fig. 1). Four large lithostratigraphic domains can be distinguished: (1) Bukulja–Venčac crystalline, (2) serpentinite, Cretaceous clastics, carbonates and flysch, (3) Paleogene–Neogene granitoid and volcanic rocks and (4) Neogene–Quaternary sediments.

(1) The Bukulja–Venčac crystalline is made of rocks of different degrees of metamorphism, mostly low-grade metamorphics and, to a smaller extent, medium-to-high-grade metamorphics. These are mostly sedimentary rocks which were subjected to regional metamorphism and also to contact metamorphism in the vicinity of the granitoid. The lowest structural position is occupied by gneisses (and also leptynolites in places), which are followed by: micaschists, sericite schists, meta-quartz conglomerates, phyllites and sericite schists, marbles, calcschists, metacalcarenites and metasiltstones. Also epidote-actinolite- and chlorite schists occur subordinately in the low-grade metamorphic complex. Rocks with a higher grade of metamorphism are found in the vicin-

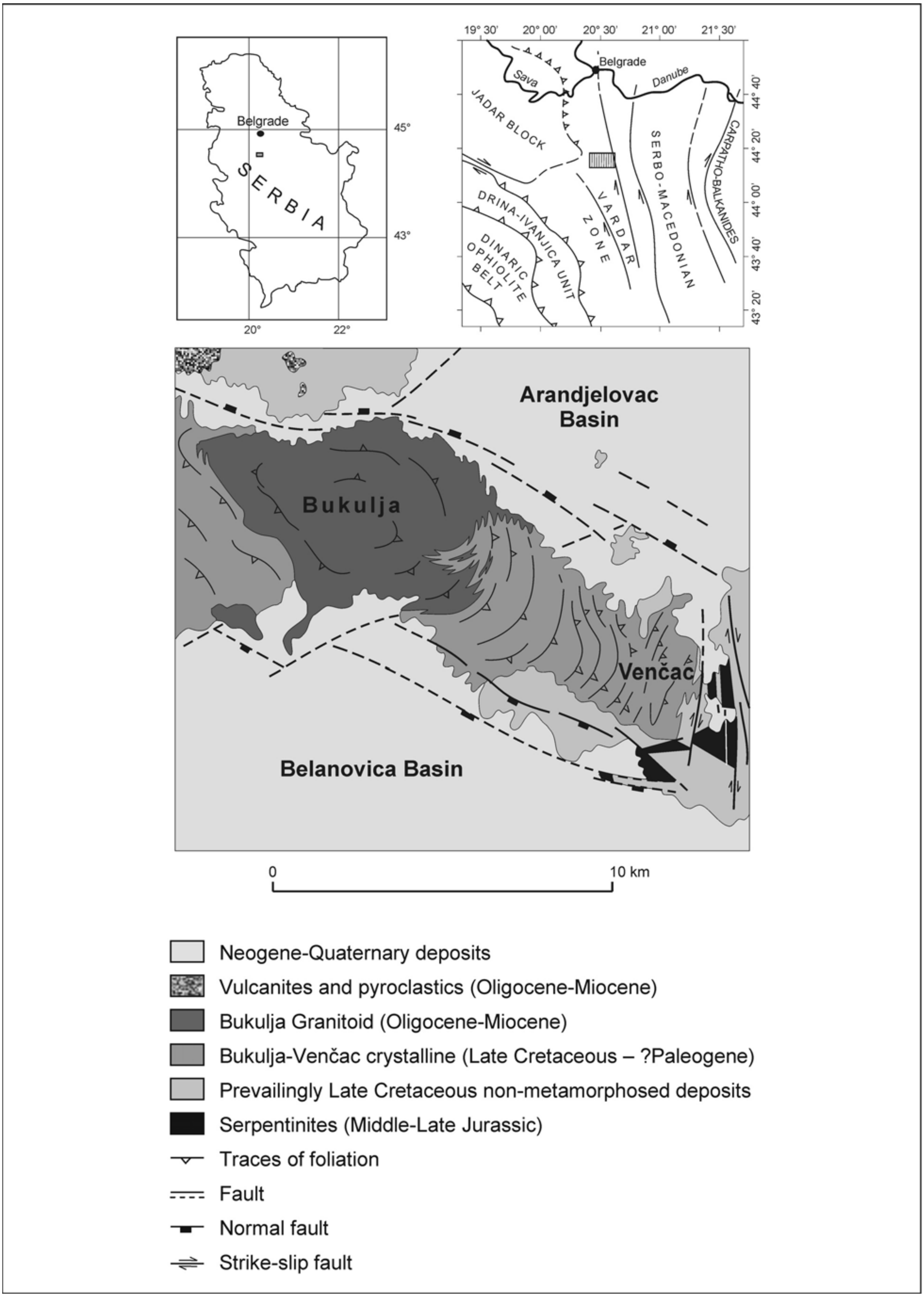

Fig. 1. Geologic sketch of the wider area of Bukulja and Venčac.

ity of the granitoid, while going away from it – towards the Venčac, low-grade metamorphics predominate. The Bukulja–Venčac crystalline is of Late Cretaceous or maybe partly even of Paleogene age. The second author (I.Đ.) is of the opinion that Venčac domain of the crystalline is of Late Cretaceous age, while the rest of it is Paleozoic and resembles the Drina–Ivanjica Paleozoic. During these investigations, rich microfloral association, which indicates Late Cretaceous age, was found in the calcschists and metacalcarenites of Venčac. This is in full agreement with the results on the crystalline age based on globotruncanas (BRKOVIĆ *et al*. 1980). However, this age most probably does not refer to the whole crystalline. Based on a lithostratigraphic correlation, FILIPOVIĆ (2005) is of the opinion that the metamorphic rocks west of Bukulja are similar to the Jadar Paleozoic, thus that they are Devonian and Carboniferous in age.

(2) Cretaceous sequence of non-metamorphosed deposits and serpentinite are exposed on the northern, eastern and southern slopes of the Bukulja–Venčac morphostructure. The Cretaceous sediments are represented by reefal and stratified limestones, rarely also by Early Cretaceous clastites and, for the largest part, by various types of carbonates, clastites and Late Cretaceous flysch (BRKOVIĆ *et al*. 1980). Smaller tectonic slices of serpentinite of Jurassic age occur locally near the Cretaceous sediments.

(3) Oligocene–Early Miocene granitoid was intruded into the Bukulja crystalline (KARAMATA *et al*. 1994; KNEŽEVIĆ *et al*. 1994). It induced also contact metamorphism of the surrounding rocks. The granite intrusion was followed by volcanic rocks, prevailingly phenoandesites, latites and their pyroclastics.

(4) A Neogene–Quaternary cover is represented by loosely bound coarse-grained, gravely-sandy, clayey-sandy and clayey deposits. These are mostly fresh-water equivalents of the Ottnangian–Karpatian and, to a lesser extent, also marine deposits of the Badenian and Sarmatian. The highest stratigraphic level is represented by different types of Quaternary deposits.

Tectonic Setting

Methodology of research

Geologic mapping of the Bukulja–Venčac crystalline (including the granitoid) and its non-metamorphosed cover of Late Cretaceous age provided information relevant for solving the tectonic setting of the area. These were data on bedding, foliation, folds of different scale and faults. They were analyzed within different scale ranges and homogeneous domains and the obtained data were incorporated in a tectonic synthesis, together with knowledge on the lithostratigraphic units.

Particular attention was paid to the determination of the orientation of fault planes and associated slip direction, which was used for the reconstruction of paleostress and deformation phases manifested from the middle Paleogene to the beginning of the Miocene.

Reconstruction of faulting succession and displacement was based on the criteria given by PETIT (1987) and GAMOND (1983, 1987). Reduced deviatoric paleostress tensors were computed for a cogenetic fault population which was separated from polyphase sets, based on field observations and kinematic compatibility. The method of numerical and graphical inversion proposed by ANGELIER & MECHLER (1977), ANGELIER (1979, 1989) and method of numerical dynamic analysis (NDA) by SPERNER *et al*. (1993) were used. Computation of the data for paleostress analysis was performed using Tectonic FP software (ORTNER *et al*. 2002).

Structural features

In a structural sense, three large homogeneous domains can be distinguished within the research area: (1) Bukulja–Venčac crystalline, (2) the thrust-fold sequence of non-metamorphosed Cretaceous deposits with tectonically incorporated slices of serpentinite and (3) Neogene basins. The first two structural domains are discussed in this paper, because they resulted from Paleogene–Early Miocene deformations, which were the subject of the research.

The structural setting of the Bukulja–Venčac crystalline is very complex with a polyphase-deformation history and at least two phases of folding. The area is dominated by a large (Dkm) brachial-antiform structure, the hinge of which plunges toward ESE. The best-developed fabric element is foliation, which actually makes this antiform (Fig. 2A). Foliation is unevenly developed: it is best-developed in gneisses and micaschists, less present in phyllites, sericite schists and calcschists, while it is poorly developed in metacalcarenite, metasiltstone and "massive" marble.

The foliation is probably the result of flattening perpendicular to the foliation planes. Isoclinal intrafolial folds of cm and dm scale are indicators of shearing along foliation. They are particularly well-visible in the metacalcarenites of Venčac, and locally, also in quartz-sericite schists (Fig. 3). The Folds are mostly rootless and represent thickened hinge zones, while their limbs are strongly flattened and sheared. These folds are west–northwest-vergent with fold axes plunging toward NNE and SSW (Fig. 2B). Crenulations of foliation are noticed locally. The crenulation axes plunge toward south–southeast to, southeast and northwest and they are genetically related to the formation of the brachial antiform (Fig. 2C). Foliation and intrafolial rootless folds could have been formed in an almost horizontal position. All this indicates refolding in the Bukulja–Venčac crystalline.

Foliation is developed in the granitoid as well. It has a periclinal distribution (Fig. 2D) compatible with foli-

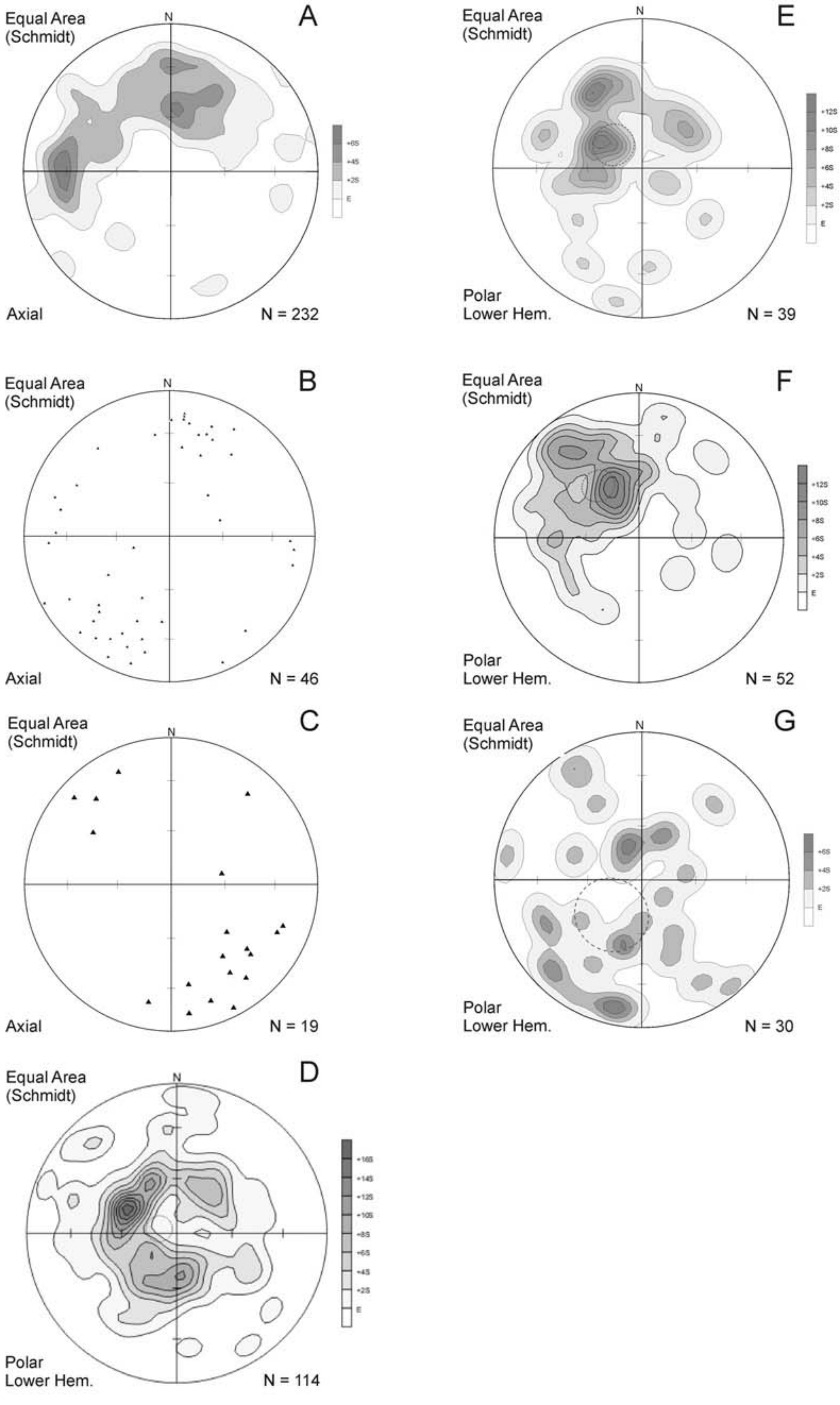

Fig. 2. Equal – area Lower hemisphere stereograms of: **A,** foliations in the crystalline; **B,** B-axis intrafolial folds; **C,** crenulation lineation; **D,** foliations in the granitoid; **E,** bedding in Cretaceous deposits north of Bukulja; **F,** bedding in Cretaceous deposits northwest of Venčac; **G,** bedding in Cretaceous deposits south of Venčac. Spheristat software was used for the analysis.

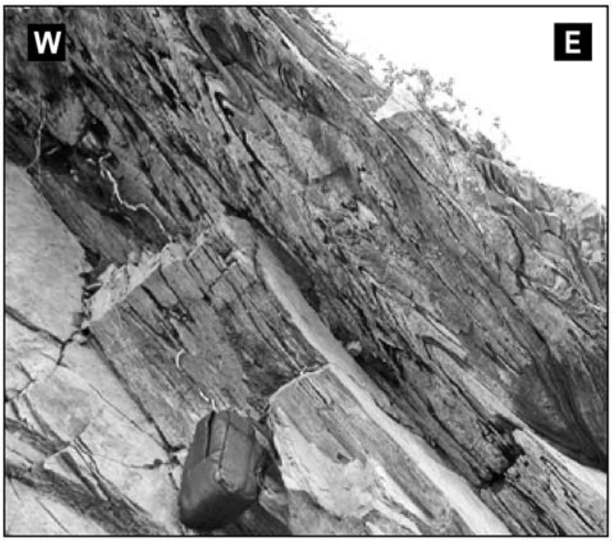

Fig. 3. Isoclinal folds in metacalcarenites of Venčac (Venčac quarry).

ation in the Bukulja–Venčac crystalline, which indicates their genetic relationship.

The thrust-fold stack of non-metamorphosed Cretaceous sediments with tectonically incorporated slices of serpentinite also have a very complex structure as well. Today, this unit is preserved within several small, more or less homogeneous structural regions on the northern, eastern and southern rims of the Bukulja–Venčac antiform. The structure is dominated by bedding and faults. The Bedding planes are well-exposed and penetrative.

Terrains on the northern slopes of Mt. Venčac are composed of non-metamorphosed deposits of Cretaceous age. Despite the fact that a large part of the area is covered with deluvium, a lot of information was acquired for fault analyses.

On the diagram F (Fig. 2), poles to bedding are mostly concentrated in the NW quadrant, marking a monoclinal dip toward southeast. However, field investigations showed that the folds in this area are not simple but that it is a folded unit with normal and overturned limbs of NNW (NW) vergent folds, similar to the folds of the first generation in the underlying Bukulja–Venčac crystalline, only less developed with less strain. Cretaceous deposits north of Bukulja are identically deformed (Fig. 2E).

East of Venčac, there is an intensely tectonized zone in the Cretaceous deposits and serpentinite. Unfortunately, this area is mostly covered, with no outcrops of Cretaceous deposits, thus a comprehensive measuremant the of bedding attitude could not be performed. According to the data from the wider surroundings (BRKOVIĆ *et al*. 1980), the area is characterized by a thrust-fold pattern marked by West-vergent recumbent folds and reverse faults, developed under dextral transpressio.

Terrains made of non-metamorphosed Cretaceous deposits on the southern and southwestern slopes of Venčac are mostly covered with deluvium and are unfavorable for structural investigations. The scattering of the bedding data, presented on diagram G (Fig. 2) is probably a consequence of the rotation of faulted blocks, but also of the small number of measurements which are statistically not representative. Field observations showed that the Cretaceous deposits here are also intensely folded, with the occurrence of overturned west–northwest-vergent folds.

Results of paleostress analysis

Paleostress analysis in the area of the Bukulja–Venčac crystalline, non-metamorphosed Cretaceous deposits and the granitoid show three kinematic stages, the first probably being of Middle Paleogene, the second of Oligocene to Oligocene–Miocene and the third of Early Miocene (Pre-Ottnangian to Karpatian) age. The relative chronology of these events is deduced from crosscutting map-scale faults in key outcrops.

Deformational event (D_1) – E–W compression

This paleostress tensor group comprises a conjugated pair of NW-trending sinistral and NE-trending dextral strike-slip faults (Fig. 4). These faults are overprinted by mainly extensional structures on numerous outcrops.

Folds of the first generation with a NNE (NE)–SSW (SW) striking axes probably originated in such a stress field. Today, they are exposed as intrafolial folds in the Bukulja–Venčac crystalline, as well as in WNW (NW) vergent folds in non-metamorphosed Cretaceous deposits.

Deformational event (D_2) – N–S-to-NE–SW extension

The second paleostress tensor group comprises WNW to NW and NE-trending normal faults (Fig. 5). These faults are probably related to an Oligocene unroofing of the Bukulja–Venčac crystalline and the granitoid intrusion. In this case, WNW to NW trending normal faults often form conjugate sets: synthetic, gently sloping northwards and antithetic, with steeper dips toward the south. They were formed above the brittle-ductile detachment zone along which the extensional unroofing occurred.

Deformational event (D_3) – wrench tectonic regime, NE–SW compression and NW–SE tension

The third paleostress tensor group comprises NNW to NW trending dextral and WNW trending sinistral strike-slip faults (Fig. 6). Fault systems with these kinematic characteristics, which originated in the stress field with NE–SW compression and NW–SE tension, can be

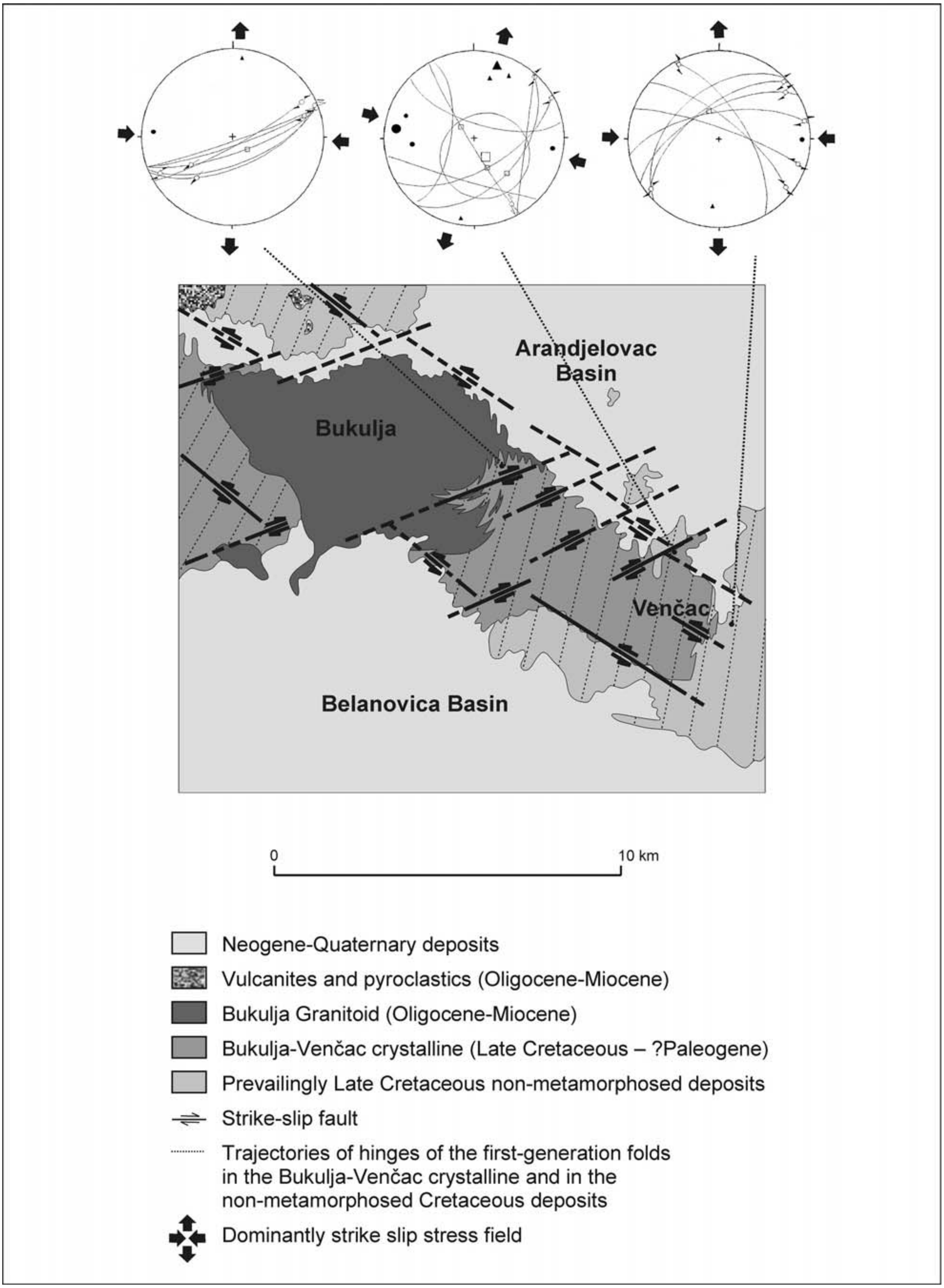

Fig. 4. Distribution of stress states related to a E–W compressional event. Stereographic projection of the measured outcrop – scale faults and calculated stress axes. The circle, rectangle and triangle represent the orientation of the maximum, intermediate and minimum principal stress axes, respectively.

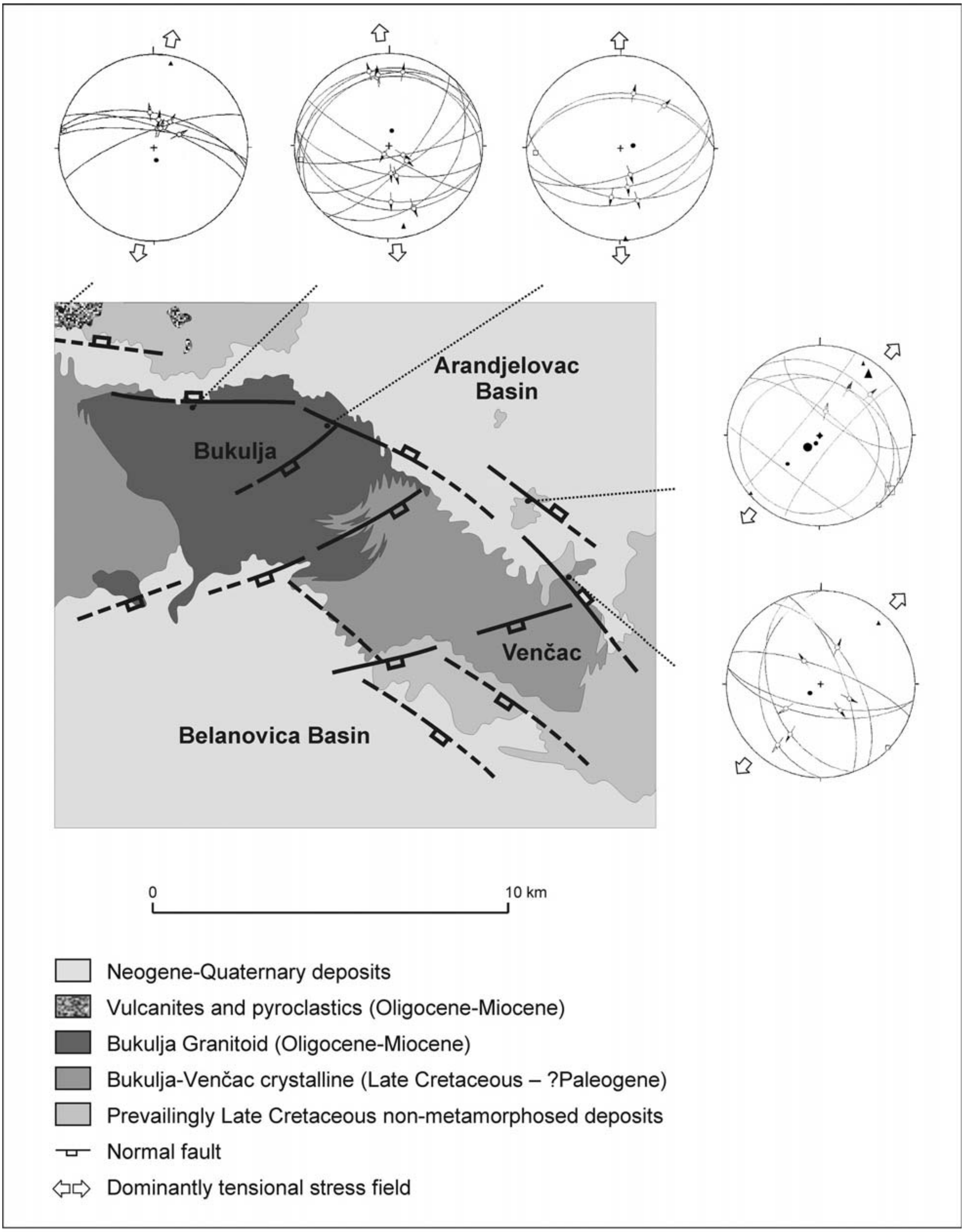

Fig. 5. Distribution of stress states related to an extensional event with N–S to NE–SW trending σ_3. Explanation the same as for Fig. 4.

related to dextral wrenching. In this case, NNW to NW trending faults could belong to the principal displacement zone (PDZ) with dextral characteristics (Y-faults), while WNW-trending sinistral strike-slip faults could represent X-faults. Such a stress field was generated at the beginning of the Miocene ("Sava phase").

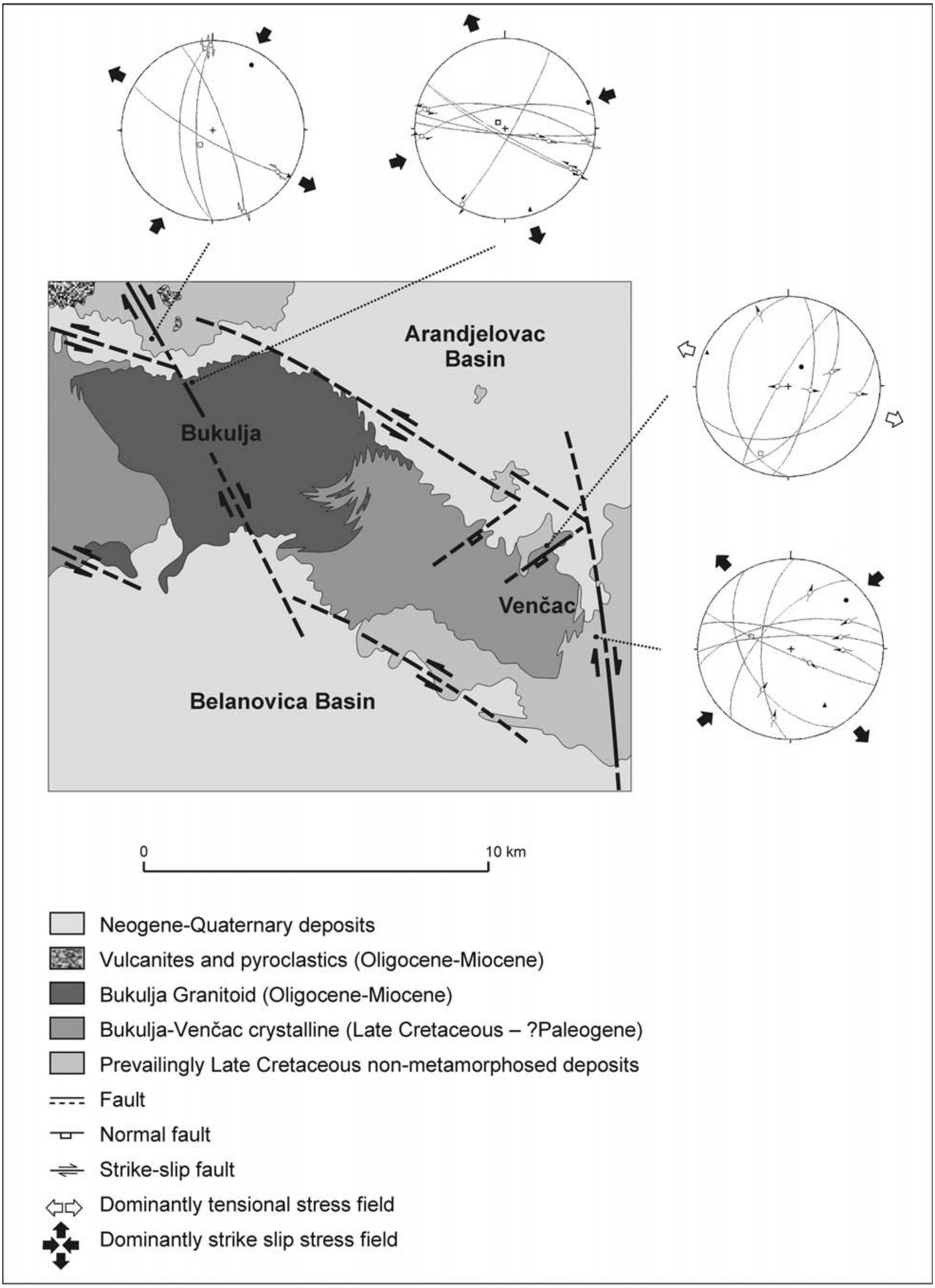

Fig. 6. Distribution of stress states related to a dextral strike-slip regime with σ_1, trending NE–SW. Explanation the same as for Figs. 4. and 5.

Discussion and Conclusions

Investigations in the area of the Bukulja–Venčac crystalline showed the following:

• The Bukulja–Venčac crystalline is of Late Cretaceous age, maybe even partly Early Paleogene. It was intruded by an Early Miocene granitoid.

• The crystalline is overlain mostly by Late Cretaceous non-metamorphosed clastic-carbonate rocks and flysch.

• Metamorphic grade in the crystalline decreases from the granitoid to the periphery and toward the upper structural levels, where there is a gradual transition into non-metamorphosed members of the Late Cretaceous.

• There is a similar manner of folding (fold shape, vergences) in both sequences of Cretaceous deposits: the metamorphosed and the non-metamorphosed ones, but deformations in the crystalline is more intense and occurred in the ductile domain. Two phases of folding are noticed.

• Reconstruction of paleostress fields points to three major phases of brittle formation : in the middle of the Paleogene, in the Oligocene–Early Miocene and in the Early Miocene.

The above presented facts point to a unique tectonic-sedimentary environment in this area during the Late Cretaceous (maybe also in the ?Early Paleogene), which was inverted in the middle of the Paleogene. Such an environment is consistent with the model elaborated by PAMIĆ (1993), PAMIĆ *et al.* (2000, 2002), according to which the northern part of the Vardar Zone (Vardar–Sava) is the result of obliteration in the Upper Cretaceous–Paleogene active continental margin of Southern Europe, with well-defined island arc and back-arc basins. This sedimentation area was inverted and included into the Dinaridic orogene by collisional processes in the Eocene. According to PAMIĆ *et al.* (2000, 2002), this phase was followed by intense deformation of the Jurassic ophiolitic mélange, metamorphism and magmatism.

The Bukulja–Venčac sedimentation and deformation area (Fig. 7) was probably generated in a similar tectonic setting. In the middle of the Paleogene, the Bukulja–Venčac area was subjected to shortening in the approximate E–W direction, when a thick WNW vergent thrust-fold sequence was formed. The second author (I.Đ.) is of the opinion that these structures were formed only in the Venčac domain of the crystalline, while, in its other parts, the Hercynian structures were refolded by a Mesozoic–Cenozoic tectonic event. The lower parts of the sequence reached the zone of ductile deformations and underwent regional low- to medium-grade metamorphism. The whole process was followed by the formation of tight and isoclinal folds with hinges striking NNE (NE)–SSW (SW) with strong axial plane cleavage, and subsequent transposition of bedding along the cleavage, the formation of foliation. Remnants of these folds are preserved today as intrafolial folds.

In the brittle-ductile and brittle domain, above the metamorphites, this phase of tectogenesis resulted in the formation of distinctly WNW (NW) vergent overturned, sometimes also recumbent, folds with axes striking NNE (NE)–SSW (SW) and the formation of conjugated NW trending sinistral and NE trending dextral strike slip faults.

Extension, probably ductile, followed by intrusion of granitoid, volcanism and exhumation of the Late Cretaceous metamorphics (metamorphic core complex) is characteristic for the second phase, which that was expressed in the Late Oligocene and up into the Early Miocene.

The process of exhumation metamorphism and emplacement of the granitoid was marked by refolding of the foliation and the previously formed folds, when the distinct brachial-antiform of the Mts. Bukulja and Venčac (with an ESE plunging axis) was formed. There are certain indications that a shallow synform), rim synform, which is presently mostly burried with Neogene–Quaternary deposits, was formed northeast of the antiform.

Unfortunately, the detachment zone along which the ductile extension occurred has not been defined, which certainly does not mean that it does not exist. Further detailed investigations are necessary for its determination.

In the brittle domain in the area of extensional allochthon, WNW to NW and NE trending normal faults were activated, often as pairs of synthetic and antithetic sets.

After the exhumation of the metamorphic core complex of Bukulja and Venčac, tectonic shortening affected the area. It is expressed through dextral transpression with NE–SW compression and NW–SE tension. Activation of the NNW–NW trending dextral and WNW trending sinistral strike-slip faults is characteristic for this phase. In the domain of the first system, small NE-trending normal faults (probably "pinnate" faults) were activated. Under transpressional conditions, west-vergent folds and thrusts were formed, particularly on the eastern periphery of Venčac. This transpressional event affected the Vardar Zone, the Serbian–Macedonian Unit and the Carpatho-Balkanides, all the way to the Moesian Plate (wrench corridor, MAROVIĆ *et al.* 2001).

The process of destruction of the previously formed structures, related to the shaping of the Pannonian Basin and its periphery, commenced after the transpressional events, already from the Ottnangian.

The performed investigations stress the problem which demands more detailed research and application of new methods in order to obtain more reliable and precise solutions. This refers, in the first place, to the necessity of performing detailed structural investigations and registering kinematic indicators of extensional processes and stress fields in general. Particular attention should also, be paid to an explanation of the

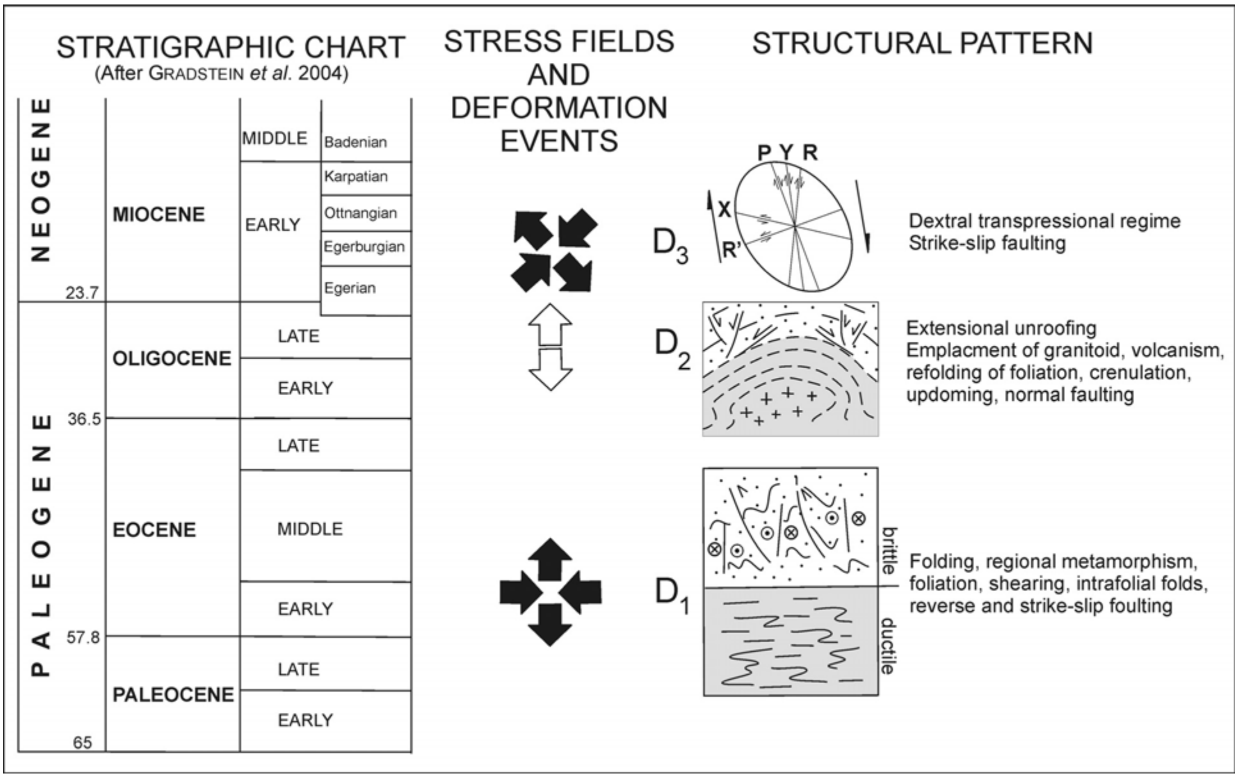

Fig. 7. Scheme of the Paleogene–Early Miocene tectonic evolution of the Bukulja–Venčac domain.

manner of extensional unroofing, transpressional tectonics and related phenomena.

In order to date the tectonic events, it will be necessary to apply methods of thermogeochronology, e.g., Ar/Ar on mica and fission-track analyses.

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Резиме

Палеогено-доњомиоценске деформације Букуљско-венчачког кристалина (Вардарска зона, Србија)

Нискометаморфни кристалин Букуље и Венчаца са својим неметаморфисаним мезозојско-кенозојским покровом је део Вардарске зоне. Сложене је геолошке грађе, посебно тектонског склопа, који је резултат вишефазног обликовања. Предмет овог рада су палеогено-доњомиоценске деформације које су најодговорније за формирање најмаркантнијих структура у овом региону.

О геолошкој грађи букуљско-венчачког кристалина постоје бројне контроверзе, почев од његове старости, наборног склопа, односа према неметаморфисаним кредним творевинама, све до геотектонске припадности.

Ова истраживања су показала, односно потврдила, да је кристалин горњокредне (можда делом и палеогене?) старости. Сагласно томе не поседује херцинске наборе, већ само алпске, који су резултат палеогено-доњомиоценских обликовања. Утврђене су три главне фазе формирања палеогено-доњомиоценског склопа.

У првој фази, средином палеогена, у напонском пољу И–З компресија, стене букуљско-венчачког подручја биле су изложене јаком сажимању, регионалном метаморфизму и деформацијама у дуктилном и brittle домену (формирани су изразито ЗСЗ-вергентни набори који су у дуктилном домену претпели још и транспозицију, формирање фолијације и shearing).

У другој фази, током горњег олигоцена до у доњи миоцен обављено је екстензионо раскровљавање и ексхумација кристалина, што је било праћено утискивањем гранитоида и пренабирањем претходно формираног наборног склопа у једноставну брахи-антиформу Букуље и Венчаца.

За последњу фазу испољену у доњем миоцену (пре отнанга), у условима СИ–ЈЗ компресије и СЗ–ЈИ тензије, карактеристична је wrench-тектонска активност.

Током све три тектонске фазе, активирани су раседи који су имали кинематска обележја сагласно напонском пољу у коме су формирани.