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DEFORMATION PATTERN OF THE PALAEOZOIC UNITS OF THE TETHYAN SUTURE IN THE CENTRAL BALKAN PENINSULA: A NEW INSIGHT FROM STUDY OF THE BUKULJA-LAZAREVAC PALAEOZOIC UNIT (SERBIA)

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ABSTRACT

This study presents and discusses new data about the lithology and deformation style of the Bukulja-Lazarevac Palaeozoic Unit (BLPz) and compares its characteristics to those exhibited by the adjacent Palaeozoic units of the complex suture of the central Balkan Peninsula, namely: the Drina-Ivanjica (DIU), the Jadar Block (JBU) and the Dičina Palaeozoic (DPz) Units. The BLPz consists of four metasedimentary and metaigneous formations metamorphosed under greenschist facies conditions. Only rare rocks show evidences of an earlier metamorphism of amphibolites facies conditions. The BLPz is lithologically similar to DIU and DPz whereas JBU is different. The study of deformation suggests that BLPz rocks underwent two ductile tectonic events, referred to as D_1 and D_2, and one brittle event, referred to as D_3. The D_1 structures are small-scale isoclinal and oblique folds with subrounded hinges and statistical B_1 axes dipping around 5-20^o towards E-ESE and SE. The D_2 structures appear as m- to dm-sized folds formed on the limbs of the larger fold structures. Statistically, B_2 axes are mainly dipping to SE, subordinately to NW and SW. The angle between B_1 and B_2 axes is uniform ranging from 35^o to 45^o. Evidences for two similar deformation events are recorded in DIU, JBU and DPz, as well. Reconstruction of the original position of B_1 axes was made by rotating their measured directions around the statistic directions of B_2 fold axes. The obtained results imply that the B_1 axes in the northern part of DIU (Drina Block) and JBU have the same primary orientation striking NE-SW. The southern part of DIU (Ivanjica Block) and BLPz Units are characterized by E-W oriented B_1 structures. Such organization suggests that all the studied Palaeozoic units probably underwent similar events of ductile deformation. These results argue in favor of the hypothesis that these units represented integral parts of Adria, and obtained their present relationships during post-Jurassic nappe stacking.

INTRODUCTION

The geology of the central Balkan Peninsula is dominated by a complex suture which formed through complex and most probably multiphase subduction and accretion processes (Robertson et al., 2009, and references therein). The suture consists of NNW-SSE elongated dismembered units that roughly include huge masses of ophiolites, trench and accretionary wedge sedimentary assemblages that sometimes form metamorphic soles, as well as dismembered Palaeozoic units. This suture assemblage is in many places covered by Early Cretaceous to Quaternary sedimentary overstep sequences which obliterate the original structural relationships. There is a wide range of opinions about the spreading and closure of the Tethyan domains mostly involving differences in the number of existing oceans, nature of the emplaced ophiolites and age and orientation of the operating subduction (Karamata, 2006; Schmid et al., 2008; Robertson et al., 2009). The interpretation of the type of Mesozoic convergent processes as well as of the nature of the fossil oceanic basins largely depends on the understanding of the units composing this complex suture.

New data on the lithology and deformation history of the Palaeozoic rocks associated with this suture is of great importance because the models of the Tethyan Mesozoic evolution in this region are based on different interpretations of the nature of the Palaeozoic units. In fact, there are views which assume that the Palaeozoic tectonic units represent terranes, i.e. microcontinents, which were separated by areas floored by oceanic crust (e.g., Dimitrijević, 1982; Robertson and Karamata, 1994; Karamata, 2006), and others which propose that during the last convergence/closure events all these Palaeozoic units were parts of the Africa-Adriatic margin (e.g., Schmidt et al., 2008).

It is generally accepted that the Palaeozoic units included in the Tethyan suture in present-day Serbia can be distinguished into Drina-Ivanjica or Golija Units, Jadar Block Unit and Kopaonik Block Unit (Karamata and Krstić, 1996; Dimitrijević, 2001; Karamata, 2006; Hrvatović and Pamić, 2005). Most authors agree that these units have a Gondwana affinity (see Pantić and Dulić, 1991), although there are other opinions as well (e.g., Pamić et al., 1998; Hrvatović and Pamić, 2005). Besides these tectonic units, there are smaller Palaeozoic blocks which occur in between or are detached from the larger ones, such as the Bukulja-Lazarevac or Dičina Palaeozoic Blocks (Fig. 1). In this study we present new evidence on the lithology and biostratigraphy and give a detailed interpretation of deformation patterns of the Palaeozoic rocks of the Bukulja-Lazarevac Unit. We compare their characteristics with those of the rocks of the adjacent Palaeozoic tectonic units using data from the literature. We emphasize similarities in lithology between the Bukulja-Lazarevac and Drina-Ivanjica and Dičina Palaeozoic Units. We further suggest that all the Palaeozoic units in this part of the suture probably underwent similar deformation events and we give a possible geodynamic interpretation.

LITHOLOGY AND BIOSTRATIGRAPHY OF THE BUKULJA-LAZAREVAC PALAEOZOIC (BLPZ) UNIT

The Bukulja-Lazarevac Palaeozoic Unit is located eastwards of the Jadar Block (Fig. 1). It consists of four forma-

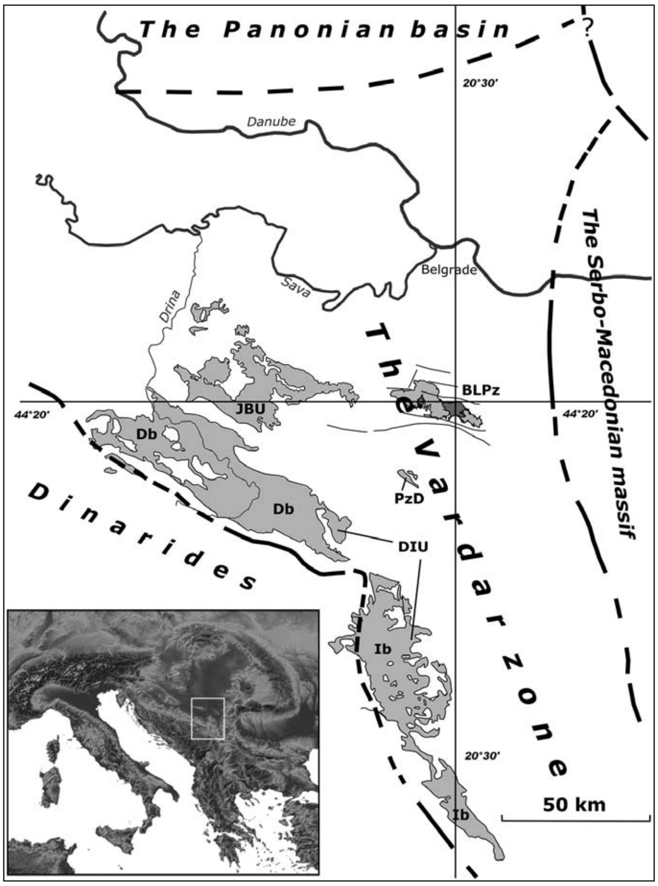

Fig. 1 - Geographic position of Palaeozoic tectonic units of the central Balkan Peninsula.
Abbreviations: BLPz- Bukulja-Lazarevac Palaeozoic Unit; JBU- Jadar Block Unit; DIU- Drina-Ivanjica Unit (Db- Drina Block; Ib- Ivanjica Block); PzD- Palaeozoic of Dičina.

tions differing in lithology and stratigraphic position (Trivić, 1998), namely: Drina Formation, Golija Formation, Formation of Kovilje Conglomerates, and Birač Formation. The whole succession of the BLPz is shown in Fig. 2.

The Drina Formation is a 900 m thick metamorphic series located westwards of the Mt. Bukulja granitoid and it represents the lowermost part of the Bukulja-Lazarevac Palaeozoic Unit. The series consists of metamorphosed clastic and clayish-marly sediments alternating with metamorphosed basic volcanic and volcaniclastic rocks. The age of these rocks is still unconstrained. The rocks of the Drina Formation are conformably overlain by the ~530 m thick Golija Formation, which is composed of metamorphosed clayish and marly arenites with intercalations of shales and siltstones. There are transitions between quartz-, feldspar- and muscovite-rich metaclastites. In the upper part cherts and layered quarz sandstones occur. The Formation of Kovilje Conglomerates is a roughly 100 m thick series of polimict conglomerates predominantly composed of quartz and chert pebbles. They are associated with microconglomerates and arenites usually showing size grading. At many places these rocks occur as 2-4 m thick layers and bands which were tectonically dismembered. The Birač Formation is the most widespread sub-unit in the BLPz. These rocks occur at both sides of the Mt. Bukulja granitoid and in the eastern part they show effects of contact-metamorphism. The lower part of the formation includes fine-grained to medium-grained arenites of variable mineralogical composition. They contain layers and lenses of clayish arenites, shales and siltstones. The presence of *Cadiospora magna* f. *plicata*, Cingulizonates sp., Knoxisporistes sp., and Jugasporites sp., Bisacata palynomorphs has proved a Late Palaeozoic/Carboniferous age of these rocks (Trivić, 1998).

The post-Palaeozoic cover predominantly consists of Early Triassic carbonates, Early Cretaceous carbonates and

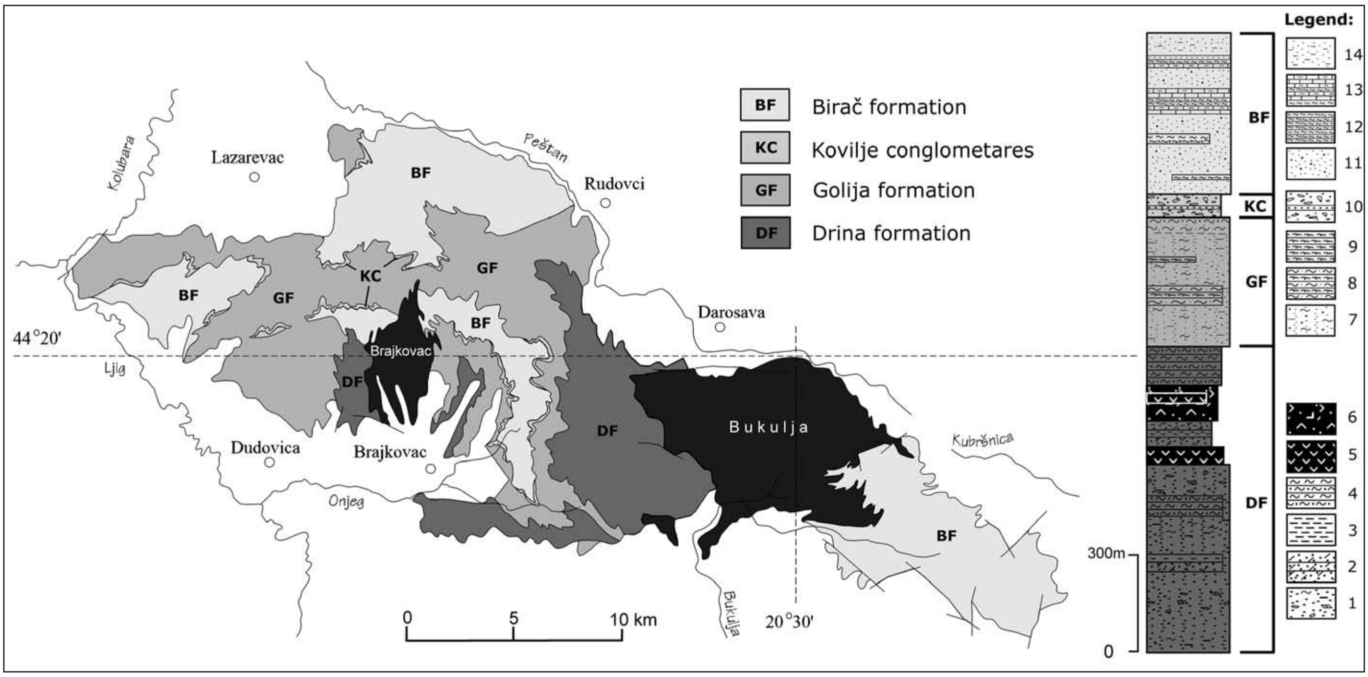

Fig. 2 - Lithostratigraphic succession of the Bukulja-Lazarevac Palaeozoic Unit.
1- arkosic sandstone and clayish-marly rocks; 2- dolomitic and marly arenites; 3- marls; 4- clayish arenites and claystones; 5- diabase and gabbro-diabase; 6- diabase, diabasic volcaniclastics and rocks of spilite-kerathophyre associations; 7- clayish-marly arenites, claystones and marls; 8- clayish arenites with intercalations of chert and siliceous sandstones; 9- cherts; 10- polymictic conglomerates, micro-conglomerates and conglomeratic arenites; 11- arenites; 12- claystones; 13- marly limestone with claystone and limestone layers; 14- clayish arenites.

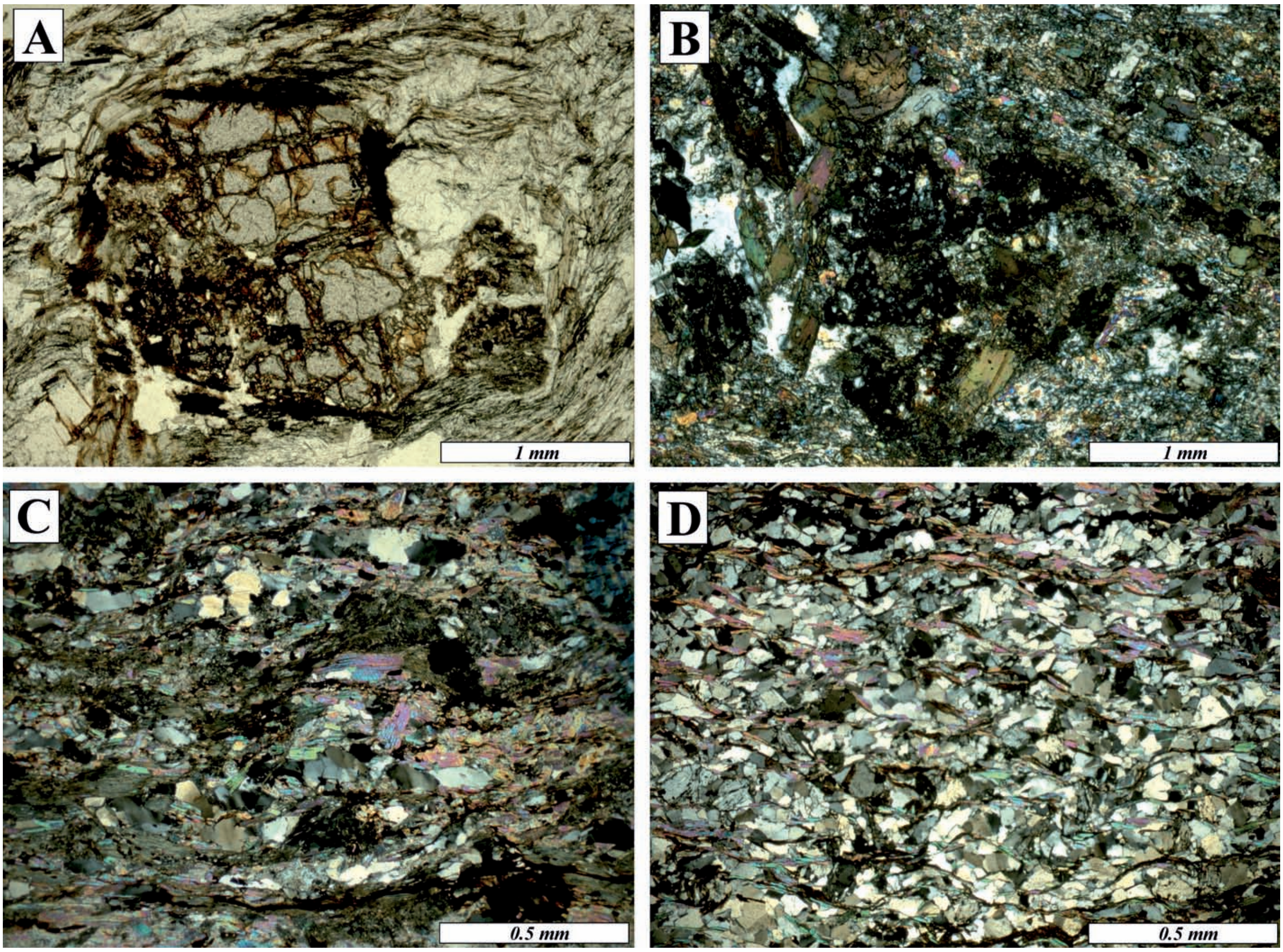

Fig. 3 - Photomicrographs of the Bukulja-Lazarevac Paleozoic metamorphic rocks. A, B) Garnet porphyroblasts in micaschist (A) and amphibolite (B); both garnet prophyroblasts show effects of retrograde transformation into chlorite and/or biotite; note that garnet in micaschist is prekinematic with respect to the present foliation displaying 'pressure shadows' (lower left and upper right part of the photo); plane-polarized light (A) and cross-polarized light (B); C) albite-muscovite-biotite schist without traces of earlier medium to high grade metamorphism; cross-polarized light; D) weakly metamorphosed sandstone from the Birač Formation; cross-polarized light.

psammitic-alevritic sediments, as well as Turonian-Senonian clayish marls and carbonate rocks of flysch type. The central and northern parts of the BLPz are mostly composed of Cretaceous deposits which transgressively overlie older Palaeozoic rocks. On the other hand, in its southernmost part there is a continuous and very narrow zone where Cretaceous sediments are in tectonic contact with Palaeozoic schists. The youngest sedimentary rocks are Middle and Late Miocene and Early Pliocene in age. The Miocene rocks are represented by basal conglomerates (lake sediments), coarse-grained clastic sediments and Sarmatian conglomerates, sandstones and clays, which are transgressively overlain by Early Pliocene coal-bearing clay sandstones.

The rocks of the Bukulja-Lazarevac Palaeozoic Unit are cut by the Tertiary Brajkovac and Bukulja granitoids. The Brajkovac granitoid is poorly known except for it belongs to the suite of Oligocene granitoids of Serbia (Karamata et al., 1992). On the other hand, Cvetković et al. (2007) reported that the Mt. Bukulja pluton is predominantly composed of a two-mica granite emplaced around 20 Ma. The results of this study show that the origin and evolution of the Mt. Bukulja pluton are related to tectonomagmatic events controlled by the early extensional phases during the opening of the Pannonian Basin.

METAMORPHISM

The metamorphic grade in the BLPz generally decreases upwards. The highest metamorphic grade is related to relatively rare garnet-bearing amphibolites and micaschists of the Drina Formation suggesting that these rocks were initially metamorphosed under amphibolite facies conditions. However, these rocks underwent a metamorphic overprint under greenschist to subgreenschist facies conditions that is evident from retrograde reactions on garnet porphyroblasts from both micaschist and amphibolite (Fig. 3A, 3B). Along with these rocks showing evidence of an earlier medium- to high grade metamorphism, also sericite-, albite-, albite-chlorite-, and muscovite-biotite schists occur (Fig. 3C), and also amphibolite schists and fine-grained gneisses that record only greeschist metamorphism. It is most likely that in these rocks the traces of higher grade metamorphism have been completely obliterated.

The rocks overlying the Drina Formation are metamorphosed under greenschist to subgreenschist facies conditions and are represented by alternating sericite schists, albite-chlorite schists, phyllite and muscovite-biotite schists. The rocks occurring within the Kovilje Conglomerate and Birač Formations predominantly consist of weakly metamorphosed metaconglomerates, phyllites, metaarenites (Fig. 3D) and argillaceous schists.

The Tertiary intrusions of Bukulja Mt. and Brajkovac produced contact metamorphic effects that, at some places, overprinted earlier regional metamorphic fabrics of the BLPz rocks. The contact metamorphic rocks appear as medium crystalline kornites, augen gneisses and wollastonite and vesuvian-bearing skarns. These contact metamorphic rocks are beyond the scope of this paper and will not be further addressed here.

Deformation pattern

The age of the metamorphic events in the BLPz Unit is not adequately constrained. Generally, these rocks display two different foliations suggesting that they underwent at least two phases of regional metamorphism (Trivić, 1998). The older foliation is probably parallel to the primary layering and is now represented by tight folds (Fleuty, 1964), while the later foliation formed by plane parallel orientation of mica flakes along the cleavage (Fig. 3A, 3B). Garnet in these foliated rocks is pre-kinematic with respect to the axial plane cleavage and has well developed 'pressure shadows' (Fig. 3A). This implies that the garnet porphyroblasts were rotated along the axial plane cleavage of the earlier generation of folds. Accordingly, we interpret that D_1 and D_2 deformations represent two ductile events that occurred under greenschist to sub-greenschist facies conditions and that postdate a medium to high grade metamorphic phase recorded only in some micaschists and amphibolites found in the Drina Formation.

Ductile deformation patterns from the D_1 and D_2 phases were recognized through careful field observations and measurements in 16 areas that we named as homogeneous structural blocks. We assumed that within these blocks the tectonic overprint caused by the D_3 deformation phase was insignificant. By confining our structural measurements to those homogeneous blocks and avoiding their boundary fault and shear zones, in which the younger brittle tectonic phase produced much higher overprints, we assured that our statistical analyses of fold axes as well as the procedure of reconstruction of the orientation of B_1 axis (see below) are sound.

First deformation phase - D_1

D_1 deformation in BLPz rocks is represented by folding of the primary foliation (S_1). It is marked by plane parallel mica flakes and prismatic minerals and is best developed in albite-chlorite schists, gneisses, micaschists, chlorite-amphibole schists and amphibolites. The relics of the primary foliation are preserved in microlitons and are easier to observe in thin-section than in the outcrop scale, whereas the secondary foliation (S_2) can be seen both at the microscope and in the field.

S_1 foliation developed along the planes of sedimentary layering folded into tight microfolds which were subsequently transformed into shear folds (Fig. 4). D_1 folds are difficult to observe at the mesoscale. For cm-dm and rarely dm-m folds only hinge parts have been preserved because they were transposed along the axial planes. They correspond to isoclinal and oblique folds with subrounded hinges and belong to class 2 (similar folds) and class 3 (Ramsay and Huber, 1987). They have variable vergence - from NW, through N and NE to W and SW. Both axial plane and bedding cleavage were observed as well as quartz rods (R-tectonites). The results of a statistical analysis of S_1 and B_1 for 16 relatively homogeneous blocks are shown graphically in Fig. 5. B_1 axes are dipping around 5-20^o towards E or ESE and SE. Axes dipping to the NW, WSW and S are also present.

Second deformation phase - D_2

The secondary foliation (S_2) is represented by plane parallel mica flakes set along earlier cleavage planes. It is best seen in micaschists, gneiss-micaschists and amphibole schists and can be observed both in thin-section and in the outcrop.

The second generation folds are best observed at the outcrop scale and they were measured in most of the homogeneous structural blocks. These structures appear as m- to dm-scale folds formed on the limbs of the larger fold structures. In the map area, these structures can be recognized as hundreds of meters to kilometer long folds. The results of the statistical analysis of these structures are shown in Fig. 6. The larger folds are open parallel folds with interlimb angles ranging from 130^o to 150^o, with eroded hinge parts and gen-

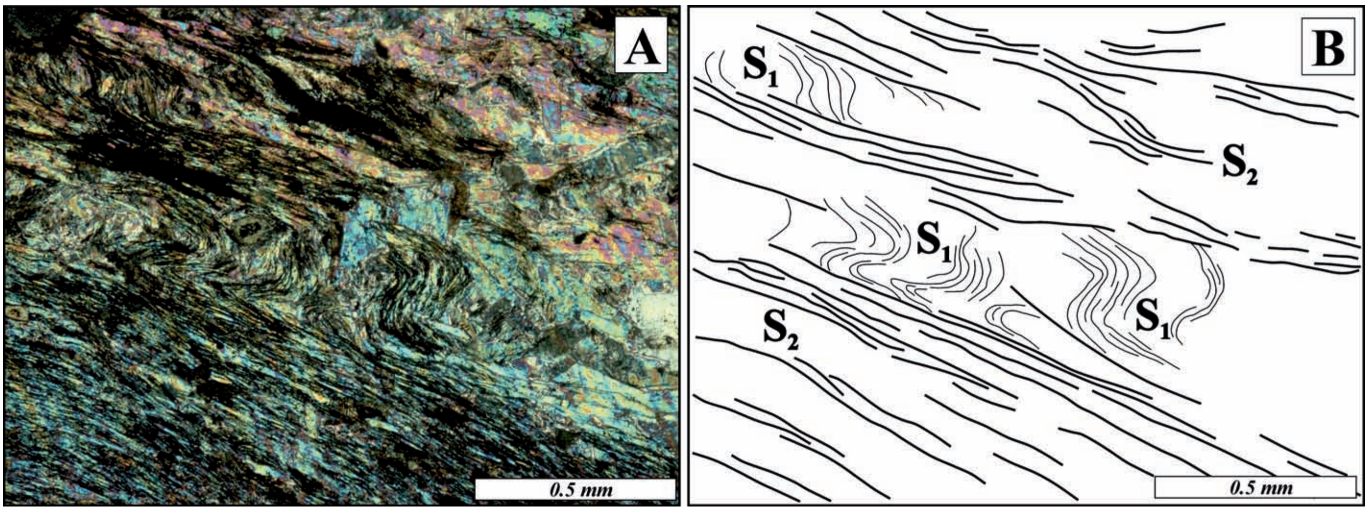

Fig. 4 - A) Photomicrograph (left) showing deformation structures in a micaschist with two planar foliation fabrics, cross-polarized light; B) sketch displaying the folded S_1 and unfolded (in microscale) S_2 foliation.

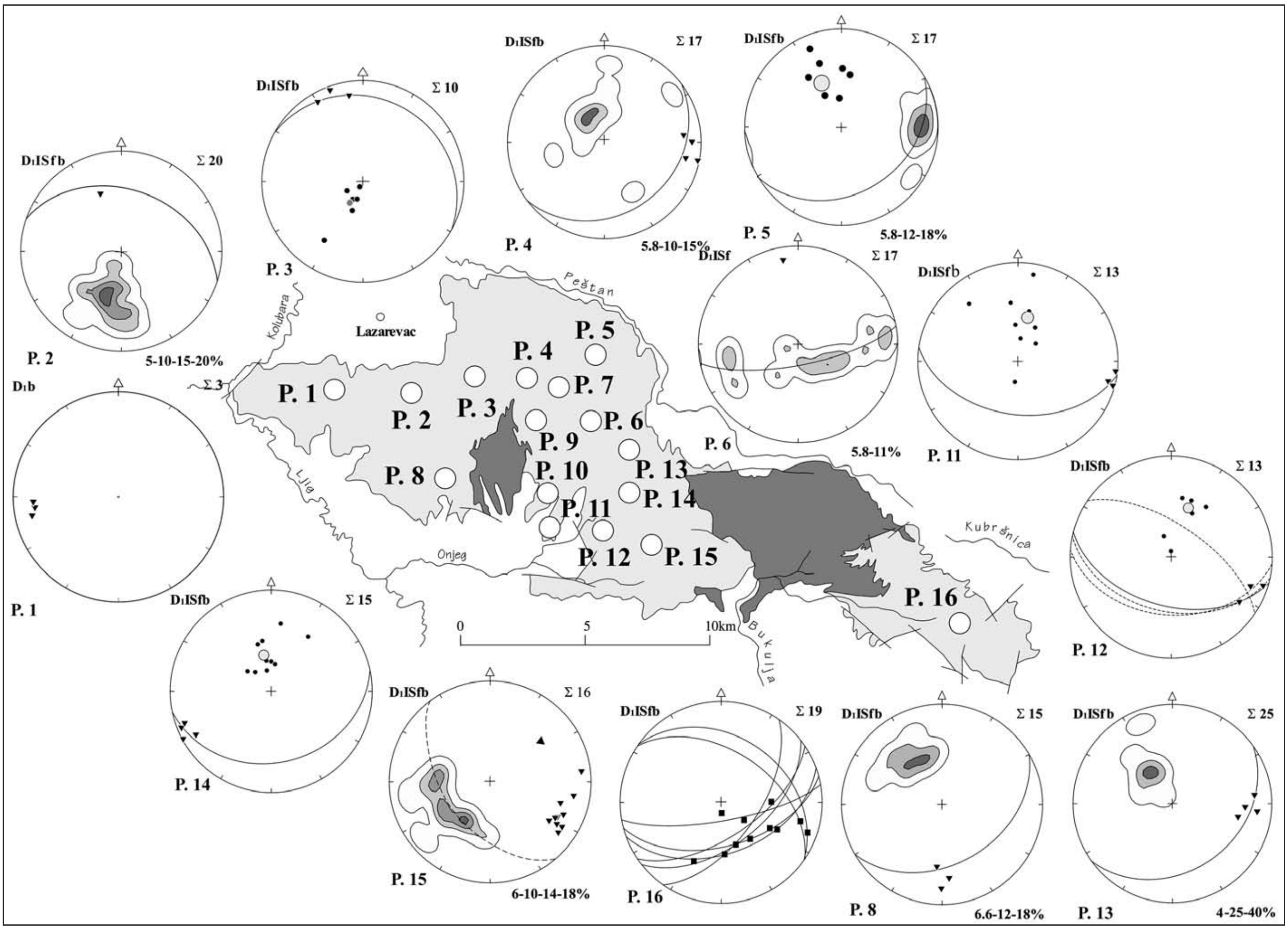

Fig. 5 - Synoptic statistical diagrams of B_1 foliation and axes developed during the D_1 deformation event (outcrop scale).

tly to moderately dipping B-axes. D_2 folds correspond to the 1B class (parallel or concentric folds) according to Ramsay and Huber (1987). In most homogeneous structural blocks these folds are non-planar and non-cylindrical and they are characterized by irregular orientations of B-axes. Statistically, B_2 axes are predominately dipping to the SE and subordinately to NW and SW. At some localities, especially in the area of larger NE-SW dextral regional faults, bending of B_2 axes was observed. As already mentioned, this effect is the consequence of brittle-ductile deformation related to later tectonic events. Similar local irregularities in the orientation of B-axes were found in the vicinity of the Tertiary Mt. Bukulja and Brajkovac granitoid bodies.

A general characteristic of the D_2 phase at the mesoscopic (outcrop) scale is the presence of an intersection lineation between foliation and cleavage. This type of lineation was used as a clue for determining the orientation of folds, especially when the fold hinges were not exposed. Elongation of minerals or mineral associations like stretching lineation, is only locally observed. It is found in amphibolite schists, muscovite-biotite schists and gneisses where this type of lineation represents the finite elongation direction. Directions of the stretching lineation as well as of the foliation-cleavage intersection lineation are roughly parallel to B_2.

An important characteristic of the tectonic pattern in this area is that the angle between B_1 (isoclinal and oblique folds formed during the D_1 deformation phase) and B_2 axes (flexural-slip folds formed during the D_2 deformation phase), in all the relatively homogeneous structural blocks is remarkably uniform and ranges from 35° to 45°. This fact is used as basic evidence for reconstructing the original direction of older (B_1) axes (see below).

On the fold limbs of the first order structures m to dm-sized secondary folds have been observed. They are predominantly asymmetric and oblique, with interlimb angle ranging from 30° to 60°. These secondary folds are congruent, i.e. their B-axis is roughly subparallel to the direction of the regional first-order fold axis. The vergence of parasitic second-order folds of the locally developed axial plane cleavage and the geopetal characteristics of foliation, indicate that they formed simultaneously to the first-order fold structures. In general, changes in characteristics of parasitic folds (Z-, M-, and S-folds) allowed us to predict the location of the hinge area of larger regional fold structures (Van der Pluijm and Marshak, 2004).

Third deformation phase - D_3

The third deformation phase (D_3) is related to tectonic events that affected the earlier folding structures in a brittle fashion. Ductile D_3 structures are only locally found. They are manifested as changes in the regional fold system and can be observed only in the surrounding of the Bukulja and Brajkovac plutons. In these areas subvertical axial planes of D_2 folds are deflected around the plutons (Trivić, 1992). However, the most widespread effect of the D_3 deformation

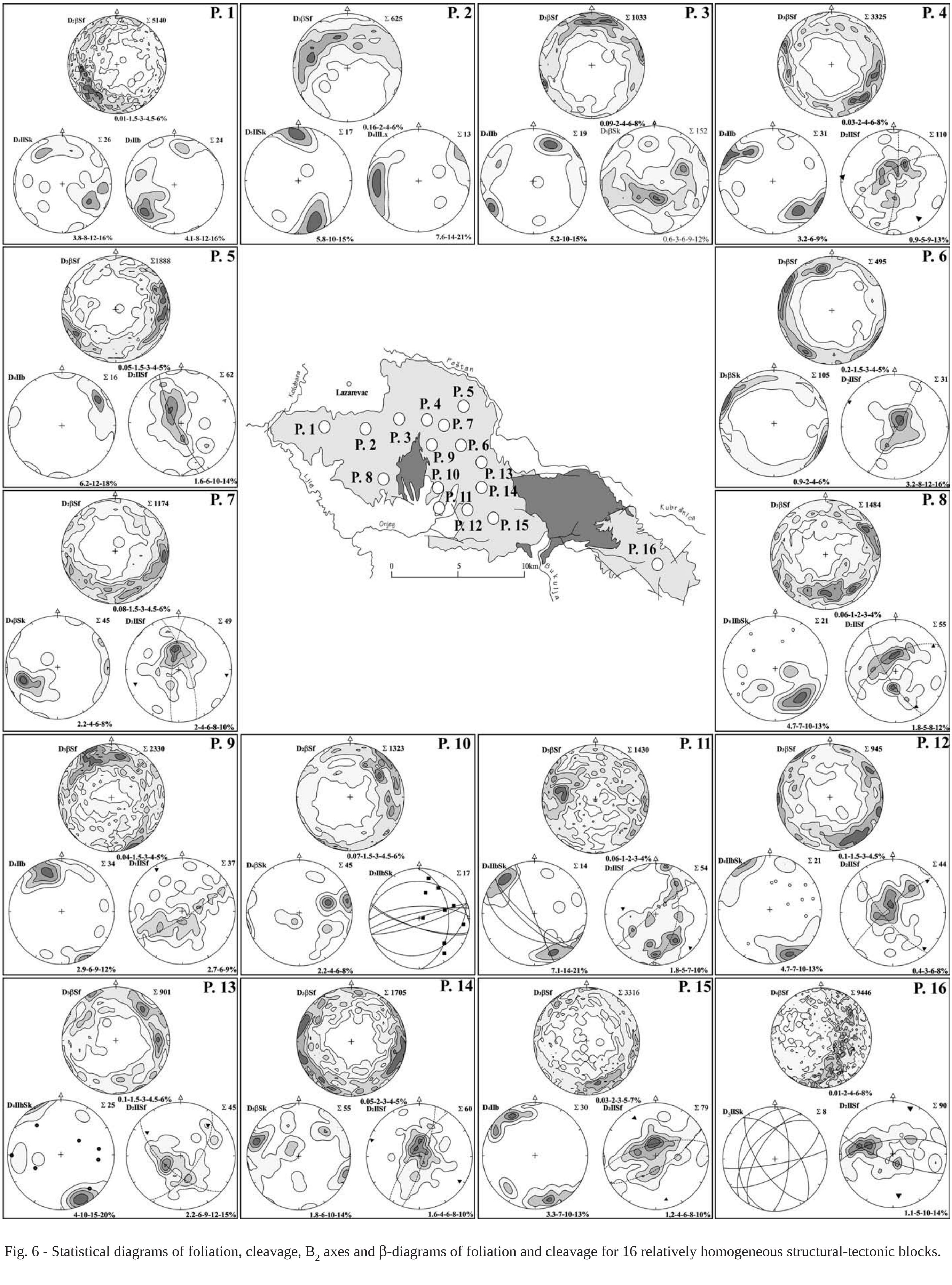

Fig. 6 - Statistical diagrams of foliation, cleavage, B_2 axes and β-diagrams of foliation and cleavage for 16 relatively homogeneous structural-tectonic blocks.

phase was brittle tectonics related to block-faulting and to relative movement along E-W, NNW-SSE and NE-SW fractures. This resulted in E-W striking normal faulting in the vicinity of the northern and southern ridges of the Bukulja Mt. and Brajkovac granitoid bodies, reverse faulting in the easternmost part of the area (NNW-SSE) and dextral strike-slip displacements along the dominant fault system with NE to SW oriented strike (Trivić, 1993).

DISCUSSION

Correlation with other Palaeozoic units - lithology, biostratigraphy and metamorphism

The following correlation is mostly based on a lithological and biostratigraphical comparison. The comparative relationships of the Palaeozoic units are schematically illustrated in Fig. 7.

The Drina-Ivanjica Unit (DIU) consists of the Drina and Golija Formations (Dimitrijević and Djoković, 1979; Djoković, 1985; Milovanović, 1984). The lower part of the Drina Formation consists of metamorphosed arenitic-silty and pelitic rocks with lenses and beds of arenites, siltites, argillaceous rocks and carbonates. They contain phytoplankton remnants and spores indicating Cambrian/Ordovician and Ordovician/Silurian ages, respectively (Ercegovac, 1975). The upper parts of the Drina Formation are composed of arenitic-silty rocks with 10-30 m thick sets of limestones as well as basaltic volcanic rocks. These upper levels contain a Visean/Namurian conodont fauna (Stojanović and Pajić, 1966-71). The Golija Formation is mostly composed of alternating arenites, siltstones and shales of Visean/Namurian age (Stojanović and Pajić, 1966-71). The Kovilje Conglomerate Formation is represented by Early/Late Carboniferous conglomerates and conglomeratic sandstones. The lower parts of the Birač Formation are composed of layered arenites intercalated with thin beds of siltstones and shales, while its upper parts consist of arenites, argillaceous turbidities and bedded limestones. A Late Carboniferous (Bashkirian/Moscovian) age of the Birač Formation is inferred from the presence of a conodont fauna (Kubat et al., 1977).

The grade of regional metamorphism in the DIU decreases from E to W. Djoković (1985) recognized three metamorphic zones of increasing metamorphic grade up to greenschist facies conditions. Milovanović (1984) reported K/Ar ages ranging from 179 to 160 Ma. The same author cited K/Ar ages from 129 to 139 Ma (Lovrić, unpublished data), obtained on phyllites and metabasic rocks that are interpreted as having originated at 350°C and around 5 Kb.

The Jadar Blok (JBU) rocks exhibit weak lithological similarities to BLPz and DIU rocks (Filipović, 1974; Filipović 1995; Stojanović-Kuzenko and Pajić, 1995). The lower sub-complex is Middle Devonian to Early Carboniferous in age. The Middle Devonian series is represented by siltstone and calcirudite that grade to conodont-bearing

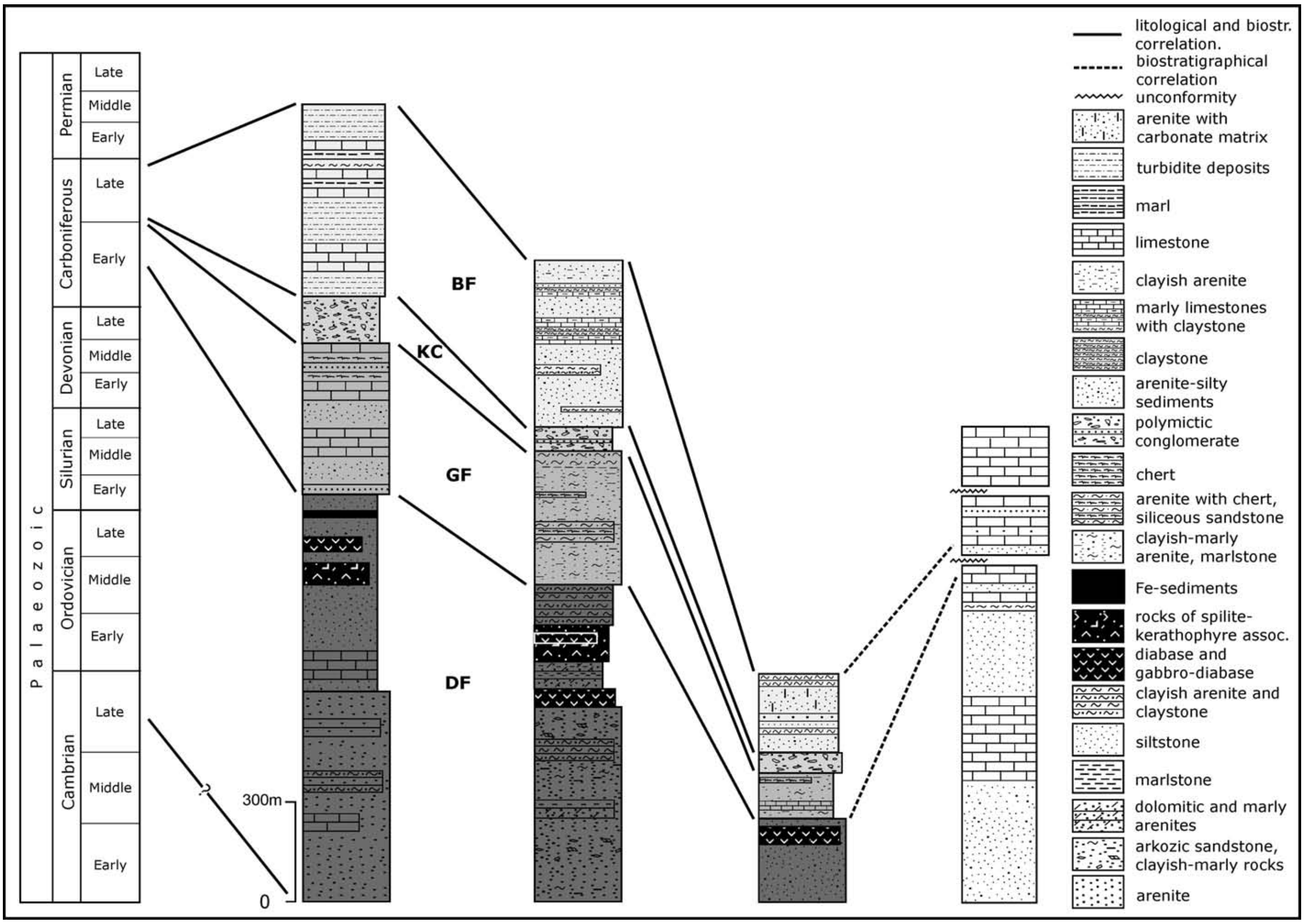

Fig. 7 - Lithological and biostratigraphical comparison between the investigated Palaeozoic units.

sandy limestone and poorly bedded to massive limestone with remnants of crinoids, trilobites, conodonts and ostracods (Filipović et al., 1975; 1993). Late Devonian rocks are clayish schists, siltstones and limestones (mostly micrite, sparite and calcirudite) containing relicts of ostracodes, condonts, goniatites and shells. Allochthonous Devonian sediments are represented by olistoliths of calcirudite and biosparite set in a silty-sandy matrix. Carboniferous sediments occur as arenites, siltstones, clayish schists and cephalopod-bearing limestones. The mentioned subunit is transgressively overlain by the middle sub-complex represented by Late Carboniferous to Early Permian olistostromes and silty limestones. These rocks consist of continental terrigenous deposits whereas the Late Permian rocks are predominantly composed of biosparite limestones. The upper sub-complex includes Middle to Late Permian unconformable silty limestones and carbonate sediments.

The protoliths composing the JBU are weakly metamorphosed, only locally recording greenschist facies conditions. They are represented by phyllites and sericite-chlorite and chlorite schists metamorphosed under temperature conditions not exceeding 300^{o}C. No data on the age of this metamorphism is available.

The Palaeozoic Unit of Dičina (DPz) contains formations equivalent to those composing BLPz and DIU (Gajić, 1996). The Drina Formation (~ 150 m) consists of an alternation of metamorphosed siltstones, alevrolitic sandstones and rare microconglomerates. In the upper part of the formation quartz keratophyres occur, along with blocks of gabbro-diabase and basaltic volcaniclastics, all set in a sandy-silty matrix. These rocks are overlain by a siltstone and sandstone series containing a relatively abundant association of Middle (Early?) Carboniferous palynomorphs (Gajić, 1996). The overlying rocks of the Golija Formation consist of a carbonate-free, arenitic-silty-clayish sedimentary series. The Kovilje Conglomerate Formation is represented by slightly metamorphosed monomict conglomerates containing numerous silty interlayers. They grade upwards to microconglomerate and coarse-grained sandstone. The Birač Formation consists of an alternation of arenitic sandstone, siltstone and clay.

Similarly to DIU and BLPz rocks, the DPz rocks are medium-grade weakly metamorphosed only locally reaching greenschist facies conditions. They are transformed into albite-sericite schist, chlorite-sericite schist, amphibolite schist, metasandstone and metasiltstone.

In summary, there is an apparent analogy among BLPz, DIU and DPz with respect to lithology and metamorphism. However, the sediments of the Drina Formation are much thicker in the DIU than in the DPz, while the Birač Formation of the DPz does not contain limestones as observed in the Birač Formation of the DIU. On the other hand, the following similarities between BLPz and JBU are remarkable: (i) Middle Permian sediments begin with white quartz sandstones overlain by variously colored arenitic-siltstones and a series composed of dolomites and schists, (ii) Late Permian rocks are represented by fossil-bearing bituminous limestones, and (iii) Permian sediments are overlain by Triassic carbonates and carbonate-terrigenous deposits. Although Triassic sediments overlie Palaeozoic rocks of both DIU and JBU, two Early Triassic rock types can be distinguished. Triassic sediments overlying DIU are composed of siliciclastic rocks whereas in BLPz (as in other Palaeozoic terrains) they are mostly overlain by carbonates. Middle Triassic and younger sequences have similar characteristics in all Palaeozoic terrains.

Correlation with other Palaeozoic units - deformation style

There is a general lack of new data on the Palaeozoic rocks of the central Balkan Peninsula. Furthermore, the structural geology and deformation history of these Palaeozoic units were treated with different methodology. Whereas a classical structural analysis on relatively homogeneous blocks has been performed on the Drina-Ivanjica Unit (Djokovič, 1985), for the Dičina and Jadar Palaeozoic rocks only few data exist (Gajić, 1996; Filipović, 1974; Pešić, 1982).

The Drina-Ivanjica Unit is divided into two structural-tectonic blocks, namely: Drina and Ivanjica Blocks. This division was originally based on the palaeo-transport direction that strikes NE-SW and E-W in the Drina and Ivanjica Blocks, respectively (Djoković, 1985). These two blocks share similar fold styles, deformation conditions and most probably time of folding, but differ with respect to the B-axis statistic directions.

The first generation folds (according to Djoković, 1985, Variscan in age) are represented by planar cylindrical folds with monoclinal symmetry. They are isoclinal and were to a great extent destroyed during transpositions and permutations. According to morphometric characteristics, this generation of folds corresponds to the D_1 structures of the BLPz. The orientations of axes in the Drina Block are dispersed with a general dip to SSW and to NNE, locally to SW and N. B_1 axes of the Ivanjica Block also yield variable dip directions. The D_2 deformation event produced planar cylindrical open structures with subvertical axial planes. According to their dimensions and mode of occurrence in the field they are similar to B_2 folds in the BLPz. The fold axes are gently dipping to ESE (120^o) and S (about 170^o) in the Drina and Ivanjica Blocks, respectively. The angle between D_1 and D_2 structures is different in the two blocks and ranges between 50-70^o (locally even 90^o) and 30-60^o for the Drina and Ivanjica Block, respectively. Along the longitudinal fractures reverse and left gravitational displacements predominate, while in the later deformation phases dextral strike-slip and normal faulting occurred as well. This group of structures bears many characteristics of the D_3 brittle phase of the BLPz.

The oldest fold fabric in the Jadar Block Unit consists of dm- to m-sized folds. They are only rarely preserved in metasandstone and metasiltstone and are also strongly overprinted by later folding (Pešić, 1982). The orientation of B_1 axes is not uniform: they dip to NE, NW and SW. The large scale tectonic fabric is mostly represented by decakilometer-sized, SE-NW and SE dipping fold structures. They belong to the second generation of folds, D_2, which are open with interlimb angles around 150°. The angles betwen B_1 and B_2 axes have a wide range (40-115°), with predominant value of approximately 90°. The youngest structures belonging to the D_3 deformation phase are oriented transversally to the earlier ones and are confined to the areas adjacent to strike-slip faults.

The Palaeozoic of Dičina is characterized by older, isoclinal folds of metric scale, with NE-SW stretching fold axes (Gajić, 1996). The younger structures are kilometers in length, with interlimb angles of approximately 35°. These folds are also characterized by sub-vertical axial planes and a statistical B_2 axis gently dipping to SE.

Reconstruction of the original direction of B_1

Evidence of a pre-D_1 event characterized by medium to high grade metamorphism has only been found in the Drina

Formation of the BLPz. However, this metamorphism did not leave behind fold structures that could allow to distinguish a separate deformation phase. In this context, the D_1 and D_2 events are the only phases of truly ductile deformation that were recorded in the investigated Palaeozoic areas. D_1 structures were observed in thin-section in the BLPz and DIU. In the latter unit this phase can also be detected in outcrop, whereas in the JBU these structures are observed exclusively in the field. D_1 structures usually occur as relics of the primary foliation represented by tight, isoclinal folds formed first by flexural slip folding and later on by shearing along the axial plane cleavage that they transform to shear folds.

The original direction of B_1 axes can be reconstructed by performing rotations of their measured directions around the statistical directions of the younger B_2 fold axes. This method is based on the fact that, in case of flexural folding, the original angle between the fold hinge (B_2, D_2) and the lineation as well as older axes (B_1, D_1), does not change during folding. In order to determine whether the plot of a deformed lineation lies in a small circle it is necessary to rotate the fold axes (along with the lineation data) until it is horizontal (Price and Cosgrove, 1990). If a lineation occurs on the limb of a non-plunging fold, the calculation of pre-tilt orientations is relatively easy. The plane on which the lineation occurs is restored to its preserved horizontal attitude by rotating it through an angle equal to its plunge around plane strike (rotational axis). The lineation is rotated passively along with the plane. On the other hand, if the fold is plunging, the unfolding procedure is more difficult. In such case, a two-stage procedure is used: first, the plunging axis of the fold is rotated to horizontal and second, the limbs are rotated around this new horizontal axis. Finally, this results with horizontal new limb positions which carry on the lineation (or B_1 older fold axis), are passively rotated along with the limbs (Marshak and Mitra, 1988). A graphical presentation of this procedure is shown in Fig. 8.

The procedure of reconstruction of the B_1 axis position in the Palaeozoic terrains of Serbia included two steps. The first one involved the presentation of statistical B_1 and B_2 axes as poles on diagrams. As already mentioned, only data obtained from the areas situated far away from the shearing zones were used for the statistical analysis. B_1 axes situated on the overturned layer were differently marked. In such a way, the statistical axes (both B_1 and B_2) represented a trend of measured axes on relatively homogeneous areas. The second step was to rotate B_1 axes around B_2 axes. By such rotations, the original strike and dip angle of the B_1 axes were determined. The rotations were made to the closer or farther periphery of the diagram, depending on weather the older statistical axis was measured on normal or overturned layers. The procedure was first applied to BLPz and than analogously to other Palaeozoic units discussed here.

The results, which also took into account whether the B_1 axes were measured on normal or overturned fold limbs, are graphically shown in Fig. 9. They reveal that in the BLPz the B_1 folds axes were originally oriented E-W, implying formation under N-S directed stress (Fig. 9b). In the DIU there are differences with respect to Drina and Ivanjica Blocks, which have NE-SW and E-W trends of the B_1 axes, respectively (Fig. 9c, 9d). The rotation procedure in the JBU showed that the oldest axes were originally oriented NE-SW (Fig. 9a), whereas the available data for the Palaeozoic rocks of Dičina were not sufficient to apply the same method.

The obtained results imply that the B_1 axes in the Drina Block of DIU and Jadar Block have the same primary orientations, striking NE-SW. The Ivanjica Block of DIU and BLPz Units are characterized by E-W oriented B_1 structures. If the Ivanjica Block of DIU along with the BLPz Unit rotated anticlockwise around a vertical axis, as already suggested by Djoković (1985), then their older axes would have the same direction as the axes in other Palaeozoic terrains (Fig. 10). This assumed rotation could have been related to post-Cretaceous geodynamic events.

SUMMARY AND GEODYNAMIC IMPLICATIONS

The results presented here suggest that there is similarity in lithology and deformation patterns exhibited by metamorphic rocks of different Palaeozoic units in the central Balkan Peninsula. The rocks of BLPz are similar in lithology and metamorphic grade to the Palaeozoic rocks of Drina-Ivanjica and Dičina, whereas the Jadar Block rocks show differences. It is generally accepted that the stratigraphy of the Jadar Block Unit is similar to that of the Palaeozoic Sana-Una and Kordun-Banija Units and to the Palaeozoic of the Bükk Mts. in Hungary (Csontos, 1999; Filipović et al., 2003).

The study of deformation imply that all the Palaeozoic units underwent two recordable ductile tectonic events re-

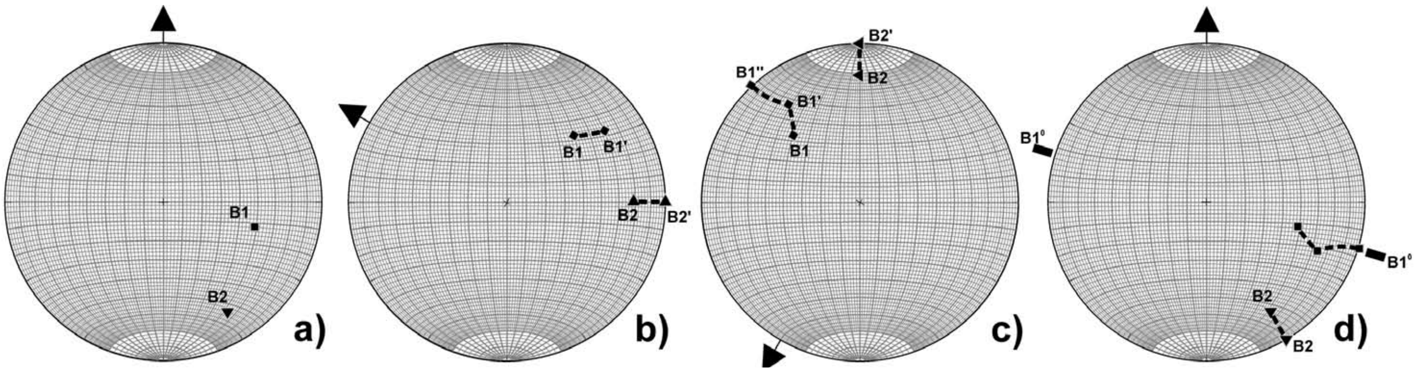

Fig. 8 - Rotation diagrams around an oblique axis: a) present position of older B_1 and younger B_2 axes, b) translating B_2 axis into a horizontal position, and rotating B_1 axis for a dipping angle in the same sense, c) rotation around B_2 axis depending on whether B_1 axis was measured on normal or overturned fold limbs (figure shows B_1 axis on a normal fold limb, and d) preexisting direction of B_1 axis after moving transparent into original position.

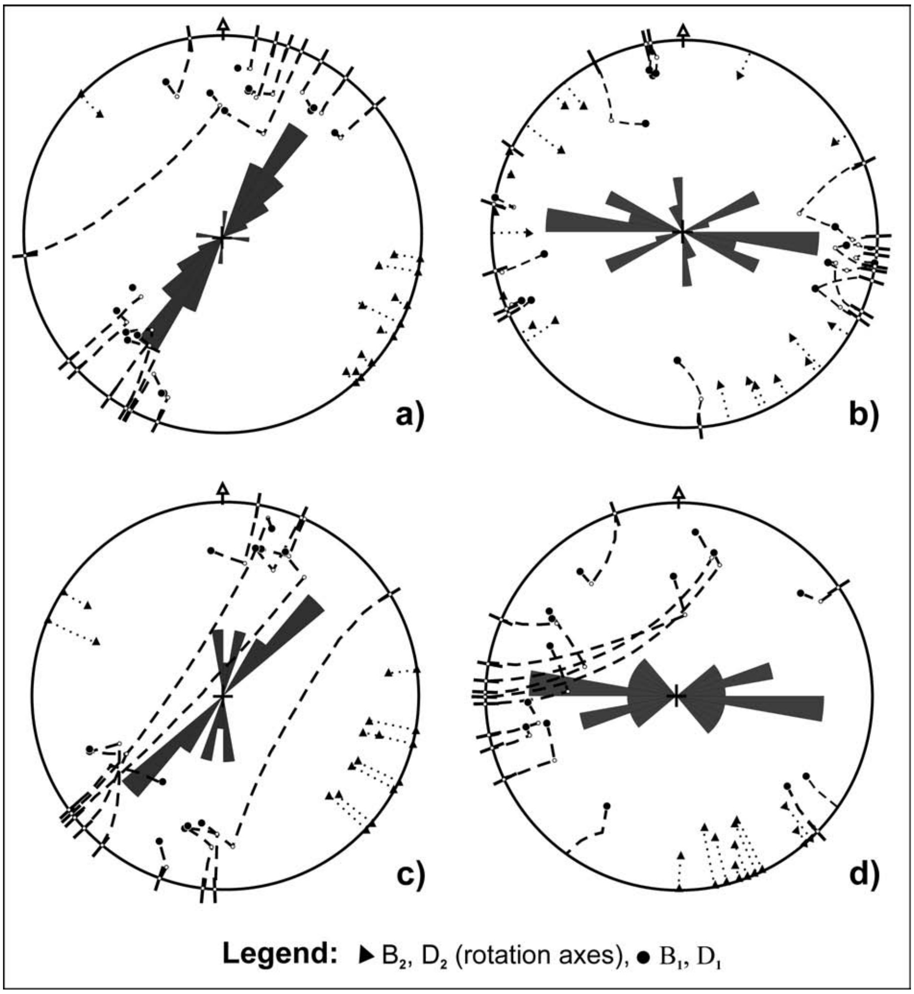

Fig. 9 - Results of rotation of B_1 around B_2 axes with rose diagrams which show the statistical direction of reconstructed B_1 axes: a) Jadar Block, b) Bukulja-Lazarevac Palaeozoic Unit, c) Drina-Ivanjica Palaeozoic Unit - Drina Block, and d) Drina-Ivanjica Palaeozoic Unit (Ivanjica Block).

sulting in small-scale isoclinal and oblique folds with subrounded hinges (B_1 axes dipping around 5-20^o towards E or ESE and SE) and m- to dm-sized folds formed on the limbs of the larger fold structures (B_2 axes dipping to SE, subordinately to NW and SW). The reconstruction of the original position of B_1 axes suggests that B_1 axes in the northern part of DIU (Drina Block) and JBU have the same primary orientation, striking NE-SW. The southern part of the DIU (Ivanjica Block) and BLPz Units are characterized by E-W oriented B_1 structures.

The age of the D_1 and D_2 events cannot be unequivocally constrained. The only radiometric data available for DIU rocks indicate that both deformation events could have been post-Variscan. If this assumption is true, then amphibolite facies metamorphism, which is recorded in some rocks of the BLPz Drina Formation, can be Variscan (or older?) in age.

There are two general opinions regarding the nature of Palaeozoic tectonic units in this part of SE Europe. They are considered: (i) as microcontinents/terranes that rifted from Adria (part of Gondwana) (Dimitrijević, 1982; Robertson and Karamata, 1994; Dimitrijević, 2001; Robertson et al., 2009), or (ii) as integral parts of Adria, i.e. its NW marginal areas, and their present relationships would have been obtained during post-Jurassic out-of-sequence napstacking (e.g., Bernoulli and Laubscher, 1972; Smith and Spray, 1984; Bortolotti et al., 2004; Bortolotti and Principi, 2005; Schmidt et al., 2008). The results reported here argue in favor of the latter interpretation because they show a lithological and deformation similarity among the studied units. The reconstructed directions of B_1 fold axes might imply that these structures formed under a single stress regime, i.e. under NW-SE compression. This would have been difficult to achieve if these units represented different terranes with different palaeogeographic positions (Djoković et al., 1995). However, to elaborate this interpretation it is necessary to have more information about the age of the studied deformation events.

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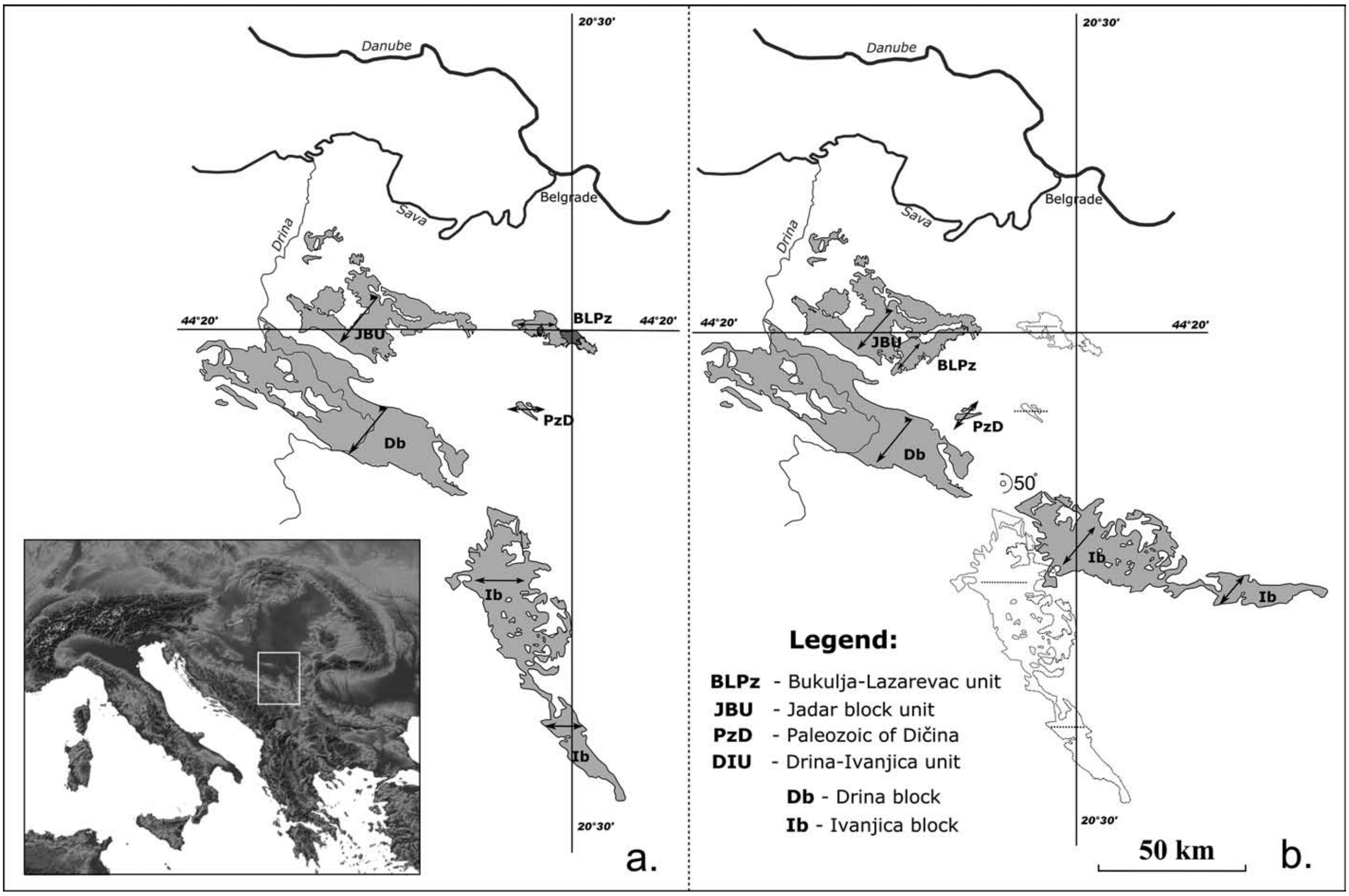

Fig. 10 - Simplified geotectonic sketch showing possible rotations inferred from reconstruction of the original B_1 direction: a) recent position of Palaeozoic units, b) position of the units before rotation.

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