

Internal structure of the Supragetic Unit basement in the Serbian Carpathians and its significance for the late Early Cretaceous nappe-stacking

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Abstract. Fault-related folds and hanging-wall structures reflect the geometry of the main thrusts in fold-thrust belts. The results of the structural analysis of the Supragetic Unit metamorphic basement in eastern Serbia at map-, outcrop- and thin-section scale, and its importance for the late Early Cretaceous nappe-stacking are presented in this paper.

The Supragetic Unit metamorphic basement includes various volcano-sedimentary rocks of Ordovician-Silurian protolith age. They were metamorphosed to the low greenschist facies with temperatures reaching 300–350°C and pressure reaching 0.3–0.5 GPa. The microscale studies show that quartz and albite demonstrate dominantly bulging and locally subgrain rotation recrystallisation, while chlorite, sericite and muscovite define spaced to continuous foliation recognised both at the outcrop- and the thin-section-scale. The statistical analysis based on the available map data shows low- to high-angle west-dipping foliation which is interpreted as an indicator of flat-ramp geometry of the Supragetic thrust, rather than east-vergent tight to isoclinal folding. At the thin-section scale ductile to semi-ductile C'-S structures indicate top to ESE thrusting. Subsequent kinking, recognised both at the outcrop- and the thin-section-scale, deform the older foliation. Those kink bands are the result of WNW–ESE to NW–SE compression and could represent the later stage of a continuous deformation event during which C'-S structures were formed. The youngest, brittle deformation is represented by subvertical joints with no offset recognised in thin-sections.

The structural characteristics of the Supragetic Unit low-grade metamorphic basement in the studied areas, combined with tectonothermal events recognised elsewhere in Dacia mega-unit, could imply a possible initiation of the late Early Cretaceous nappe-stacking in the ductile to semi-ductile/semi-brittle domain.

Key words: structural analysis, flat-ramp geometry, Supragetic Unit, late Early Cretaceous thrusting

Апстракт. Набори везани за раседање и структуре у повлатном блоку, изнад површи навлачења, рефлектују геометријске карактеристике главних навлака у наборно-навлачним појасевима. У овом раду су представљени резултати структурне анализе метаморфне основе Супрагетикума у источној Србији, изведене у размери карте, изданка и микро-препарата, и значај структура различитог реда величина за реконструкцију доњокредне еволуције навлака.

Метаморфна основа Супрагетикума укључује различите вулканогено-седиментне стене чији су протолити ордовицијумске до силурске старости, метаморфисане у фазији зелених шкриљаца на температурама око 300–350°C и притисцима од 0,3–0,5 GPa. Микроскопска проучавања указују да су кварц и албит доминантно прекристалисали по “bulging” типу и са локалном ротацијом суб-зрна, док хлорит, серицит и мусковит дефинишу пенетративну фолијацију препознатљиву и на изданцима и у микропрепаратима. Статистичка анализа заснована на доступним подацима са геолошких карата, указује на фолијацију која благо до стрмо пада ка западу што је интерпретирано као индикатор “flat-ramp” геометрије супрагетске навлаке, много вероватније него као источно-вергентни тиснути до изоклини набори. У микропрепаратима дуктилне до семи-дуктилне C'-S структуре указују на навлачење

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ка исток-југоистоку. У наставку деформација у семи-“brittle” домену су развијене “кинк” структуре, препознате на изданцима и у микропрепаратима, по којима је деформисана старија фолијација. Те “кинк” зоне су резултат запад-северозапад-исток-југоисточне до северозапад-југоисточне компресије која може представљати касније етапе у континуираном деформационом догађају током којег су формиране и С'-S структуре. Најмлађе, “brittle”, деформације су представљене субвертикалним пукотинама без видљивих смицања у микропрепаратима.

Структурне карактеристике нискометаморфне основе Супрагетикума у проучаваним областима, у комбинацији са тектонотермалним догађајима препознатим у другим деловима Дакијске мега јединице, могу да указују на потенцијалну иницијацију касно доњокредног навлачења у дуктилним до семи-дуктилним/семи-“brittle” условима.

Кључне речи: структурна анализа, “flat-ramp” геометрија, Супрагетикум, касно доњокредно навлачење.

Introduction

The highly curved Carpatho-Balkan orogenic system was formed during the polyphase Alpine tectonic evolution. The initial nappe-stacking in the South and Serbian Carpathians segments started during the late Early Cretaceous (CSONTOS & VÖRÖS, 2004; SCHMID et al., 2008). A lot of studies about the kinematics of brittle structures postdating the formation of regional nappe system of Carpatho-Balkanides (i.e. Late Cretaceous to recent times) were published (LINZER et al., 1998; ZWEIGEL et al., 1998; MATENCO & SCHMID, 1999; MATENCO & BERTOTTI, 2000; GIBSON, 2001; KOUNOV et al., 2011; MLADENVIĆ et al., 2014).

The late Early Cretaceous nappe-stacking resulting in ductile deformations was researched in Western Bulgaria (KOUNOV et al., 2010). The same tectonic event was also recognised in tectonothermal studies conducted in other parts of the orogen (BOJAR et al., 1998; GRÖGER et al., 2013; ANTIĆ et al., 2016).

The aim of this study is to constrain the internal structure of the Supragetic Unit basement of Serbian Carpathians (Caraş group of IANCU et al., 2005b; Caraş terrane of BALINTONI et al., 2009 and BALINTONI et al., 2014) and to estimate its significance for the late Early Cretaceous nappe-stacking in terms of the geometry of the regional thrusts and crustal levels in which the thrusting occurred.

Geological settings

The most prominent tectonic unit of the Eastern and Southern Carpathians, the Dacia Mega-Unit (sensu SCHMID et al., 2008) was built of various nappes, of which the Supragetic-Getic system (KRÄUTNER & KRSTIĆ, 2002; SCHMID et al., 2008) was formed during the late Early Cretaceous nappe-stacking. Those two nappe-sequences are in contact along the complex, high-offset thrust, along which metamorphic basement of the Supragetic Unit is thrust on the top of Getic sedimentary cover (KALENIĆ & HADŽI-VUKOVIĆ, 1973; SCHMID et al., 2008).

In the Serbian Carpathians segment of the Carpatho-Balkanides Mts., the Supragetic nappe is mostly covered with Miocene to Quaternary sediments of the Velika Morava Corridor (i.e. the southern prolongation of the Pannonian Basin), but it crops out in three regions (Fig. 1) - between the towns of Golubac, Petrovac and Kučevo, north of Despotovac, and southwest of Paraćin. This study is focused on the northernmost of the three regions, on the areas of Golubac (Fig. 2) and Kučevo (Fig. 3). These areas were chosen for this research due to the great number of the available outcrops and evident and not overprinted structural contact between the Supragetic and the Getic Units.

Generally, the Supragetic Unit is represented by low-grade metamorphic basement and the Late Paleozoic to Mesozoic sedimentary cover (Fig. 4; IANCU et al., 2005a). In the studied areas, the Supragetic Unit metamorphic basement includes a thick series of metamorphosed volcano-sedimentary rocks with the protolith age interpreted as Ordovician-Silurian (IANCU et al., 2005b, and references therein). The lowermost outcropping sequence of the basement is represented by chlorite schists with albite and epidote intercalated with quartz-sericite-chlorite schists and marbles. This sequence is covered with the first horizon of quartzite and quartzite conglomerates. Stratigraphically higher volcano-sedimentary sequence includes sericite schists, sericite phyllites, sericite quartzites, sericite-chlorite schists and marbles, overlain by the second quartzite horizon. Acidic metavolcanics, metapelites and metasammities represent the third metamorphic sequence that is also overlain by the third quartzite horizon. The highest outcropping metamorphic sequence of the Supragetic Unit basement includes metaconglomerates, metasandstones, sericite schists, and metadolerite. Devonian volcano-sedimentary rocks cover a very small area and are not significant for the regional geological settings of the Supragetic Unit. The Late Paleozoic sedimentary cover consists of the Late Carboniferous transgressive coal-bearing clastic rocks and Permian shallow-water marine to fluvial red sandstones (Fig. 4, KALENIĆ et al., 1980). The Mesozoic sedimentary cover is relatively thin, has a limited surface extension and is not preserved in the studied areas.

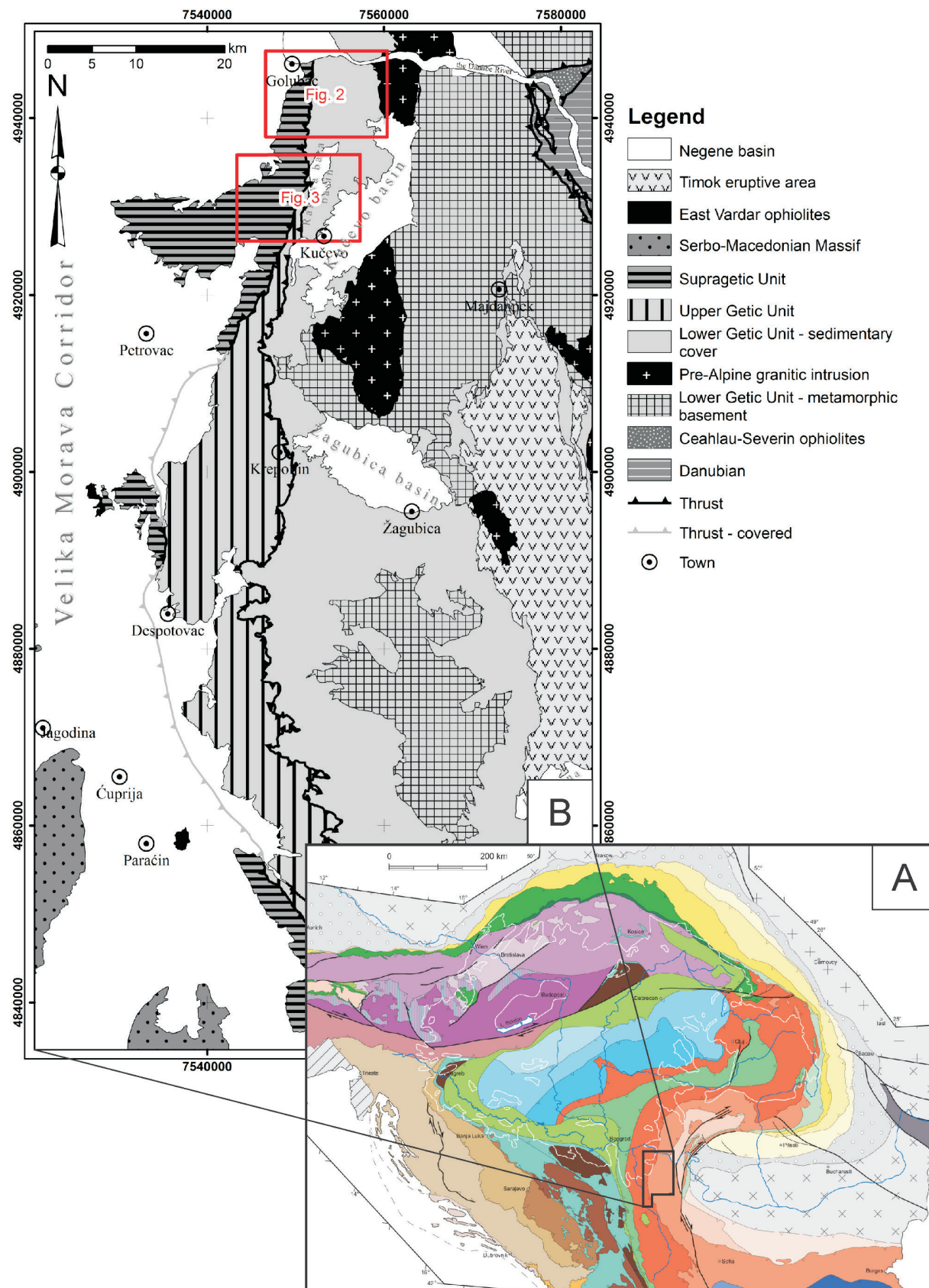


Fig. 1. **A.** Regional tectonic map of the studied area. The black polygon indicates position of Fig. 1B (modified after SCHMID et al., 2008). **B.** Tectonic map of the internal Serbian Carpathians with positions of the studied areas (red rectangles) presented in Fig. 2 and Fig. 3. The map projection is WGS 1984 Transverse Mercator (modified after KRÄUTNER & KRSTIĆ, 2003).

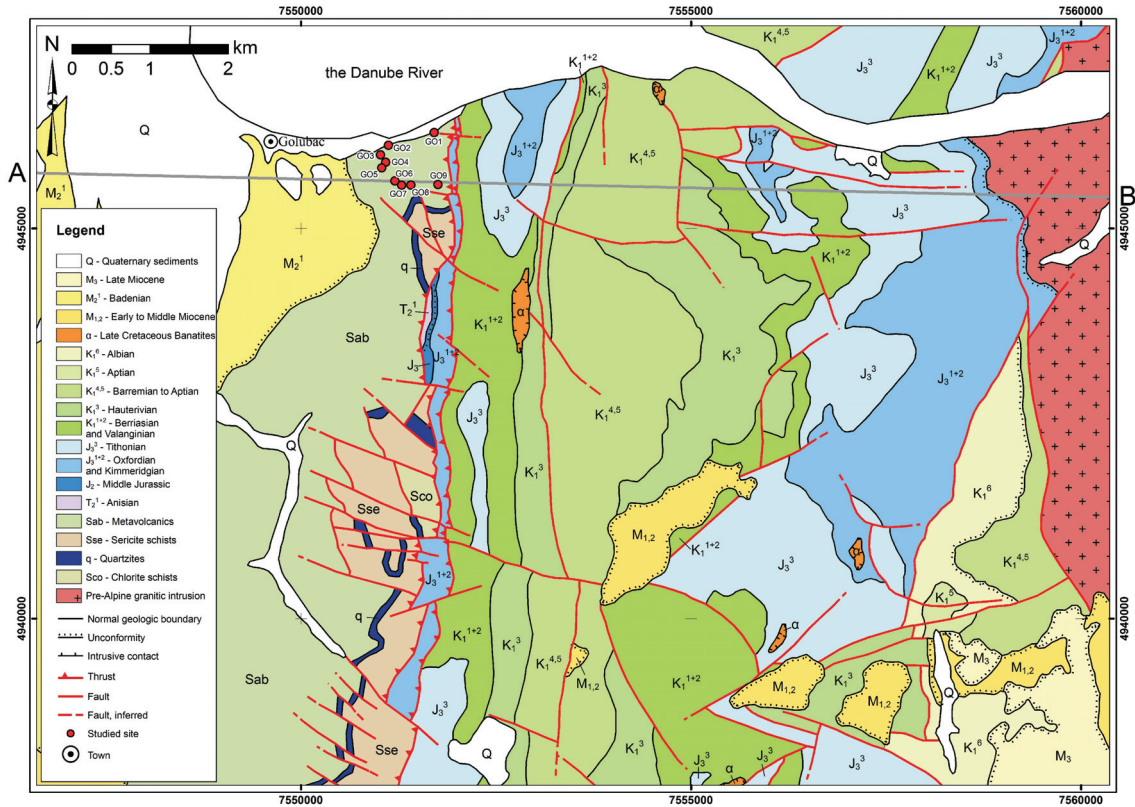


Fig. 2. Geological map of the Golubac area. The gray line represents the cross section A-B in Fig. 5. The map projection is WGS 1984 Transverse Mercator (modified and simplified after KALENIĆ & HADŽI-VUKOVIĆ, 1973).

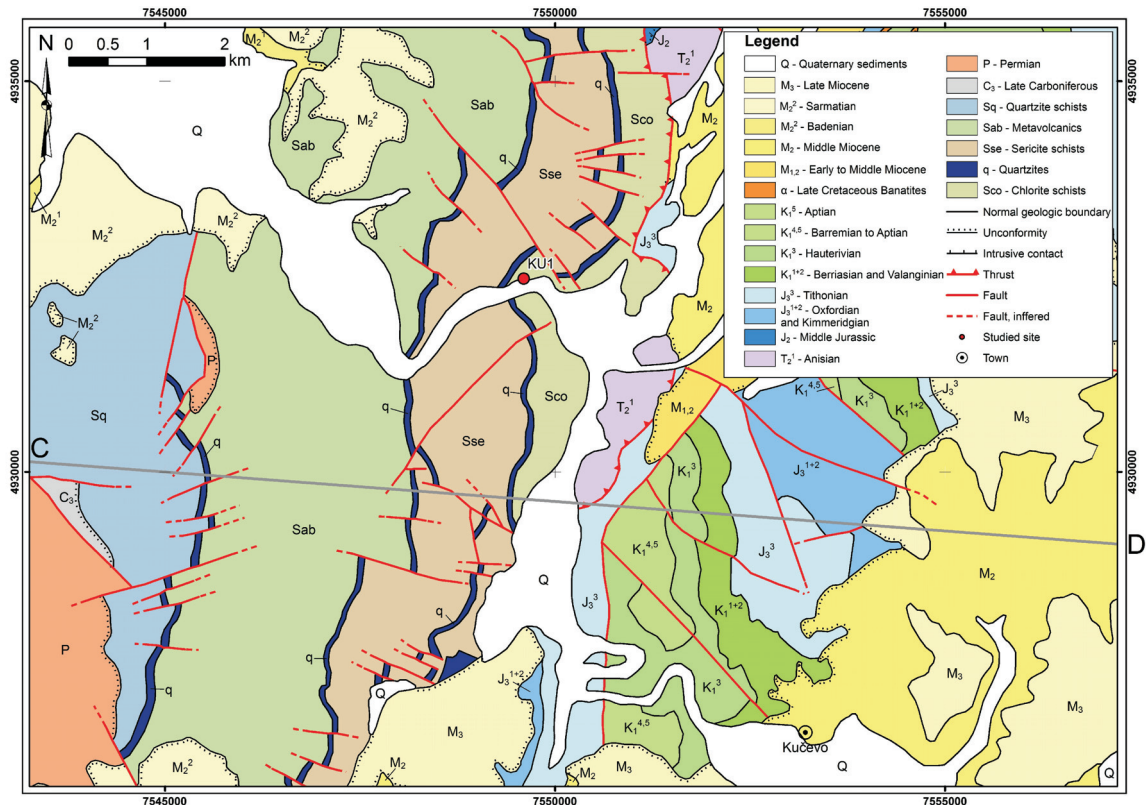


Fig. 3. Geological map of the Kučevo area. The gray line represents the cross section C-D in Fig. 5. The map projection is WGS 1984 Transverse Mercator (modified and simplified after KALENIĆ & HADŽI-VUKOVIĆ, 1973).

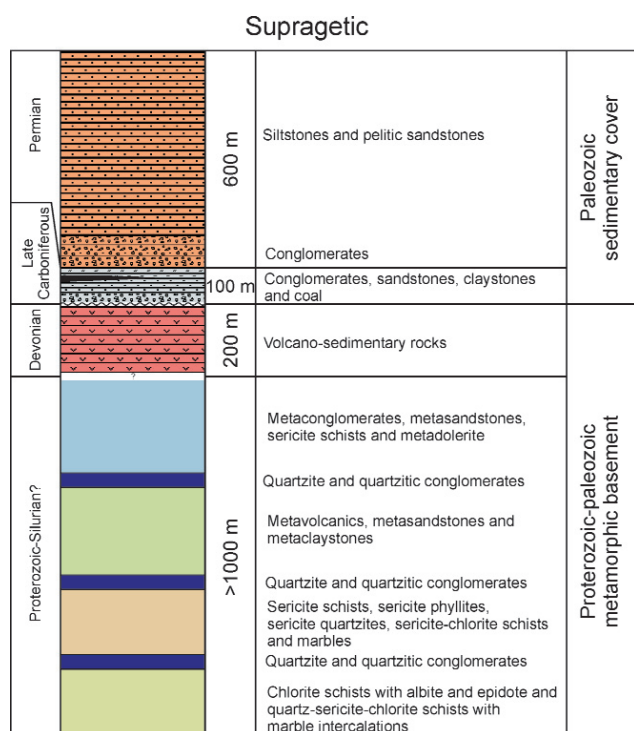


Fig. 4. Geological column of the the Supragetic Unit in the the studied areas (modified after KALENIĆ & HADŽI-VUKOVIĆ, 1973 and KALENIĆ et al., 1980).

The Upper and Lower Getic units, the parts of the Getic nappe system, are located structurally below the Supragetic Unit (Fig. 5). They are represented by the high-grade to low-grade metamorphic basement and the Permian to Late Cretaceous sedimentary cover (i.e. KALENIĆ & HADŽI-VUKOVIĆ, 1973; KRÄUTNER & KRSTIĆ, 2003; IANCU et al., 2005a; IANCU et al., 2005b). The Permian sediments of the Getic nappe sequence do not outcrop in the studied areas and their position in the cross sections (Fig. 5) is interpreted based on their surface exposure south of the studied areas (ATONIJEVIĆ et al., 1963; VESELINOVIĆ et al., 1964; KALENIĆ & HADŽI-VUKOVIĆ, 1973).

The Early Miocene to Quaternary sedimentary cover is represented by the lacustrine infill of Kučevo and Rakova Bara basins and smaller intramontane depressions, as well as by lacustrine to marine sediments of the Velika Morava Corridor that cover most of the Supragetic Unit west of the studied areas (Fig. 1B; KALENIĆ et al., 1980).

Tectonic framework

The Dacia mega-unit of the Eastern, Southern and Serbian Carpathians was initially part of the active continental margin of Europe, which was partially separated from the continent during the Jurassic opening of the Ceahlau-Severin branch of the Alpine

Tethys (SCHMID et al., 2008). The obduction of the East Vardar ophiolites on top of the Dacia mega-unit occurred during the latest Jurassic (CSONTOS & VÖRÖS, 2004; SCHMID et al., 2008). Although the true nature of the East Vardar ophiolites is highly debated, the thermal and metamorphic events of Late Jurassic age were recognised in the Dacia mega-unit (REISER et al., 2017, and references therein).

The late Early Cretaceous nappe-stacking, the ‘Austrian’ phase, in the Dacia mega-unit, followed the closure of the Ceahlau-Severin Ocean and its collision with the Moesian platform (CSONTOS & VÖRÖS, 2004; SCHMID et al., 2008). This event was recognised in various parts of the Dacia mega-unit (i.e. GRÖGER et al., 2013, and references therein, in the Eastern Carpathians; BOJAR et al., 1998, IANCU et al., 2005a in the Southern Carpathians; REISER et al., 2017, and references therein, in the Apuseni Mountains; ANTIĆ et al., 2016 in the Serbo-Macedonian Massif in southeastern Serbia; KOUNOV et al., 2010 in the Kraishte zone in western Bulgaria). However, the direction of the thrusting varies, in today’s coordinates, along the strike of the orogen, due to the significant (up to 90°) Late Cretaceous-Cenozoic clockwise rotation which was reported and discussed for the Eastern and the Southern Carpathians and the Apuseni Mountains (i.e. DUPONT-NIVET et al., 2005; FÜGENSCHUH & SCHMID, 2005; USTASZEWSKI et al., 2008; MERTEN et al., 2011; and references therein).

The late Early to early Late Cretaceous, post ‘Austrian’, cooling event which was reported in Serbo-Macedonian Massif (ANTIĆ et al., 2016) was interpreted as post-collisional extension. The Late Cretaceous Banatitic magmatism in the Apuseni-Banat-Timok-Srednogorie magmatic arc is associated with that extension (VON QUADT et al., 2005; GALLHOFER et al., 2015).

The ‘Laramian’ phase overthrusting of the whole Dacia nappe-stack over the Ceahlau-Severin and the Danubian Units took place after the cessation of the Late Cretaceous Banatitic magmatism, during the latest Cretaceous-Early Paleocene (BOJAR et al., 1998; IANCU et al., 2005a; SCHMID et al., 2008; ANTIĆ et al., 2016, and references therein).

The interplay of extension in the Pannonian basin and Paleogene-Neogene clockwise rotation and oroclinal bending of the Dacia mega-unit around Moesian promontory had a significant influence on tectonothermal and structural evolution of the orogen (LINZER et al., 1998; SCHMID et al., 1998; MATENCO & SCHMID, 1999; USTASZEWSKI et al., 2008, BALÁZS et al., 2016). This was associated with orogen-parallel extension and significant strain partitioning (FÜGENSCHUH & SCHMID, 2005; KRÉSZEK et al., 2013). The subsequent collision and locking in the Eastern Carpathians and the inversion in the Pannonian basin in the Miocene-Pliocene times represent the last stage in the tectonic evolution of the Dacia mega-unit (ZWEIGEL et al., 1998; MATENCO

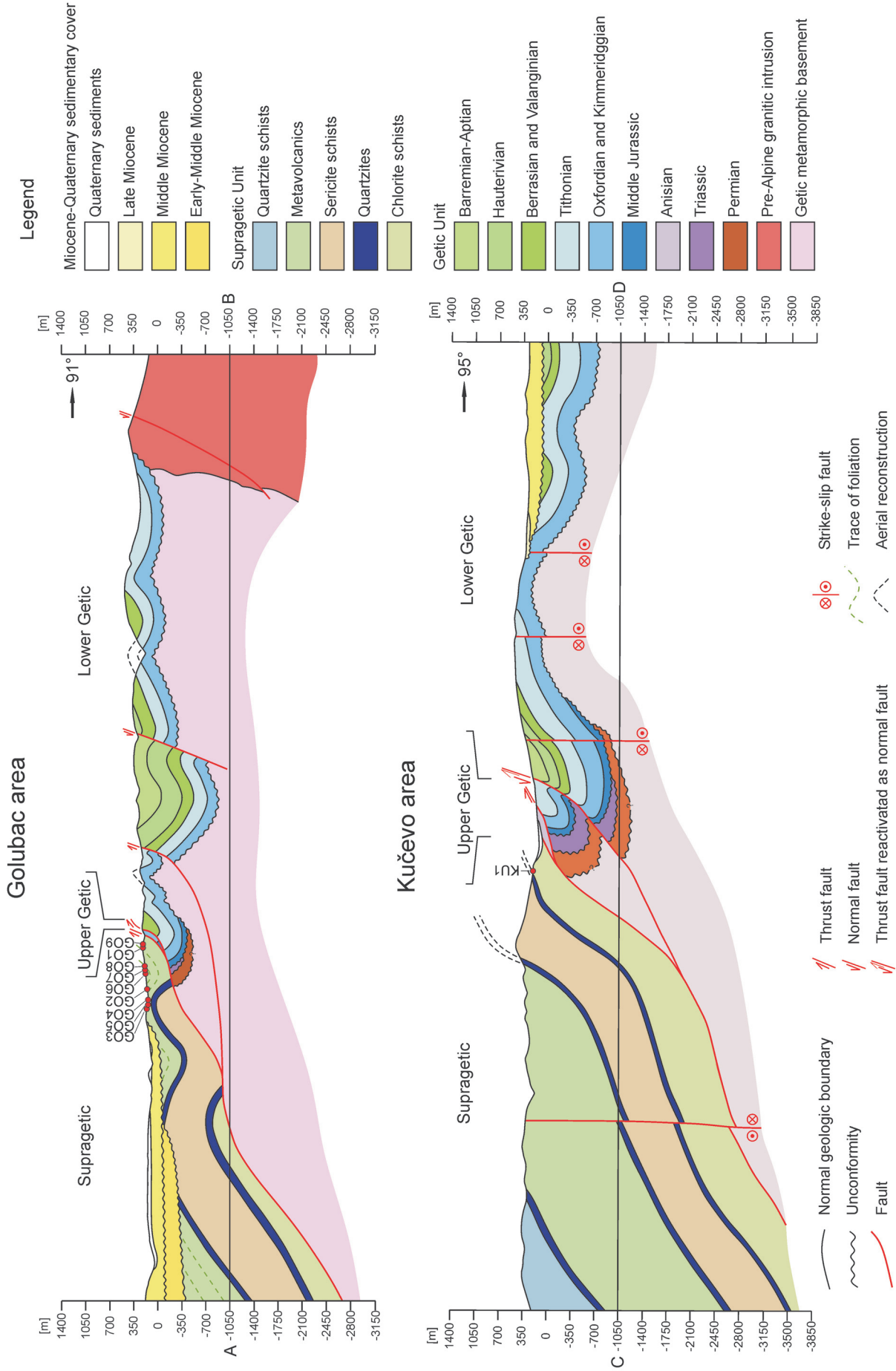


Fig. 5. Generalised cross sections through the Supragetic, the Upper Getic and the Lower Getic Units in both studied areas, with no vertical exaggeration. Positions of the cross sections A-B and C-D are indicated in Fig. 2 and Fig. 3 respectively. The red circles represent the approximate locations of the studied sites in cross sections.

& BERTOTTI, 2000; MAŢENCO, 2017, and references therein).

Methods

In order to constrain the internal structure of the Supraetic Unit basement, research at map-, outcrop- and thin-section-scales was conducted.

The regional-scale structures and the data collected during the geological mapping in the studied areas (KALENIĆ & HADŽI-VUKOVIĆ, 1973) were analysed at the map-scale. In this way, the statistical mean orientation of foliation in the three stratigraphically lowermost metamorphic sequences of the Supraetic Unit basement was obtained. Those metamorphic sequences were chosen for the analysis because they were expected to record deformations at the deepest levels. This analysis was performed separately for Golubac and Kučevo areas (Fig. 2, 3) in order to constrain possible changes in the geometry of the hectometre-scale structures along the strike. On the basis of the map and field data, two regional cross sections were constructed (Fig. 5) for both studied areas and were analysed independently afterwards.

The field studies included observations and measurements (studied sites in Fig. 2 and Fig. 3) of the outcrop-scale structures, collecting samples for microstructure analysis and the determination of the grade of metamorphism. The kink bands in the foliated rocks can be used as paleostress indicators (i.e. DEWEY, 1965; GAY & WEISS, 1974; SRIVASTAVA et al., 1999). The kink bands can be conjugate, either symmetric or asymmetric, or monoclines. The geometry of a single kink band includes the external and internal foliation separated by two kink planes or boundaries (see Fig. 1 of GAY & WEISS, 1974). In order to perform paleostress analysis of kink bands, the field orientation of the internal foliation and the kink plane was measured. In a kink band, the slip direction is parallel to the kink plane and perpendicular to the intersection of the kink plane and the internal foliation (SRIVASTAVA et al., 1999). The sense of movement was determined based on the geometry of the kink band. The paleostress analysis was carried out using the NDA method in TectonicsFP software (ORNTER et al., 2002). A 60° θ angle between σ_1 and the kink plane was used as an optimal angle for the kink bands, taking into account that this deformation occurs at deeper levels than the brittle deformation (SRIVASTAVA et al., 1999).

For micro-scale studies, six oriented samples were collected, four of them in the metavolcanics near Golubac (sites GO1, GO7, GO8 and GO9 in Fig. 2) and two in the chlorite schists in Kučevo area (site KU1 in Fig. 3). The optical microscopy technique was used for the thin section analysis. Based on mineral assemblages of the two metamorphic sequences

and recrystallisation types of dominant minerals the metamorphic grade was determined. The microstructures were analysed for determining a deformation sequence and the tectonic transport at the thin-section scale.

Results

The observations were carried out at three scales and the corresponding results are presented in this section.

Thin section-scale deformations

In four samples from Golubac area (sites GO1, GO7, GO8 and GO9, Fig. 2) the main rock-forming minerals are quartz, albite, sericite, chlorite, muscovite and metallic minerals, while zircon and apatite are accessory (Fig. 6A-C, 7A, B). The protolith of this rock is interpreted to be acidic to intermediate tuff. Based on the grain morphology, quartz and albite demonstrate dominant bulging recrystallisation and locally sub-grain rotation recrystallisation (Fig. 6A-C). Undulose extinction is a common feature in quartz and albite. The observed mineral assemblage as well as the quartz and albite grain features indicates lower greenschist facies metamorphism with temperatures reaching 300°C and pressure of 0.3 GPa (p/T estimates based on BEST, 2003).

In slightly deformed metavolcanics, the most prominent structure recognised in thin sections of this metamorphic sequence is a spaced foliation defined by narrow bands of chlorite, sericite and muscovite, separated by wider bands of coarser quartz and albite. The second set of structures, cutting the older ones at the acute angle and forming C'-S structures that demonstrate top to ESE to top to SE reverse tectonic transport is less evident (Fig. 7A, B).

Two thin sections from the lowermost metamorphic sequence of the Supraetic Unit basement (Kučevo area, site KU1 in Fig. 3) show that, compared to samples from Golubac area (Fig. 6D-F, 7C-F), this rock is built of finer mineral grains (generally less than 0.1 mm in diameter, except for albite). The main rock-forming minerals here are quartz, sericite, epidote, chlorite, calcite and metallic minerals and they define protolith as Ca-rich quartz keratophyre. As in the metamorphic sequence analysed above, in this rock quartz grains demonstrate dominant bulging recrystallisation and undulose extinction (Fig. 6D-F). The analysis of the mineral assemblage and dynamic recrystallisation of quartz implies that this sequence was metamorphosed under lower greenschist facies with temperatures reaching 350°C and pressure of 0.5 GPa (p/T estimates based on BEST, 2003).

The penetrative spaced foliation observed in thin sections is the most dominant structure of this lower-

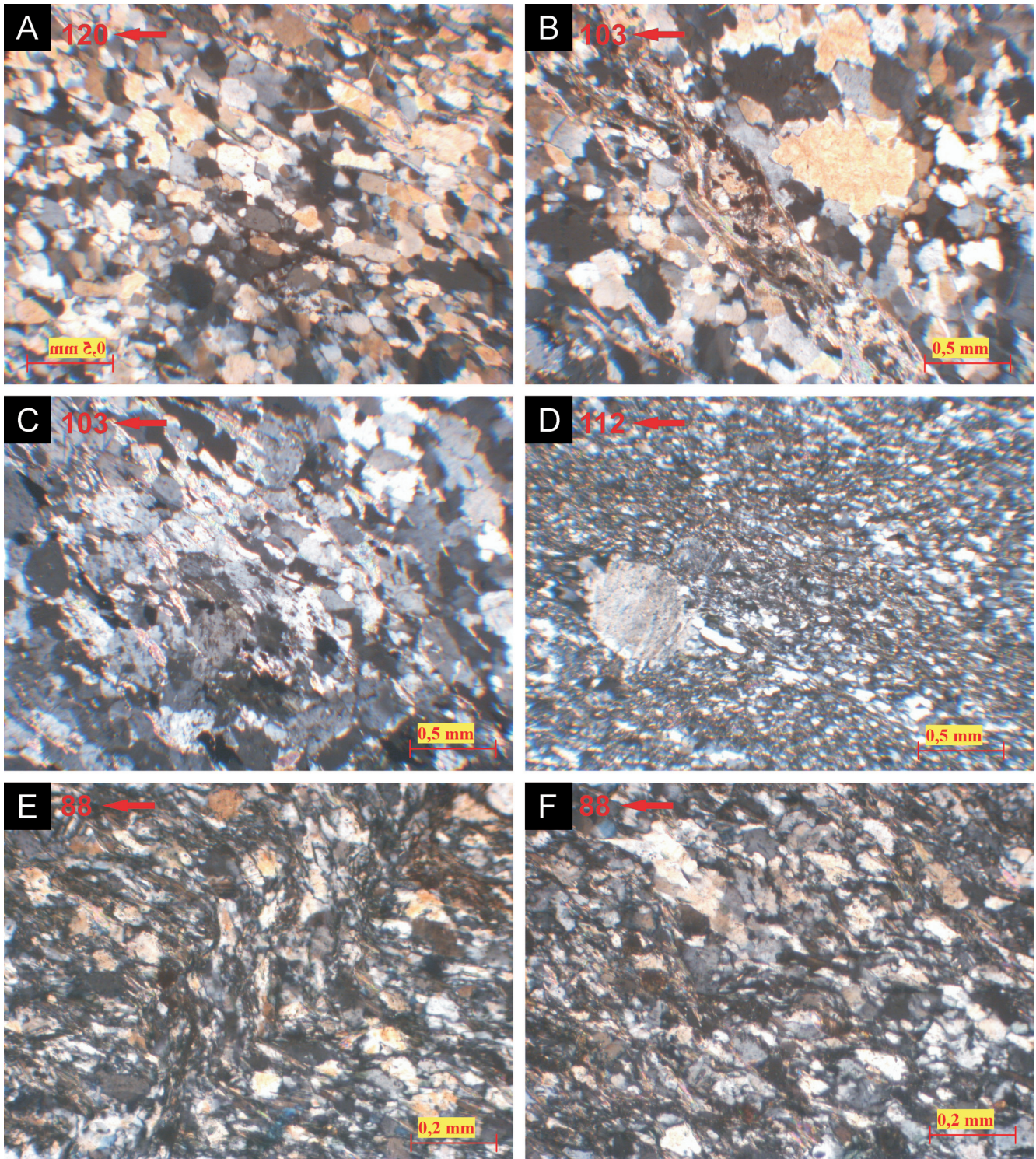


Fig. 6. Oriented thin sections in crossed-polarized light. The number in the top left corner indicates the orientation of the photo. Thin sections are parallel to the stretching lineations. **A.** the sample taken at the site GO9; **B, C.** the samples taken at the site GO7; **D, E, F.** the samples taken at the site KU1.

most metamorphic rock sequence. It is defined by alternating narrow bands of chlorite and sericite and wider bands of dominantly quartz, calcite and albite. The second foliation cuts the previous foliation at the acute angle, forming C'-S structures. C'-S structures together with chlorite and sericite growth in strain

shadows of albite porphyroblasts clearly define top to ESE reverse shearing (Fig. 7C, F). Both sets of the previously described foliations (S and C') are deformed by thin section-scale kink bands that are antithetic to sub-perpendicular to S planes and demonstrate a reverse sense of shearing (Fig. 7E).

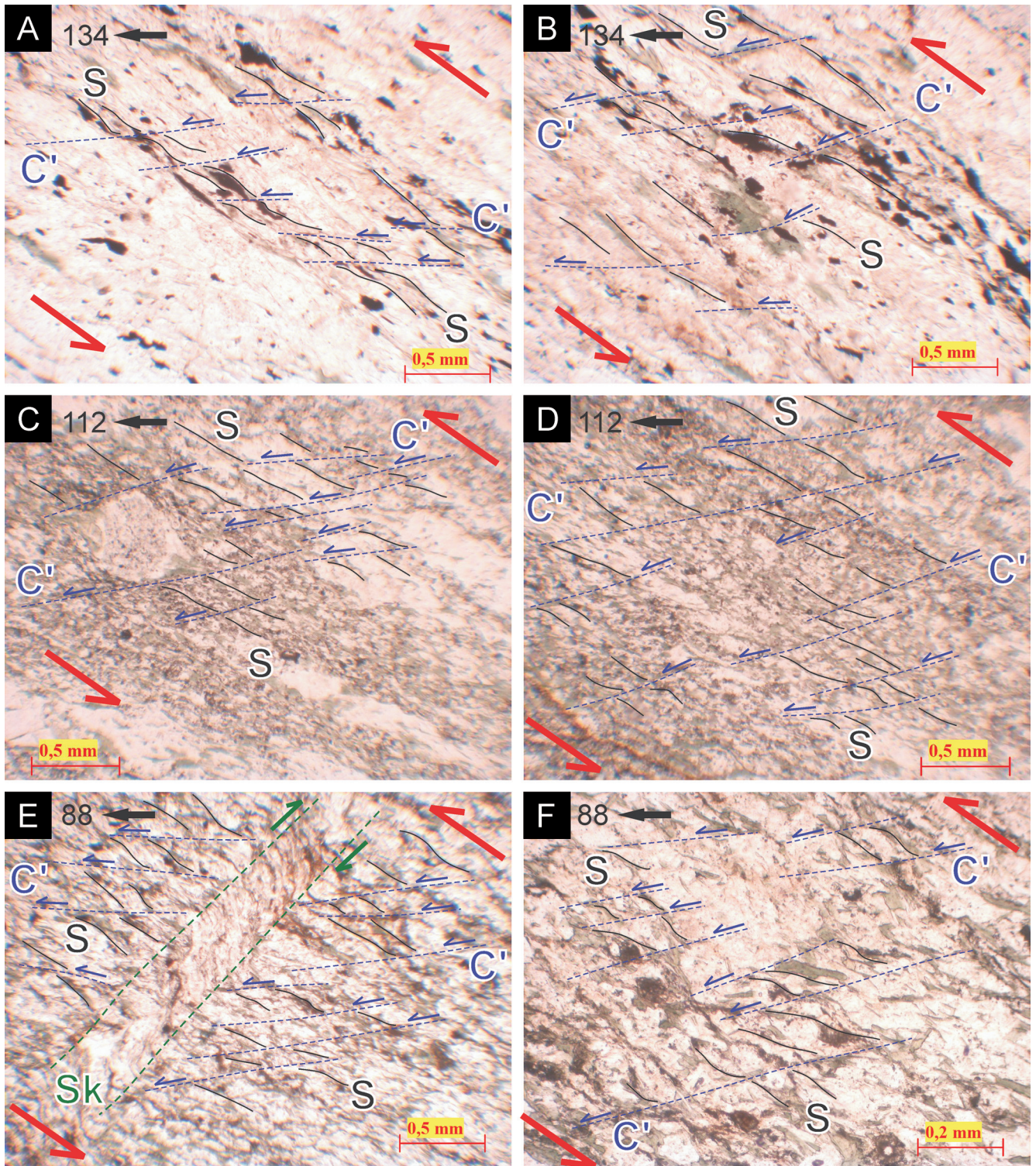


Fig. 7. Interpreted photos of oriented thin sections. The number in the top left corner indicates the orientation of the photo. The thin sections are parallel to the stretching lineations (Fig. 9D). Dip angle of s plane traces is dip angle of the stretching lineations measured in the outcrops. S - main foliation; C' - C' plane; Sk - kink plane; A, B, the sample taken at the site GO1; C, D, E, F, the samples taken at the site KU1.

Outcrop-scale deformations

The most dominant structure at the outcrop-scale in both studied areas is a penetrative foliation which was

also observed in thin sections. This foliation generally has west to northwest dipping at variable (from low to high) angles. Low- to moderate-angle eastward-dipping foliation was observed only at GO2 site (Fig. 2, 5).

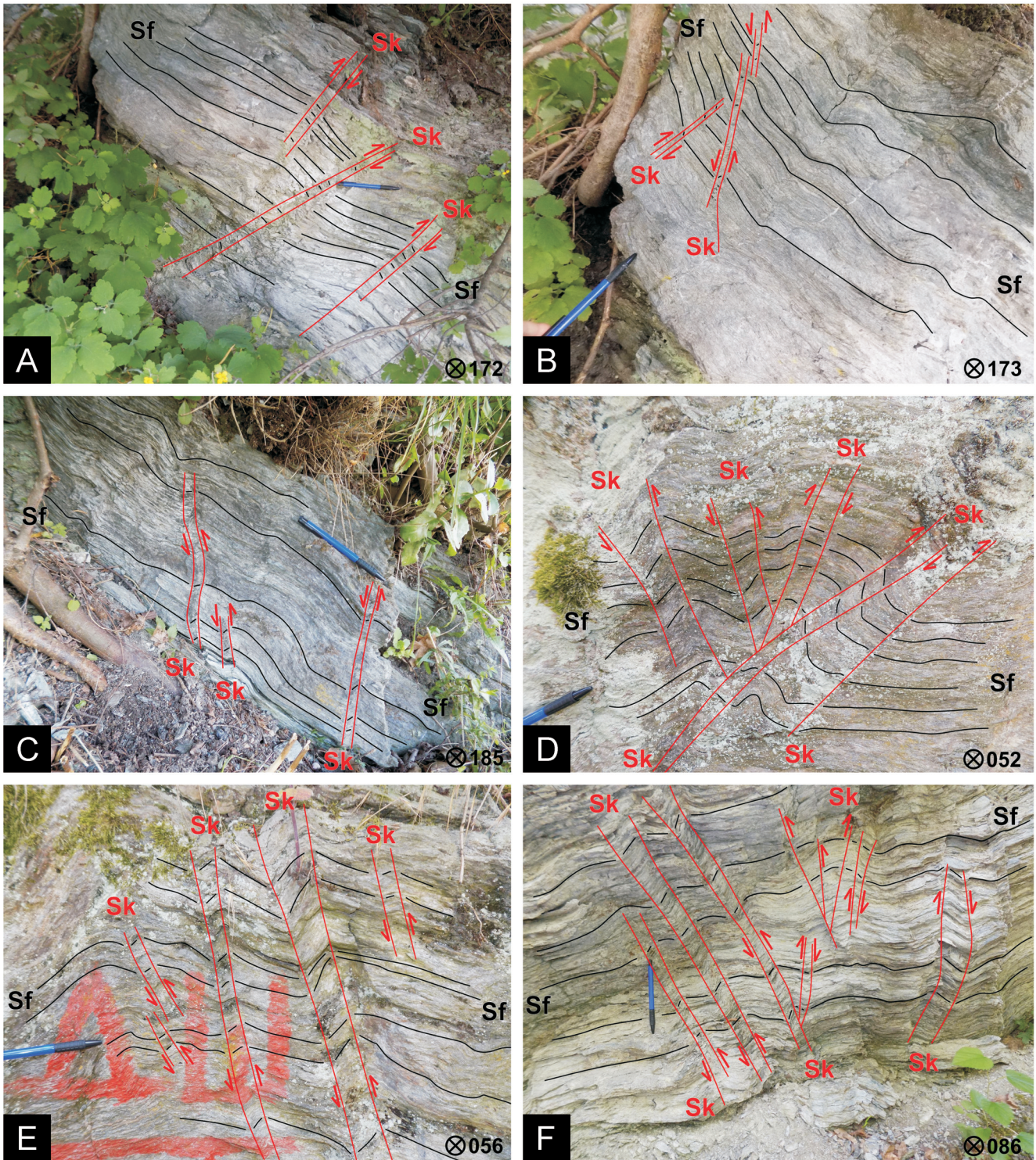


Fig. 8. Interpreted photos of the structures observed in the outcrops. Sk - kink plane; Sf - foliation; The camera view azimuth is indicated in the lower right corner of each photo. Note the blue pen as a scale in each photo.

A different orientation of kink bands deforming the main foliation (Sf) was observed in Golubac area (Fig. 8A-F). One set of conjugate kink bands striking NE-SW (Fig. 8B, D, F) and the second set of kink bands, striking NW-SE (Fig. 9C) were recognised. As for the single monocline kink bands, the most com-

mon orientation of the kink planes (Sk) is antithetic in respect to external foliation (i.e. Fig. 8A). This is the case for both the eastward- and westward-dipping external foliation. However, in respect to external foliation, synthetic kink bands were also recognised (Fig. 8E). Paleostress analysis of all the kink bands recog-

nised in Golubac area resulted in quite uniform stress axes, with σ_1 302/03, σ_2 032/01 and σ_3 141/86 (Fig. 9C), indicating NW–SE compression.

Stretching lineation statistical analysis, based on the standard Gaussian counting model in SpheriStat with the following statistics parameters: mean $E=0.26$, standard deviation $S=0.357$ and kappa $k=100$, resulted in maximum of 304/40 (Fig. 9D).

The other structures recognised in outcrops of the Supragetic Unit basement are changes of foliation dip angle at the decimetre scale (Fig. 8C). No older tight or isoclinal folds or any evidence of transposition was observed in the field.

Map-scale structures

The total of 85 measurements in the Supragetic Unit basement (Sco, Sse and Sab units in Fig. 2, 3) were used for the purpose of the statistical analysis of foliation in Golubac area. The standard Gaussian counting model in SpheriStat was used with the following statistics parameters: mean $E=0.85$, standard deviation $S=0.645$ and kappa $k=100$. The results show the stretched maximum in 270/31, and the less pronounced submaximum in 267/85 (Fig. 9A).

In Kučevo area, 64 foliation measurements were statistically analysed using the standard Gaussian

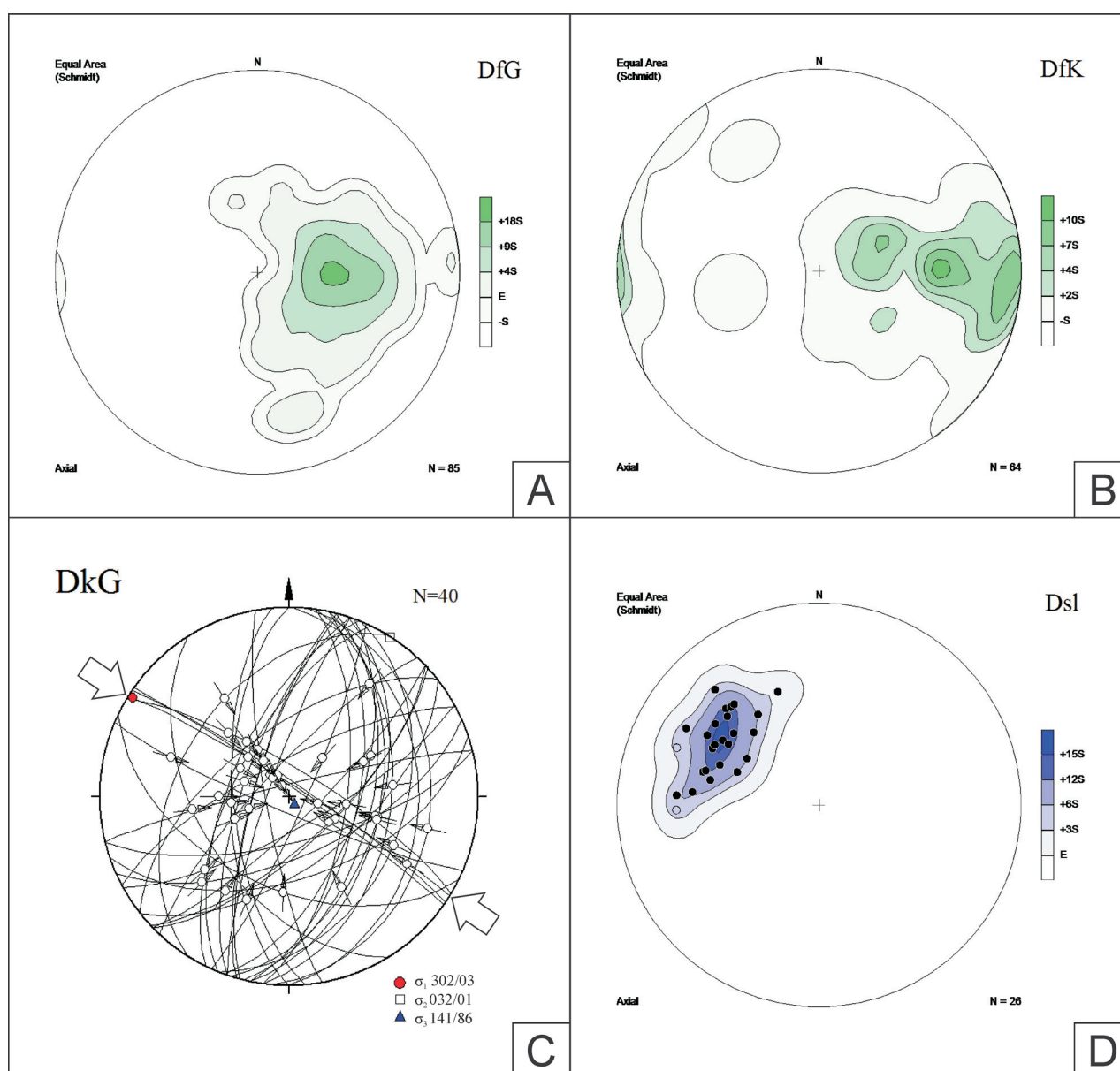


Fig. 9. **A.** Results of the statistical analysis of foliation in the Golubac area. Maximum is 270/31, and submaximum is 267/85; **B.** Results of the statistical analysis of foliation in the Kučevo area. Maximum is 270/49, and two submaxima are 246/28 and 274/82; **C.** Results of the paleostress analysis of kink-bands in the Golubac area; **D.** Results of the statistical analysis of stretching lineation. The black circles represent the stretching lineation poles in the Golubac area, while the white circles are the stretching lineation poles in the Kučevo area. The maximum is 304/40.

counting model ($E=0.64$, $S=0.56$, $k=100$). The results show similar west-dipping foliation with a more pronounced variation in dip angles than in Golubac area. The statistical maximum is 270/49, and the two sub-maxima are 246/28 and 274/82 (Fig. 9B).

Discussion

In fold-thrust belts, fault-related folds can have various geometries depending on different mechanical and rheological characteristics of the deforming rocks (SHAW et al., 2004). Such folding and other structures related to the thrusting can be used to infer the geometry of the main thrust fault (JOHNSON & BERGER, 1989; SAVAGE & COOKE, 2003).

The results of the statistical analysis of the foliation measurements (Fig. 9A,B) and the field observations indicate west-dipping foliation at various dip angles. This can be interpreted in two ways. The first one is that significant variations in dip angles but not in dip directions can be the result of hectometre-scale tight east-vergent folding. The alternative interpretation is that these statistical results indicate a flat-ramp geometry of the Supragetic thrust. However, both of these interpretations, as well as the mineral assemblage and the termochronological data (BOJAR et al., 1998; KOUNOV et al., 2010; GRÖGER et al., 2013; ANTIĆ et al., 2016, REISER et al., 2017) indicate that the Supragetic Unit basement was deformed in ductile domain during the late Early Cretaceous. Furthermore, the field observations also show E-dipping foliation in the northernmost sections (site GO2 in Fig. 2) representing the western limb of a fault-related syncline in the hanging wall of the flat segment of the thrust (Golubac area cross section, Fig. 5).

The ductile to semi-ductile shearing recognised both at the outcrop- and the thin section-scale (Fig. 7, 8) demonstrate top to ESE tectonic transport. The WNW-dipping stretching lineation (Fig. 9D) is in accordance with this observation. Furthermore, kink bands deforming the penetrative foliation also imply WNW–ESE to NW–SE compression phase (Fig. 9C). Foliation parallel shearing and conjugate NE–SW striking kink bands are interpreted as the result of continuous deformation event starting in the ductile domain and continuing in the semi-ductile/semi-brittle domain when kinking occurred as hanging-wall strain accommodation (see Fig. 10; BONINI et al., 2000; SCHLISCHE et al., 2014; ROSAS et al., 2017). The dominant opposite dip-direction of kink bands and main foliation is regarded as an interesting observation. Such configuration is expected for the kink bands of the hanging wall which are antithetic to main thrust (BONINI et al., 2000; ROSAS et al., 2017). This was generally the case in the studied locations, however the field observations of the opposite dipping kink bands and foliation in the E-dipping fold limb

indicated that the kink bands could have been formed along the axial planar cleavage of the pre-existing fault-related fold. The kink bands striking NW–SE are interpreted as parts of semi-ductile tear faults, transferring strain between lateral segments of the nappe during thrusting. Faults of, generally, the same orientation were also recognised at the map-scale (Fig. 2, 3, KALENIĆ & HADŽI-VUKOVIĆ, 1973).

The offset of the Supragetic thrust increases southwards, outcropping deeper sequences of the basement in the hanging wall of the thrust front (Fig. 2, 3, 5). Corresponding to this are the mineral assemblages and micro-scale deformations of different metamorphic sequences, all indicating 1.5–2 km greater exhumation in Kučevo area compared to Golubac area.

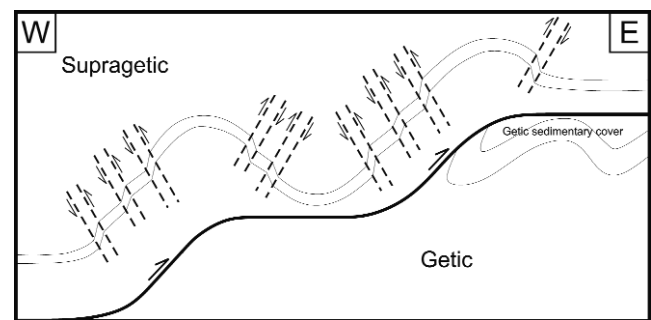


Fig. 10. The schematic cross section representing the relations between the main Supragetic thrust geometry and the secondary structures in the hanging wall.

In this study, based on all the available data, the mineral assemblages, the amount of deformation at outcrop- and thin-section-scale and the lack of observable tight or isoclinal folds and inverse foliation, the internal structure of the Supragetic Unit basement is interpreted as an indicator for flat-ramp geometry of the main thrust (Fig. 10). These structures were formed during the late Early Cretaceous, starting in ductile to semi-ductile/semi-brittle domain. This interpretation does not completely exclude the possibility of tight to isoclinal folding of the Supragetic Unit metamorphic basement related to the Alpine nappe-stacking.

Conclusions

The structural analysis of the Supragetic Unit metamorphic basement at different scales was performed in order to constrain its internal geometry and its relations to the late Early Cretaceous nappe-stacking.

Based on microstructural observations, field evidence and map data analysis, it was concluded that the Supragetic thrust most possibly has a flat-ramp geometry, and that this geometry is reflected in the internal structure of its hanging wall represented by the Supragetic Unit metamorphics. The main foliation which

was deformed during the late Early Cretaceous nappe-stacking suggests a fault-related folding and flat-ramp geometry that was subsequently deformed by kinking. Kinking accommodated strain in the hanging wall during transition from ductile to brittle domain. Moreover, the data presented in this study indicate an increase in the offset and the amount of exhumation along the Supraetic thrust from north to south.

These conclusions were made based on the available data and the published papers. However, further research is needed in order to constrain more precisely the timing of deformations in the Supraetic metamorphic series.

Acknowledgements

The authors would like to thank Dr MARTIN KASPAR REISER and Dr IOAN MUNTEANU for their constructive reviews and suggestions which significantly improved the manuscript. The support of Professor NEBOJŠA VASIĆ during this research is highly appreciated. This study was supported by the Serbian Ministry of Education, Science and Technological Development, Projects No. OI176015 and OI176019.

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Резиме

Интерна структура основе Супрагетикума у српским Карпатима и њен значај за касно доњокредно навлачење

Сложена геолошка грађа Карпато-Балканида источне Србије последица је полифазне тектонске еволуције током Алпске орогенезе. Иницијално формирање навлака у Јужним Карпатима и њиховом продужетку у источној Србији и Бугарској обављено је током касне доње креде (CSONTOS & VÖRÖS, 2004; SCHMID et al., 2008; KOUNOV et al., 2010). У овом раду, анализирана је интерна структура метаморфне основе Супрагетикума и њен значај за геометрију регионалних навлака и нивоа коре у којима је навлачење извршено.

Супрагетикум, једна од структурно виших навлака у навлачном пакету Дакијске мега јединице, је изграђена од нискометаморфне основе представљене различитим вулканогено-седиментним јединицама метаморфисаним у фацији зелених шкриљаца, млађе палеозојским седиментним покровом и веома танким и просторно значајно ограниченим мезозојским седиментима (IANCU et al., 2005a,b).

За потребе ове студије, анализирана је структурна грађа три, у стубу најниже, метаморфне јединице Супрагетикума, у величинским подручјима карте, изданка и микропрепарата, на два истраживана подручја, у околини Голупца и околини Кучева.

Минералне асоцијације дефинисане у препаратима, као и тип и степен прекристализације квар-

ца и албита указују на метаморфизам у фацији зелених шкриљаца на температурама око 300–350°C и притисцима око 0,3–0,5 GPa. Пенетративна фолијација и С'-S микроструктуре показују реверсни тектонски транспорт према исток-југоистоку. Фолијација је деформисана млађим "кинкигом" препознатим и у микропрепаратима и на терену. Коњуговане и моноклине "кинк" зоне пружања североисток-југозапад представљају млађу етапу континуираног деформационог догађаја, када је извршено примарно навлачење и прелазак метаморфита Супрагетикума из дубљих, дуктилних, у "brittle" услове. Формирање оваквих структура је последица акомодације деформација у повлатном блоку регионалне навлаке (BONINI et al., 2000; SCHLISCHE et al., 2014; ROSAS et al., 2017). Овакав "кинкинг" је највероватније развијен по кливажу аксијалне површи регионалних набора везаних за навлачење. Раседи везани за акомодацију различитог степена навлачења у бочним сегментима навлаке, у семи-дуктилним условима су праћени трећим сетом "кинк" зона правца пружања северозапад-југоисток. Статистичка анализа фолијације указује на "flat-ramp" геометрију главне навлаке по којој интензитет навлачења расте према југу и ексхумација је око 1,5–2 km већа у околини Кучева у односу на област Голупца.

Закључци, да је примарно навлачење извршено током краја доње креде у дуктилним до семи-дуктилним/семи-"brittle" условима, по навлаци која има "flat-ramp" геометрију, су донети на основу прикупљених података и доступне литературе. Ипак, ради прецизног утврђивања старости деформација у метаморфној основи Супрагетикума, даља истраживања су неопходна.

Manuscript received August 5, 2017

Revised manuscript accepted October 10, 2017