TECTONIC SETTING OF THE VARDAR SUTURE ZONE (DINARIC-HELLENIC BELT): THE EXAMPLE OF THE KOPAONIK AREA (SOUTHERN SERBIA)

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ABSTRACT

In the tectonic setting of the Dinaric-Hellenic belt, the Vardar Zone is represented by a NW-SE to N-S striking assemblage of oceanic and continental units, each showing different metamorphic grade and deformation features. In this paper, a detailed description of the stratigraphic and structural features of the tectonic units cropping out in the Kopaonik area, belonging to the Vardar Zone of Serbia, is presented. In addition, a 1:50.000 scale geological map of the studied area is also provided.

In the Kopaonik area is present a stack of tectonic units, originated during the Alpine deformation phases and referred to both External and Central Vardar Zones of Dimitrijević (1997). These units are represented, from bottom to top, by the Kopaonik Metamorphic Complex, the Brzeće Unit, the Subophiolite Mélange, the Ophiolite Unit and the Brus Unit. The stack of tectonic units is intruded by Early Oligocene granitoids, referred to as the Kopaonik Intrusive Complex. Moreover, the relationships among the tectonic units are unconformably covered by Miocene volcanic rocks and sedimentary deposits.

The stratigraphic and structural dataset presented in this paper allows some considerations about the paleogeographic domain of origin for the successions of the different units as well as some interpretations about the tectonic history of the Vardar Zone.

INTRODUCTION

In the Dinaric-Hellenic belt, the Vardar Zone is a NW-SE to N-S striking assemblage of oceanic and continental units, each showing different metamorphic grade and deformation features. In addition, the Vardar Zone is characterized by a wide range of syn- to post-collisional magmatic rocks, whose age spans from Late Cretaceous to Miocene. According to these features, the Vardar Zone is interpreted as the suture developed in Late Cretaceous through the closure of the NeoTethys oceanic basin and the following collision between the Adria and the Eurasian continental margins.

According to this picture, the Vardar suture zone preserves the record of a long-lived, complicated tectonic history whose features are able to provide valuable constraints for the reconstruction of the geological evolution of the Dinaric-Hellenic Belt. Despite its importance, the Vardar Zone is still poorly studied and modern reliable data are lacking. Within the Vardar Zone, the Kopaonik area represents a key example where a pile of tectonic units of both oceanic and continental origin, each showing different deformation and metamorphism, is intruded by granitoid rocks of Oligocene age. This area can be thus regarded as representative of the Vardar Zone tectonic setting, and it can provide a large amount of useful data for its reconstruction.

In this paper, a detailed study of the Kopaonik area by multidisciplinary approach, ranging from stratigraphy to petrography and structural geology, is presented. In addition, a geological map at 1:50.000 scale is provided.

GEOLOGICAL FRAMEWORK

The Dinaric-Hellenic Belt (Fig. 1) is a 2000 km long orogenic chain of Alpine age derived from the Mesozoic to Neogene convergence between Adria and Eurasia. In the classical reconstructions, the geodinamic evolution of the Dinaric-Hellenic Belt includes a rifting stage, developed during the Early Triassic along the northern margin of the Gondwana macroplate (Dimitrijević, 1982; Pamić et al., 2002; Robertson, 2002; Dilek et al., 2005), that evolved into the Middle to Late Triassic oceanic spreading phase (Bortolotti and Principi, 2005; Bortolotti et al., 2007). The following spreading and drifting phases resulted in the development of a wide basin characterized by MOR (mid-ocean ridge) oceanic lithosphere (Çollaku et al., 1992; Bébien et al., 1998; Pamić et al., 2002; Bortolotti et al., 2004a; 2008; Saccani et al., 2004). This oceanic basin, with (Robertson and Karamata, 1986; Karamata et al., 2000; Dimitrijević 2001) or without (Pamić et al., 1998; Bortolotti et al., 2005; Schmid et al., 2008) a microcontinent within it, was located between the Adria and Eurasia continental margins. Convergence began during the Early Jurassic, with intraoceanic subduction followed by the formation of new oceanic lithosphere in the fore-arc basin (Beccaluva et al., 1994; Shallo, 1994; Bortolotti et al., 2002; Hoeck et al., 2002; Dilek et al., 2007; Saccani et al., 2008a). A back-arc oceanic basin formed close to the Eurasian continental margin in the Middle Jurassic (Saccani et al., 2008b and quoted references). During convergence, the oceanic lithosphere of the lower plate was totally destroyed; when the continental margin approached the subduction zone, in Middle to Late Jurassic, oceanic lithosphere slices were obducted onto the continental margin of the Adria Plate (Çollaku et al., 1992; Robertson and Karamata, 1994; Dimitrijević, 2001; Pamić et al., 2002; Bortolotti et al., 2004b; 2005; Djerić et al., 2007; Gawlick et al., 2008). Obduction was associated to development of a metamorphic sole and a mèlange at the base of the ophiolite nappe (Shallo, 1991; Bortolotti et al., 1996; Wakabayashi and Dilek, 2003; Dilek et al., 2005) as well as a foredeep basin in front of it (Mikes et al., 2008; Luzar-Oberiter et al., 2009; Marroni et al., 2009). Convergence between Adria and Eurasia led subsequently to a mature continental collision stage, as demonstrated by compressional deformations in the hinterland, i.e. the rim of the Eurasia Plate (Ricou et al., 1998; Kilias et al., 1999; Liati, 2005; Kounov et al., 2010). The age of this stage is still a matter of debate; some authors (e.g. Pamić et al., 2002) have proposed a Late Jurassic - Early Cretaceous age, whereas others (e.g., Schmid et al., 2008) suggest that continental collision occurred later, during Late Cretaceous - Early Paleogene. After continental collision and up to Neogene time, the continuous convergence, still active today, mainly affected the continental margin of the Adria Plate, that was progressively deformed in westward-vergent, thick-thinned thrust sheets. However, tectonics continued also in the inner zone of the Dinaric-Hellenic Belt, i.e. in the Vardar and Serbo-Macedonian Zones, where a transition from compressional to extensional deformations occurred probably in the Early Tertiary (e.g. Dinter and Royden, 1993, Dinter, 1998; Zelic et al., 2010). In the Vardar Zone, continental collision was also accompanied by emplacement of calc-alkaline granitoids, mainly of Late Eocene - Early Oligocene age (e.g. Pamić and Balen, 2001).

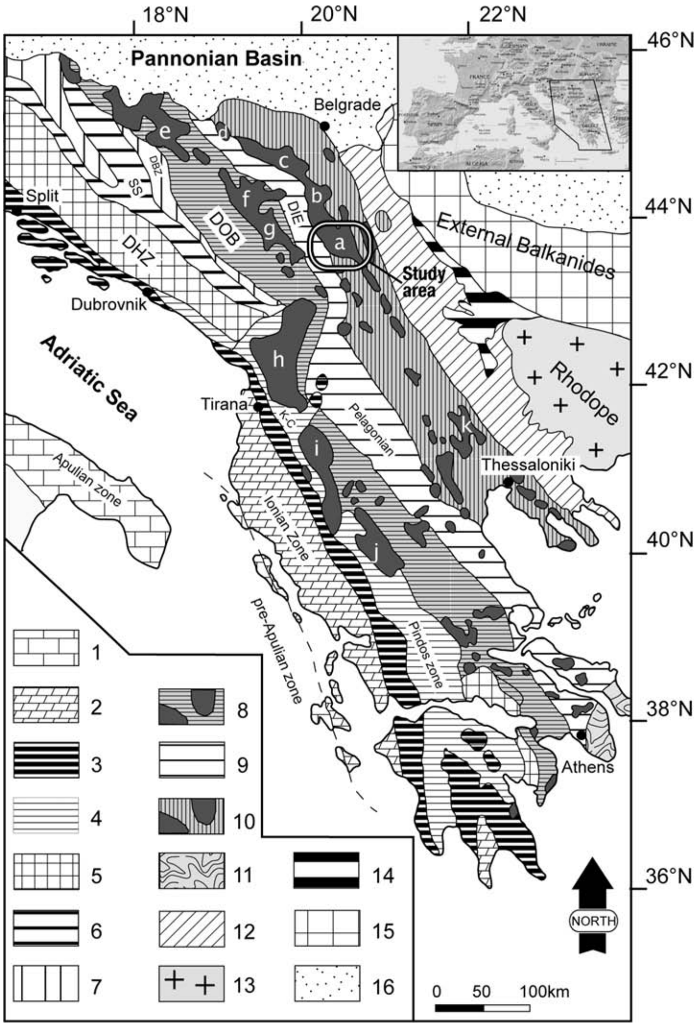

Fig. 1 - Tectonic sketch-map of the Dinaric-Hellenic Belt.
Legend and abbreviations: 1. Apulian and Pre-Apulian Units; 2. Ionian Units; 3. South Adriatic Units: Kruja, Gavrovo and Tripolitsa; 4. Budva, Krasta-Cukali (K-C) and Pindos Units; 5. Dalmatian-Herzegovian (DHZ) Units; 6. Sarajevo-Sigmoid (SS) Unit; 7. East Bosnian-Durmitor Unit (DBZ); 8. Dinaric Ophiolite Belt (DOB, dark grey: ophiolites); 9. Drina-Ivanjica and Pelagonian Units (DIE); 10. Vardar Units (VZ, dark grey: ophiolites); 11. Lavrion Blueschist Unit; 12. Internal Dinarides and Hellenides; 13. Rhodope Massif; 14. Internal Balkanides; 15. Intermediate and External Balkanides; 16. Pannonian and Tertiary European Foreland basins. Ophiolites: a- Ibar; b- Troglav; c- Maljen; d- Zvornik; e- Krivaja-Konjuh; f- Zlatibor; g- Bistrica; h- North Mirdita; i- South Mirdita; j- Pindos; k- Guevgueli. The study area is indicated.

This long-lived geodynamic evolution produced the present-day structure of the Dinaric-Hellenic Belt, that can be described as an assemblage of NW-SE to N-S trending zones, corresponding to the modern concept of terranes (see discussion in Bortolotti et al., 2004a). Each zone consists of an assemblage of variably deformed and metamorphosed tectonic units of oceanic and/or continental origin. Along a northern transect of the Dinaric-Hellenic Belt, running from Serbia to Bosnia and Croatia, four main zones can be identified (Aubouin et al., 1970; Dimitrijević, 1997; Pamić et al., 1998; Karamata, 2006; Schimd et al., 2008). These zones correspond, from west to east, to: 1- The Deformed Adria Zone, 2- the External Ophiolite Belt, 3- the Drina-Ivanjica Zone and, 4- the Vardar Zone. These zones are bound to the west by the Undeformed Adria Zone, presently located in the Adriatic Sea, and to the east by the Serbo-Macedonian-Rhodope Massif, interpreted as part of the deformed margin of the Eurasia Plate (Fig. 1).

The Deformed Adria Zone consists of a west-verging imbricate stack of tectonic units detached from the continental margin of the Adria Plate (Hrvatović and Pamić, 2005; Schimd et al., 2008). According to its overall stratigraphy and age of deformation, this zone can be subdivided in the northern part of the Dinaric-Hellenic Belt into South Adriatic, Budva, Dalmatian-Herzegovian, Sarajevo and East Bosnian-Durmitor Units (Dimitrijević, 1997). On the whole, these units are characterized by unmetamorphosed sedimentary sequences, including Triassic to Paleogene neritic and pelagic carbonate sequences topped by widespread Late Cretaceous to Miocene siliciclastic foredeep deposits. In some units, as for instance in the East Bosnian-Durmitor one, the Mesozoic to Tertiary sedimentary sequences have a Paleozoic basement. The age of inception of foredeep deposition, that ranges from Late Cretaceous in the Sarajevo zone to Miocene in the South Adriatic Zone, is regarded as record of the westward migration of deformation across the Adria continental margin. These units are thrust onto the undeformed Adria margin, presently recognized by seismic profiles in the Adriatic offshore (Dal Ben, 2002).

Eastwards, the Deformed Adria Zone is overthrust by the units of the External Ophiolite Belt, recognized as a continuous nappe from Argolis, Othrys, Pindos and Vourinous in Greece, to Mirdita in Albania, Bistrica and Zlatibor in Serbia up to Krivaja in Croatia (e.g., Bortolotti et al., 2004a). This nappe is characterized by Jurassic ophiolites showing MOR and SSZ magmatic rocks (Pamić and Desmond, 1989; Lugović et al., 1991; Pamić, 1993; Robertson and Karamata, 1994; Pamić et al., 2002; Bazylev et al., 2009). However, evidence for MOR Triassic ophiolites has been also provided by Vishnevskaya et al. (2009). As evident in Albania and Greece (e.g., Bortolotti et al., 2002; 2005), the different ophiolite sequences originated in different areas of the same oceanic basin starting in the Middle Triassic. The External Ophiolite Belt shows at its base a sub-ophiolite mélange, consisting of an assemblage of continental and oceanic units built-up by multi-stage events, starting during the Middle Jurassic inception of obduction and ending in the final stages of continental collision (Dimitrijević and Dimitrijević, 1973; Robertson and Karamata, 1994; Babić et al., 2002). During obduction and the westward thrusting of the ophiolitic units onto the Adria continental margin, the Subophiolite Mélange probably incorporated fragments of the formations on which it overthrust.

Eastwards, the External Ophiolite Belt units are thrust onto the Drina-Ivanjica Zone (Dimitrijević, 1997) that can be correlated with the Pelagonian and Korab Zones in Greece and Albania. This zone includes an assemblage of tectonic units consisting of a pre-alpine basement covered by Permian to Early Triassic siliciclastic deposits followed by Middle Triassic to Late Jurassic carbonates. The Drina-Ivanjica Zone is topped by the units belonging to the Vardar Zone.

The Vardar Zone represents the easternmost assemblage of tectonic units of the Dinaric-Hellenic Belt (e.g., Brown and Robertson, 2004). This zone, located west of the Serbian-Macedonian Massif, consists of a composite assemblage of continental and oceanic-derived units, including also Triassic and Jurassic ophiolites (Karamata, 1994; 2006). The latter form the internal ophiolite belt of the Dinaric-Hellenic chain. According to Dimitrijević (1997) the Vardar Zone can be subdivided into three subzones, referred to as External, Central and Internal Subzones. The External Subzone includes an assemblage of oceanic and continental units, the latter characterized by a Paleozoic basement covered by Middle to Late Triassic, mainly carbonatic sequences. The oceanic units are represented by both Triassic and Jurassic ophiolites, mainly consisting of serpentinized mantle rocks. According to Schmid et al. (2008), the ophiolites show features (age, geochemistry, stratigraphy and deformations) similar to those recognized in the External Ophiolite Belt. As in this last Belt, a sub-ophiolite mélange occurs at the base of the ophiolite sequences (Pamić, 2002; Robertson et al., 2009). In addition, slices of Late Cretaceous turbiditic sequences are also recognized (Dimitrijević, 1997; Ustaszewski et al., 2009). The Central and Internal Subzones include mainly oceanic units associated with slices of Paleozoic basement and Early to Late Cretaceous turbidites. In the Vardar Zone, Oligocene to Pliocene magmatic rocks, both intrusive and effusive, showing calcalkaline affinities are widespread (Pamić and Baljen, 2001; Cvetković et al., 2004). On the whole, the Vardar Zone is regarded as a suture developed after the collision between Eurasia and Adria, as suggested by occurrence in its northern border of slices of metamorphic rocks affected by blueschist metamorphism (Majer and Mason, 1983; Milovanović et al., 1996). In this frame, the ophiolites from the External belt and Vardar Zone can be interpreted as belonging to a nappe derived from a same wide oceanic basin, i.e. the Vardar Ocean, characterized by MOR, IAT and BABB oceanic sequences (Bortolotti et al., in press).

On its eastern boundary, the Vardar Zone disappears below the Serbo-Macedonian Massif. This zone represents the northernmost continuation of the metamorphic associations cropping out in Macedonia and eastern Greece, where the Serbo-Macedonian and the Rhodope Massifs can be regarded as a single domain belonging to the Eurasian Plate (e.g., Ricou et al., 1998). As in Greece, the Serbo-Macedonian Massif includes a complicate set of different metamorphic units of Paleozoic and older ages, intruded by granitoids of Oligocene age (Pamić and Balen, 2001). In the Serbo-Macedonian Massif scattered bodies of metamorphic ophiolites are preserved, probably remnants of a Triassic or older oceanic basin (e.g., Bonev and Dilek, 2010). In Greece, the units from the Serbo-Macedonian Massif underwent Cretaceous shortening deformations with both top-to-the-west and to-the-east sense of shear, under amphibolite facies metamorphism (e.g., Kilias et al., 1999). This tectonic history can be extended to the analogous units at the boundary among southern Serbia, Macedonia and western Bulgaria, where evidence of Cretaceous shortening is suggested by data from Kounov et al. (2010). However, the present structural setting of the Serbo-Macedonian Massif was achieved through extensional tectonics that followed the Cretaceous shortening. These events, very similar to those recognized in the Vardar Zone (e.g. Zelic et al., 2010a), are regarded as Eocene-Miocene in age, as recognized in the whole hinterland of the Dinaric-Hellenic Belt.

GEOLOGY OF THE KOPAONIK AREA

Geological setting

The structure of the Kopaonik area (Fig. 2) consists of a stack of tectonic units intruded by granitoids, here reported as Kopaonik Intrusive Complex, whose minimum age of emplacement has been determined as 31.5±0.3 Ma (Early Oligocene) by Rb-Sr whole-rock-biotite method (Zelic et al., 2010b). These units, originated during the Alpine deformation phases, are referred to both the External and Central Vardar Zones (Dimitrijević, 1997). From bottom to top, the following units have been distinguished: the Kopaonik Metamorphic Complex (named in previous works as “Series of the Central Kopaonik”; Dimitrijević, 1974) and the Brzeće, the Subophiolite Mélange, the Ophiolite and Brus Units, with the latter corresponding to the Paraflysch Unit of the Central Vardar Subzone by Dimitrijević (1997). The large scale structure consists of a wide N-S elongated dome with a core of granitoids sorrounded by the stack of tectonic units. In both the northern and western areas scattered outcrops of granitoids occur, probably related to E-W striking transtensive faults. The internal structure of the Kopaonik Intrusive Complex is onion-like, with three concentric magmatic facies. This complex shows in the whole area intrusive relationships with the Kopaonik Metamorphic Complex (KMC), i.e. with the lowest tectonic unit. However, in the southwestern corner of the intrusive complex the granitoids come into contact with serpentinites of the Ophiolite Unit. Roof pendants of the KMC have been mapped in the northern area of the intrusive complex. The KMC is characterized by polyphase folding and metamorphism as apparent also in the map. The formations belonging to the KMC form N-S trending elongated bodies that can be interpreted as deformed synclines and anticlines, originated during the polyphase deformation history. In addition, the KMC is subdivided into several sub-units by low-angle shear zones, as recognized in northwestern areas. The same low-angle shear zones represent the boundary between the Kopaonik Metamorphic Complex and the overlying Brezće Unit as well as between the Ophiolite Unit and the Subophiolite Mélange. Along this shear zone the Brezće Unit is generally missing,

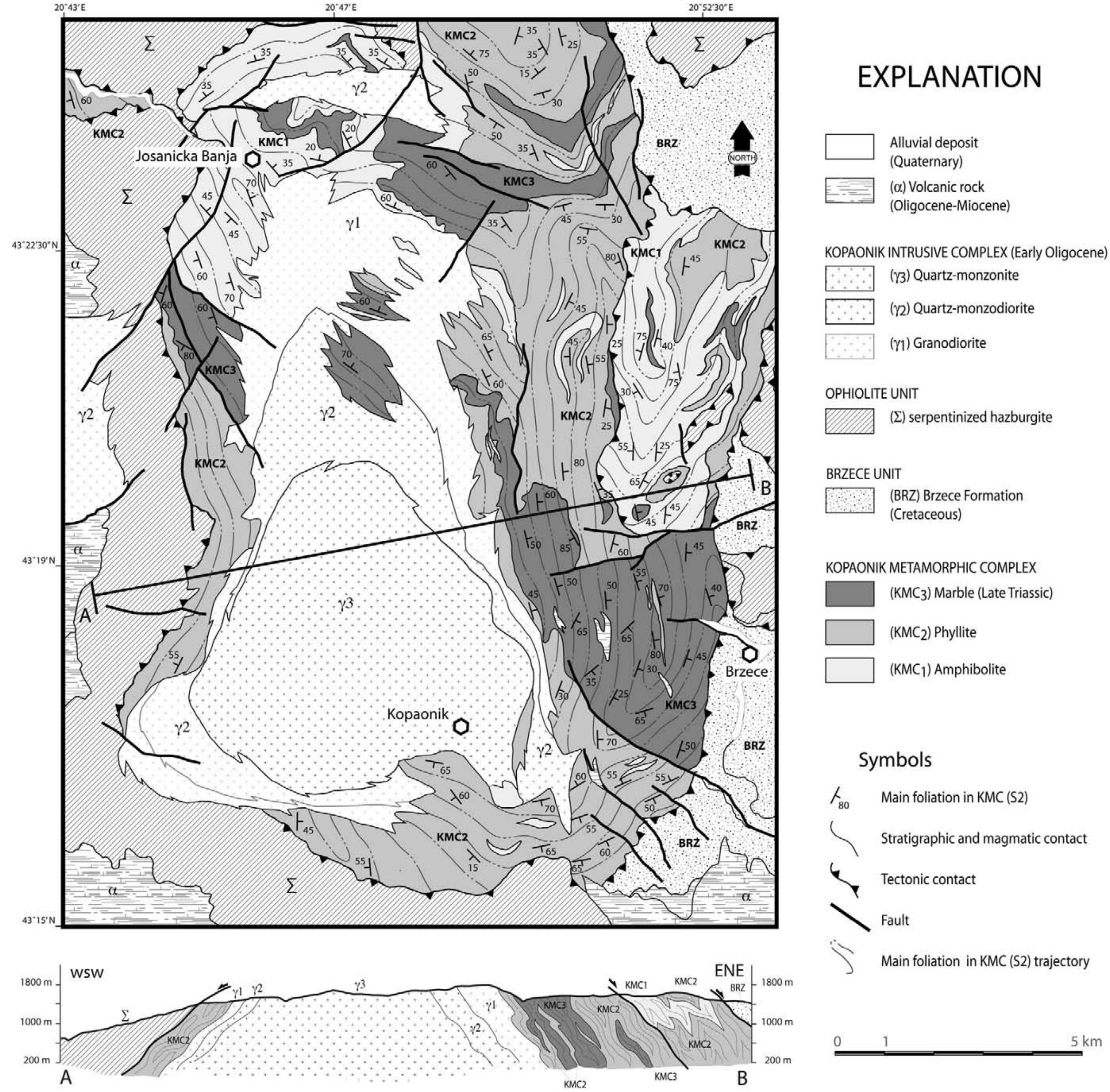

Fig. 2 - Simplified geological sketch-map of the Kopaonik area.

suggesting that this structural element, showing opposite shear sense along the flanks of the intrusive dome, can be interpreted as normal faults. Only in the south-east corner of the map, the Brezće Unit crops out with relevant thickness and good exposures. In addition, tectonic windows of the Kopaonik Metamorphic Complex below the Brezće and Ophiolite Units and klippen of the latter ones at the top of the first one have been identified, mainly in the eastern areas. The uppermost tectonic unit is the Brus Unit, that crops out only in the eastern side of the Kopaonik dome, where the best outcrops occur along the Graševača River valley and its confluents. Notably, the shear zone at the base of the Brus Unit is considered by Dimitrijević (1997) as the boundary between the Central and External Subzones of the Vardar Zone. In the mapped area both stacks of tectonic units are covered by very thin bodies of volcanic rocks of Oligo-Miocene age, showing a wide range of compositions. According to Dimitrijević (1997), the volcanic rocks belong to two different cycles; the first one is characterized by pyroclastic rocks, ranging in composition from latite to quartz-latite, followed by a second one, where the pyroclastic rocks show dacite to andesite compositions. These rocks have been found as scattered outcrops over the Kopaonik Metamorphic Complex in the eastern flank of the dome, the widest outcrops being in the southern part of the mapped area, along the Djerekari Valley. In addition, along the same valley, Miocene post-orogenic basin sediments have been identified. They consist of Middle Miocene sands and marls covered by Late Miocene to Early Pliocene fresh-water successions, starting with shales interbedded with conglomerates passing upwards to a 30-300 m thick coal level. This level is in turn topped by sands, conglomerates and shales where vulcanoclastic deposits have been found. These deposits, the underlying units and the intrusive complex are cut by a conjugate system of transtensive, subvertical faults showing NE-SW to WNW-ESE strikes.

Stratigraphy

In this chapter we describe the stratigraphy for each unit, from bottom to top (Fig. 3) and the main lithological and sedimentological features, the arenite composition and the paleontological ages. The Oligo-Miocene volcanic and sedimentary rocks are not described.

Kopaonik Metamorphic Complex

The Kopaonik Metamorphic Complex (Fig. 3) includes a deformed and metamorphosed succession mainly consisting of phyllites (KMC_2) showing a transition to marbles (KMC_3) of Late Triassic age (Zelic et al., 2010a and quoted references). The phyllites are thick sequences of m-thick layers, alternating with minor cm-thick layers of fine-grained marble. Rare cm-thick layers of fine-grained mica-rich quartzite also occur. The protoliths of these rocks are probably an alternance of limestone, shale, sandstone and siltstone (Fig. 4a). The phyllites are topped by marbles, to which they grade with an increase of frequency and thickness of the marble layers. The marbles layers alternate with very thick layers of meta-dolostones. A conodont assemblage of Late Triassic age (Sudar, 1986) has been found in the marbles. Bodies of amphibolites (KMC_1) have been also recognized in the Kopaonik Metamorphic Complex (Fig. 4b), with a geochemical affinity with basaltic magmas generated in a continental arc setting (Zelic et al., 2005). The pristine stratigraphic position and the age of the amphibolites cannot be assessed, owing to their strong deformation and metamorphism, even if their location at the base of the succession has been proposed (Zelic et al., 2005).

Brzeće Unit

The Brzeće Unit, about 700 m thick, is characterized by different turbidite facies associations, where a broad group of deposits, ranging from blocks to pebbly-mudstones, conglomerates, breccias, coarse-grained arenites and thin bedded turbidites and mudstones, is present. The Brzeće Unit (Fig. 3) includes a single formation (*Brzeće Formation, BRZ)* where three different members, from bottom to the top, have been recognized.

Thin Bedded Turbidite Member: this member (BRZ_1), cropping out mainly in the Brzeće area and along the road Brzeće-Blaževo (Fig. 4c), is characterized by thin-bedded turbidites with thin to medium beds (10-30 cm) of fine- to medium-grained arenites and coarse-grained siltites, showing a siliciclastic to mixed composition, alternating with 10 to 100 cm thick beds of carbonate-free shales, showing a sand to shale ratio generally <1. The arenite beds are characterized by a good lateral continuity. Td-e and subordinately Tc-e base missing Bouma sequences can be recognized and traction plus fall-out structures, such as ripples and climbing ripples, are common. The stratigraphic and sedimentological features of these deposits point to low density turbidity currents as main type of genetic flow.

Arenitic Member: The BRZ_1 Member grades to the Arenitic Member (BRZ_2). This latter crops out mainly in the right side of the Brezće Valley and is characterized by thick to very thick beds of medium to coarse-grained mixed arenites alternating with carbonate-free shale and subordinate shaly-marls (Fig. 4d). The nannofossil assemblage is represented by *Micula* sp and *Watznaueria* sp, that indicating an age not older than Late Coniacian (CC 14). The sand to

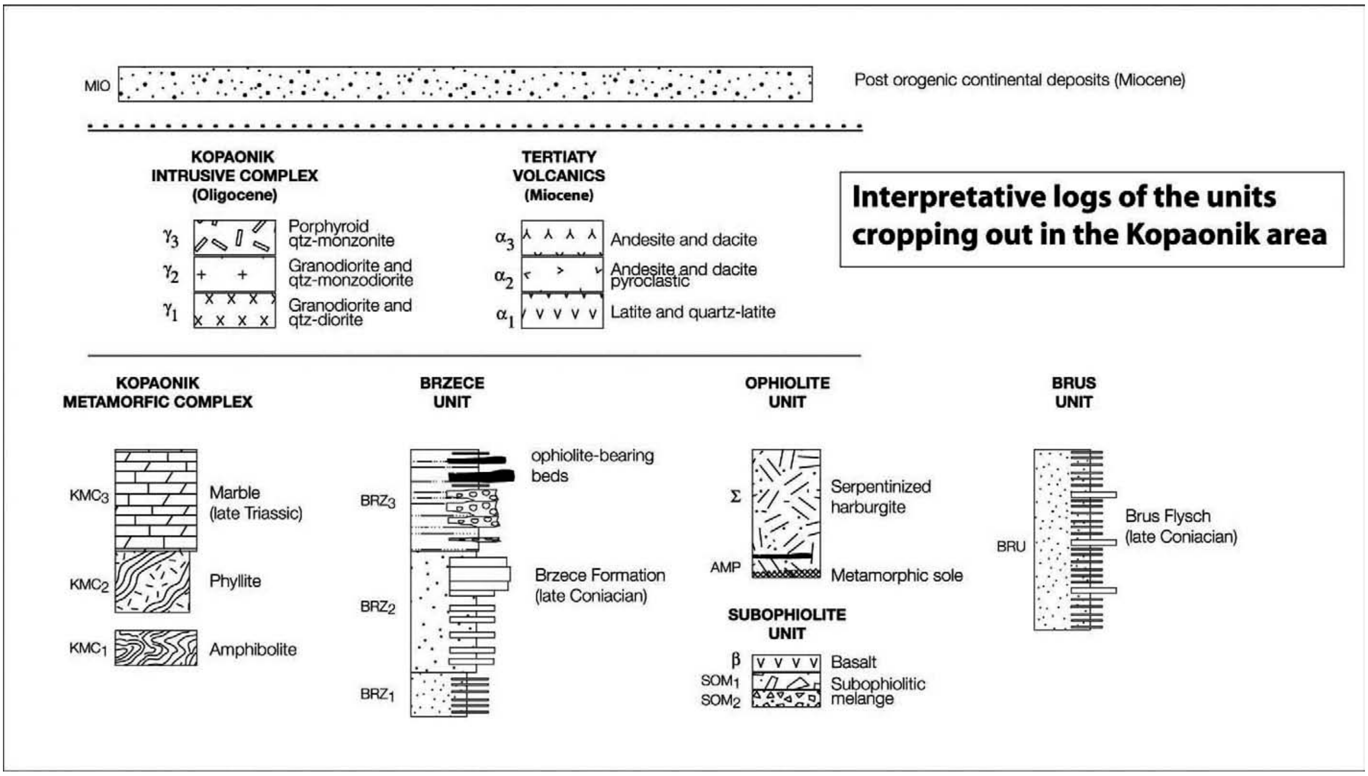

Fig. 3 - Stratigraphic log of the tectonic units cropping out in the Kopaonik area.

shale ratio is generally <1 but in the uppermost part of the sequence it reaches values >>1, due to the presence of sand lobes characterized by coarse-grained arenitic and ruditic amalgamated beds. These beds show a gentle lenticular shape and a thickness ranging from 20-30 cm up to several meters, even if the limits of the single beds are difficult to detect and the amalgamated beds are widespread. The "in mass deposition" seems to be the dominant process according to the presence of F_3 and/or F_5 facies of Mutti (1992) and the sedimentological features point to high density turbidity currents as main type of genetic flow.

These two members have a mixed carbonatic-siliciclastic sublithoarenitic composition, characterized by lithic (mainly carbonatic) rock fragments, quartz and feldspar monocrys-

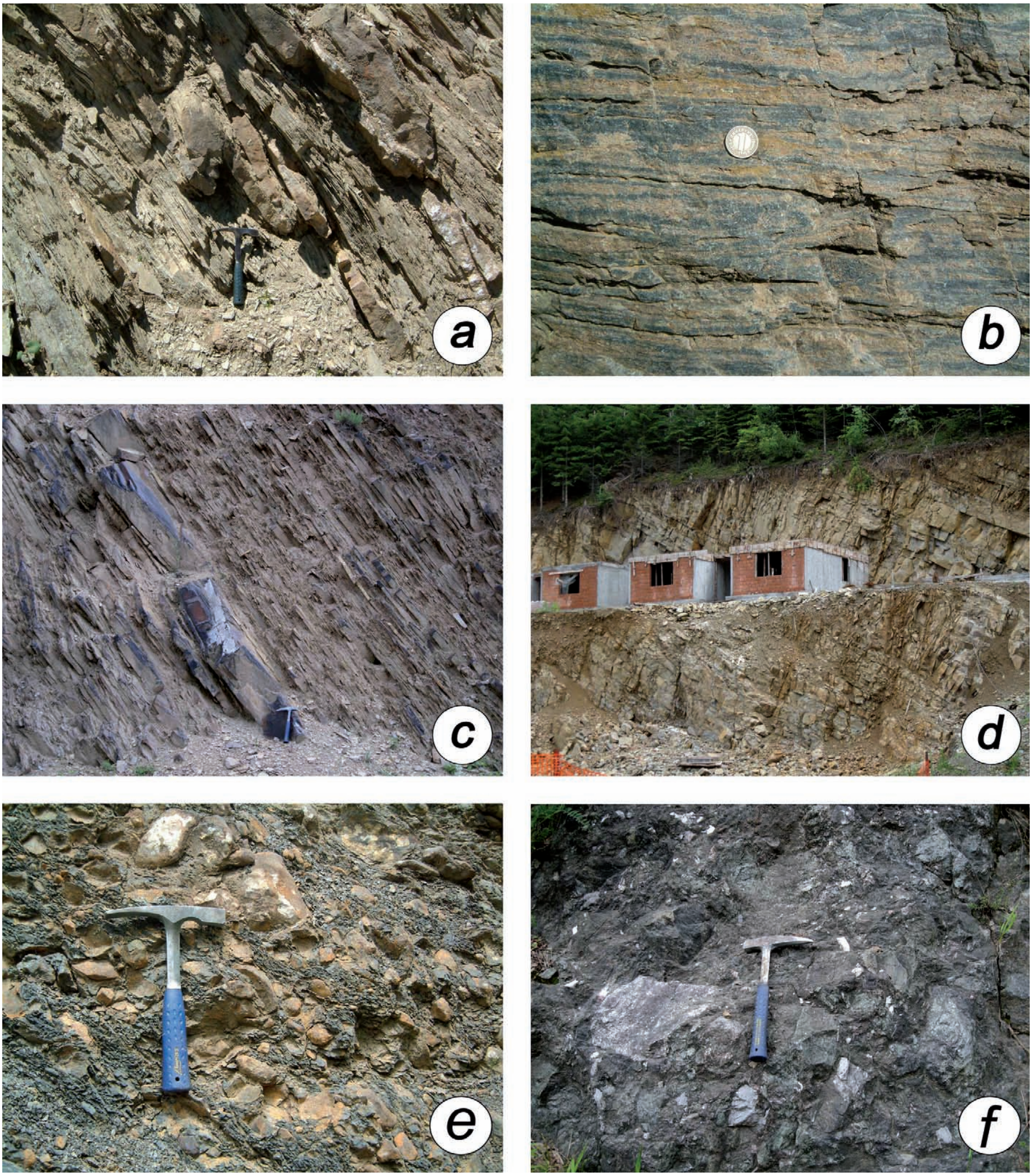

Fig. 4 - Field occurrence of the main lithologies. Kopaonik Metamorfic Complex. a- alternance of shale and metalimestone in the Phyllites formation; b- Amphibolites formation in the Kopaonik Metamorphic Complex. Brzece Unit. c- Thin Bedded Turbidite Member; d- Arenitic Member; e- pebbly mudstone in the Paraconglomeratic Member; f- ophiolite-bearing, clast-supported breccia in the Paraconglomeratic Member.

talline fragments (Fig. 5a). The lithic fragments are extrabasinal carbonate rocks mainly carbonate platform rocks, represented by oolitic and peloid grainstones, wackestones and mudstones, probably of Triassic-Jurassic age. Moreover, low-grade metamorphic rock fragments, such as micaschists and schists are widespread. In the uppermost part of the Arenitic Member the carbonatic extrabasinal rock fragments can be dominant and the arenites can be classified as calclithites, *sensu* Zuffa (1980)

Paraconglomeratic Member: This member (BRZ_3), at least 200 m thick, mainly crops out along the Brzeće-Brus road. It consists of mud- to clast-supported conglomerates (pebbly mudstones, pebbly sandstones and orthoconglomerates), coarse arenites, mainly derived from debris flows and high density turbidity currents. The term "debris flow" is here used with a general descriptive meaning and it includes a broad spectrum of deposits derived from cohesive debris flows, fluidal debris flows, grain flows (Pickering et al., 1989) and hyper-concentrated flows (Costa, 1988). The most common facies (Fig. 4e) is represented by monomict pebbly mudstones in which pebble- to boulder-sized clasts are enclosed into a predominant muddy and sometimes varicoloured matrix. The thickness of the beds ranges from a few decimeters to some meters, the shape is generally lenticular with lack of significant erosional features at the base. The matrix is made of arenitic to ruditic soft clasts of carbonate-free mud, mainly derived from hemipelagic shales (Fig. 5b). These sediments can be interpreted as cohesive debris flow deposits (F_1 and F_2 facies of Mutti, 1992).

In the uppermost part of this member ophiolite-bearing cohesive debris flow and hyper-concentrated flow deposits (Fig. 4f) are associated with subordinate coarse-grained high density turbidity current deposits. The grain size of these deposits ranges from small pebbles to coarse sands. Thick to medium beds without internal structures and with poor sorting (facies F_5 of Mutti, 1992) are widespread. Arenites (Fig. 5c) have a lithoarenitic composition, characterized by rock fragments and minor quartz and feldspar monocrystalline fragments. The lithic fragments are mainly ophiolite-derived rocks such as serpentinized mantle rocks, fine-grained basalts, radiolaria-bearing siliceous packstones and minor amphibolites from the metamorphic sole (Fig. 5d). The extrabasinal carbonate rock fragments are carbonate platform rocks, represented by oolitic and peloid grainstones, wackestones, mudstones, Cretaceous benthic foraminifera (e.g., *Paleodictyoconus arabicus* and undeterminable lamellibranchia fragments, Fig. 5c), probably of Jurassic - Early

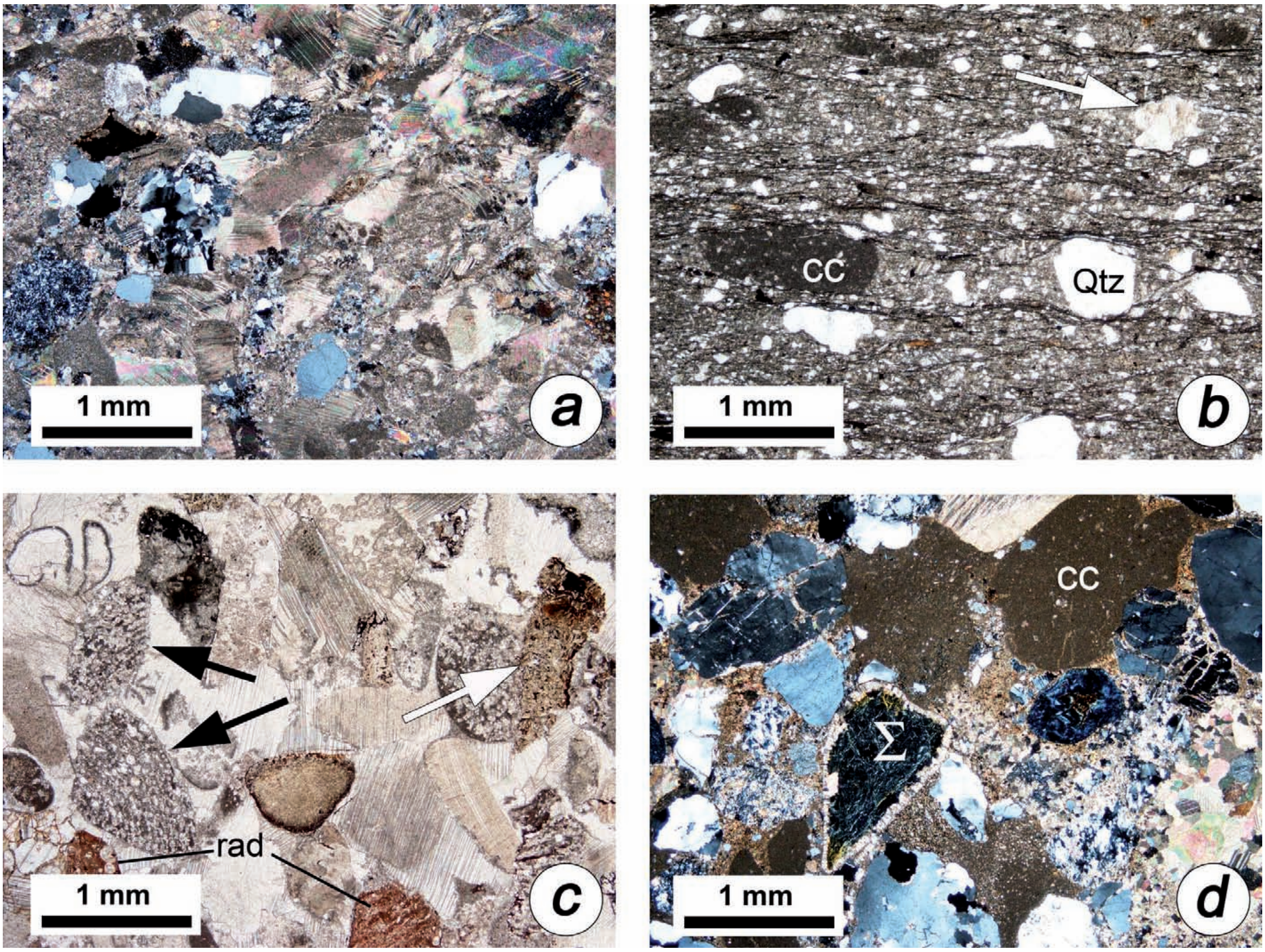

Fig. 5 - Photomicrographs of the Brzeće Formation arenites. a- mixed carbonatic-siliciclastic sublithoarenitic composition in the arenites from Arenitic Member. Crossed polars; b- arenitc matrix in the Paraconglomeratic Member, cc-mudstone, Qtz-quartz. Parallel polars; c- ophiolite bearing lithorenite from the Paraconglomeratic Member, rad-radiolarite, white arrow-basalt, black arrows: foraminifera fragment (*Paleodictyoconus arabicus*). Parallel polars; d-ophiolite bearing lithorenite from the Paraconglomeratic Member, cc:mudstone, σ- serpentinite. Crossed polars.

Cretaceous age. Finally, minor low-grade metamorphic rock fragments, such as micaschists and schists, have been also recognized in the arenites. These data point to a source area characterized by the reworking of ophiolites and related sedimentary cover.

The Subophiolitic Mélange

A sub-ophiolitic mélange crops out in the studied area between the Ophiolite and the Brzeće Units. In the Kopaonik area the Subophiolitic Mélange consists of thrust sheets (up to some hm in size) derived from oceanic domains (serpentinized peridotites, basalts, cherts and metamorphic sole-derived amphibolites). Three different tectonic slices have been recognized and mapped (see enclosed geological map).

The uppermost slice crops out in the Raporito area and it is made of massive basalts (β). It consists of a sequence about 50 m thick of pillow-lava basalts whose age is still undetermined. Below the basalts, a slice characterized by a quasi-monogenic breccia (SOM_1), consisting of serpentinite fragments in arenite matrix, has been identified (Fig. 6a). The lowermost slice consists of an assemblage of different types of sediments (SOM_2) ranging from clast-supported conglomerates (Fig. 6b) to coarse arenites, mainly derived from high density turbidity currents (cf. F_3 facies of Mutti, 1992). These beds, derived from high density erosive flows are characterized by frequent basal erosional features. The clasts are amphibolites, basalts, and minor serpentinites and radiolarites. These data point to a source area characterized by reworking of ophiolites and related sedimentary cover of the Ophiolite Unit.

The Ophiolite Unit

In the Kopaonik area, the Ophiolite Unit belongs to the Ibar hazburgite-serpentinite massif (Dimitrijević, 2001). It mainly consists of harzburgites, with slices of metamorphic sole at their base. Few km outside of the mapped area a subordinate intrusive sheeted-dyke complex occurs, where boninitic rocks have been reported (Marroni et al., 2004a). This finding suggests origin of these ophiolites in a fore-arc oceanic basin.

The harzburgites are generally strongly serpentinized and the only preserved structures are pyroxenite-rich, cm-thick layers. Rare lenses of dunites and scattered boudins of rodingites are also recognized in the field. In few outcrops, remnants of metamorphic soles have been detected. They mainly consist of alternating fine-grained amphibolites (Fig. 6c), coarse-grained augen amphibolites, and fine- to medium-grained, sometimes garnet-bearing, amphibolites, but quartz-rich and quartz-poor micaschists also occur (Fig. 6d). The thickness of the metamorphic sole ranges from 5-10m to more than 50 meters. The thickness reduction is probably the result of brittle deformation that produced a strong boudinage during thrusting.

Brus Unit

The Brus Unit includes a single formation about 500 m thick, here referred to as Brus Flysch (BRU), mainly consisting of thin-bedded turbidites, showing a sandstone to shale ratio generally >1. The thin-bedded turbidites are characterized by thin to medium bedded fine to medium grained siliciclastic arenites alternating with carbonate-free mudstones (Fig. 7a). These turbidites display Td-e and subordinately Tc-e base missing Bouma sequences and abundant traction plus fall-out structures, such as ripples and climbing ripples. Subordinate medium- to coarse-grained arenites showing the complete Ta-e Bouma sequence have been also recognized. The stratigraphic and sedimentological features of these deposits point to low density turbidity currents as the main type of genetic flow. The arenites of the Brus Flysch show a siliciclastic composition ranging from subarkose to arkose (Fig. 7b), and are characterized by prevalent monocrystalline quartz and feldspar fragments. Lithic fragments are mainly derived from granitoids and low grade metamorphic rocks, such as micaschists and gneiss even if acidic volcanics are also present. Rare quartzites are also present. Carbonatic and ophiolite derived rock fragments are lacking. The nannofossils assemblage detected in the mudstones includes *Micula* sp and *Watznaueria* sp, that indicate an age not older than Late Coniacian (CC 14).

The Kopaonik Intrusive Complex

The Kopaonik Intrusive Complex forms in the geological map a north-south elongated body, with two separated minor masses located north and west of the main body. The main body of the complex displays an onion-like structure consisting of three, concentric magmatic facies, hereafter referred to as A (γ_1 in the map), B (γ_2) and C (γ_3). According to the map facies distribution, the qtz-monzonites of facies C lie at the core (lowermost level), whereas the qtz-diorite of facies A (uppermost level) occurs at the contact with the host rocks. According to Urosević et al. (1973a), the transition between these magmatic facies is gradual and continuous, without clear and sharp contacts between them. The core of the Kopaonik Intrusive Complex is constituted of porphyroid qtz-monzonites and minor granodiorites (facies C, Fig. 6e), with an apparent thickness of 3 km. This facies is characterized by coarse-grained texture with cm-long crystals of K-feldspar and amphibole, whose long axes orientations are roughly distributed in a dome-like shape, with a continuous strike change from north-south in western and eastern areas to east-west in the northern and southern areas. Granodiorites and qtz-monzodiorites, medium grained to the north and fine grained to the south (Fig. 6f) are representative of facies B, whose apparent thickness ranges from 1 km, in the southern area, to 2-3- km in the northern ones. Facies A consists of 2-3 km thick fine-grained granodiorites and qtz-diorites. The main characteristic of this facies is the well developed magmatic foliation consisting of well-oriented crystals of plagioclases, K-feldspars, biotites and amphiboles. The foliation shows the same trend detected for facies C. The minor bodies consist of fine-grained granodiorites and qtz-diorites similar to those recognized in facies A and granodiorites with qtz-monzodiorites of facies B (Jošanička Banja).

In addition, along the northwestern margin of the Kopaonik Intrusive Complex, stocks and dykes of rocks with dioritic and qtz-dioritic compositions, cutting the granodiorites and qtz-monzodiorites of facies B, have been detected (Dimitrijević, 1997). The host rocks, mainly belonging to the Kopaonik Metamorphic Complex (Zelic et al., 2010b), are affected by thermo-metamorphism (Urosević et al., 1973a), well developed along the eastern and southern margins of the Kopaonik Intrusive Complex (see enclosed geologic map).

Structural Geology

The structural analysis was performed at different scales in order to outline the ductile deformation history of all the tectonic units cropping out in the Kopaonik area, from the Kopaonik Metamorphic Complex up to the Brzeće and the Brus Units. The brittle deformations are not addressed in this paper. The meso-scale structural analysis was carried through the 1:15,000 and 1:25,000 scale geological mapping of the study area. In all of these units a 1:15,000 scale

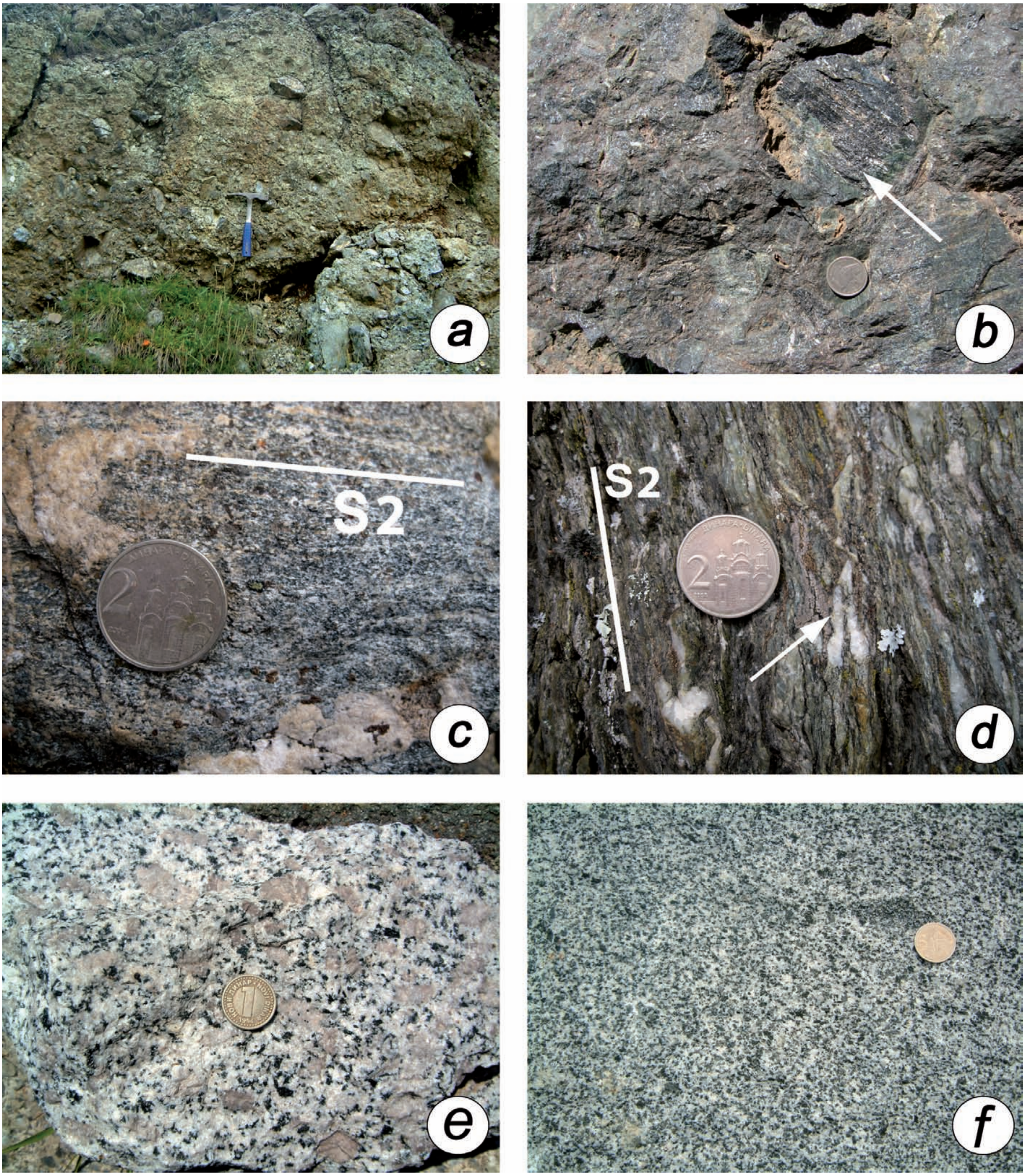

Fig. 6 - Field occurrence of the main lithologies. Subophiolitic Mélange. a- quasi-monogenic breccia (SOM_1), consisting of serpentinite fragments in an arenite matrix; b- clast-supported conglomerates (SOM_2) consisting of clasts from the metamorphic sole (white arrow) and the basalts. Ophiolite Unit. c- fine-grained amphibolites, the main S_2 foliation is indicated (S2); d- quartz rich micaschist, the main S_2 foliation is indicated (S2), white arrow indicate an intrafolial and rootless F_2 folds showing similar isoclinal geometry. Kopaonik Intrusive Complex. e- porphyroid qtz-monzonites (facies C); f- medium to fine grained granodiorites (facies B).

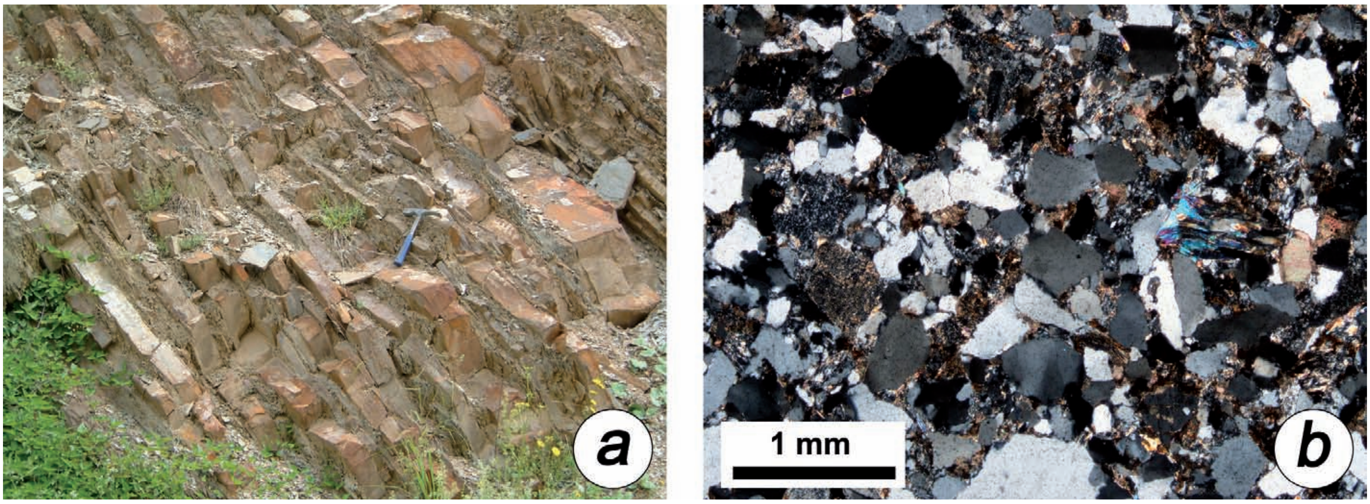

Fig. 7 - Field occurence (a) and coarse-grained arenite photomicrograph (b) of the Brus Formation. Photomicrograph crossed polars.

structural mapping was performed. The collected data have been analyzed statistically and projected on the lower hemisphere of the Schmidt net. During the field work about 100 oriented samples were collected for optical analyses in order to outline the microstructures of the deformed rocks and the metamorphic mineral assemblages. The thermo-metamorphic imprint connected with the granitoids intrusion was disregarded.

By contrast, the main body of the Ophiolite Unit does not display evidence of ductile deformation, according to its interpretation as an oceanic slice emplaced onto continental crust by an obduction process. As assessed in the literature (e.g., Michard et al., 1991) the obducted ophiolites escaped ductile deformations and metamorphism, which are instead concentrated at the base of the nappe, in the metamorphic soles. Thus, the deformation features for this unit can be detected only in the metamorphic soles, that crop out only in three small areas. In addition, the small extent as well as the very poor quality of the outcrops hampered the collection of structural data for the Subophiolite Mélange. Thus, no data about the mélange are here provided.

Kopaonik Metamorphic Complex

The oldest structure recognized in the Kopaonik Metamorphic Complex is the S_1 foliation, detected as relic in the microlithons inside the S_2 foliation. (Fig. 8a). In thin sections of phyllites (Fig. 8b) and amphibolites, the S_1 foliation is continuous and defined as schistosity consisting, respectively, of aligned white mica + chlorite + quartz ± Fe-oxides and oriented amphibole + plagioclase ± quartz ± biotite ± chlorite.

D_2 structures mainly consist of tight to isoclinal F_2 folds (Fig. 8c), generally symmetric, within the fine-grained marbles and phyllites, with subrounded to subangular hinges and thickened hinge zones. The limbs are generally affected by boudinage and necking, pinch-and-swell structures are also well developed. When asymmetric, the F_2 folds show a westward vergence. In addition, they are strongly non-cylindrical, as a result of non-coaxial deformation during the D_2 phase. Restored from the subsequent deformations, a NNW-SSE trend of the A_2 axes plunges towards SSE (Fig. 9). L_2 mineral lineations have been recognized as aligned white mica and quartz or as stretching lineations, represented by boudinaged millimetric pyrite and quartz grains associated with oriented growth of quartz fibers. The L_2 composite lineation shows an E-W trend (Fig. 9), however the most widespread D_2 structure is the S_2 foliation. In phyllites and amphibolites the S_2 foliation is a well-developed, continuous and transpositive anisotropy, generally sub-parallel to the bedding, whereas in the fine-grained marbles the S_2 foliation is well spaced and less penetrative. In thin section, the S_2 foliation within the phyllites is characterized by synkinematically recrystallized grains of white mica, biotite, chlorite and quartz (Fig. 8b). In the amphibolites (Fig. 8d), the S_2 foliation occurs as a schistosity mainly defined by oriented grains of amphibole, mainly hornblende, and plagioclase. However, in the coarse-grained lithologies, the S_2 foliation shows microlithons and/or porphyroclasts in which the S_1 relic foliation is preserved. In these samples the S_2 foliation can be classified as a crenulation cleavage. The S_2 foliation within the marbles is marked by synkinematically oriented grains, mainly calcite, dolomite and minor quartz. The mineral chemistry indicates that both the D_1 and D_2 phases developed at P = 0.20-0.60 GPa and T = 420-470°C (Zelic et al., 2010a).

The D_3 deformation phase formed symmetric, upright horizontal, moderately inclined horizontal, to upright moderately plunging F_3 cylindrical folds. The F_3 folds are open, close to tight, showing subangular to subrounded hinge zones. The A_3 axes generally show a NNW-SSE trend and very gentle plunges in all the domains of the studied area (Fig. 9). F_3 folds developed an axial plane cleavage, parallel to the vertical or subvertical axial planes (Fig. 8e). The LS_2-S_3 intersection lineation is mainly represented by a foliation/bedding intersection and mullion structures. Associated with F_3 folds, thrusts have been recognized as moderately inclined brittle shear zones, mainly N-S striking and with top-to-the-west kinematics. The S_3 foliation can be described in the phyllites and metabasites as a zonal, discrete to gradational crenulation cleavage, showing rough shapes of cleavage domains with parallel relationships (Fig. 8f).

The P-T conditions of the D_3 phase cannot be accurately estimated, but recrystallized crystals of calcite showing twins belonging to Types 1 and 2 of the Burkhard (1993) classification indicate a temperature ranging from 150 to 200°C. Even if the pressure cannot be estimated, decreasing P and T conditions can be assumed for the D_3 phase.

The D_4 structures are represented by F_4 symmetrical, cylindrical folds, showing sub-horizontal and horizontal axial planes. F_4 folds are very open, even gentle, having interlimb angles from 160° to 80° and mostly rounded hinge zones. Associated with F_4 folds, shear zones, characterized by brittle cataclasites and mainly located along the pre-existing D_3 thrusts, were recognized. The S-C kinematic indicators and brittle tectonic structures indicate normal motion

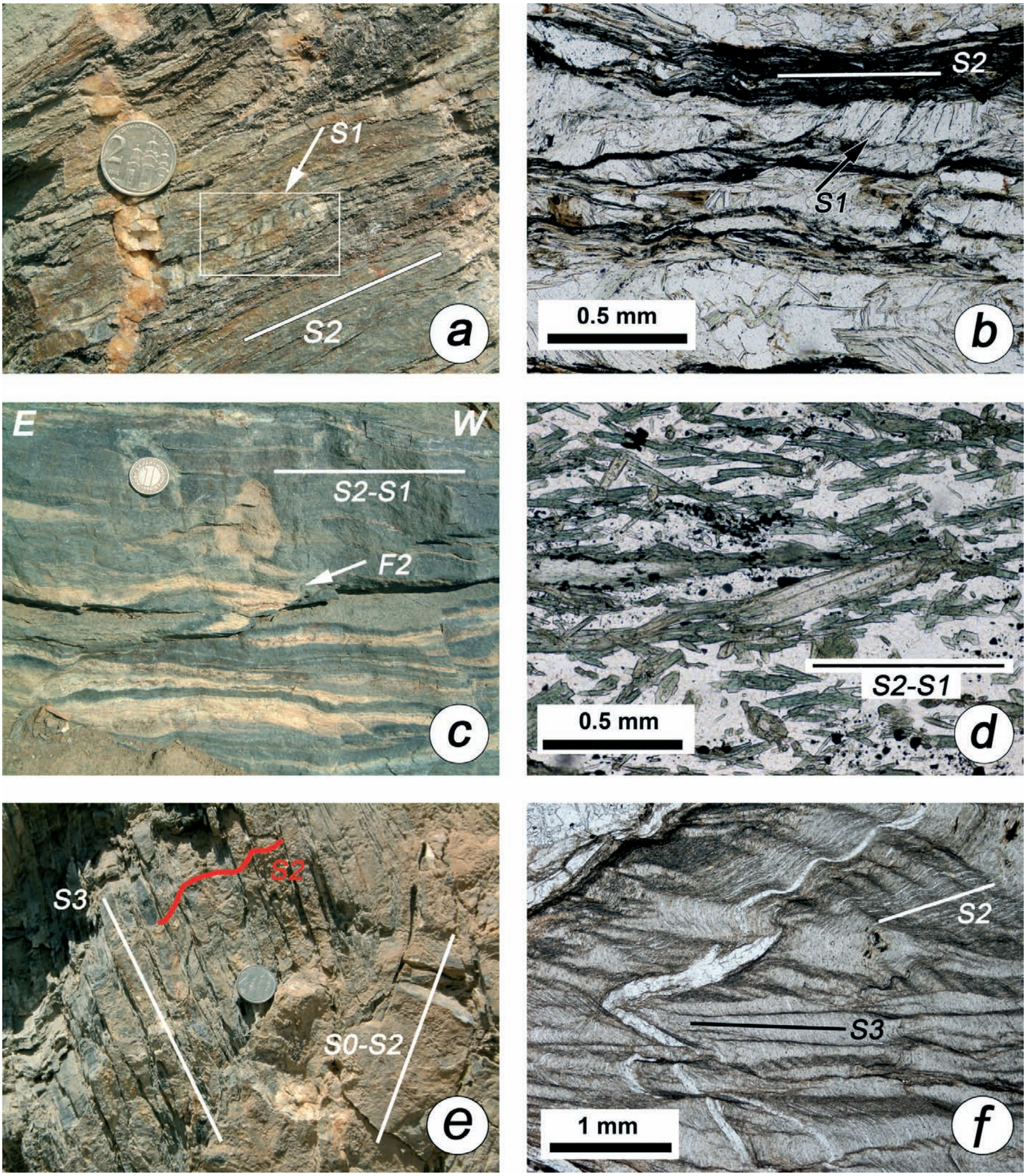

Fig. 8 - Field occurence and photomicrographs of meso- and microstructures in the Kopaonik Metamorphic Complex. a- Relationship between S_1 and S_2 foliations in the Phyllite Formation. In the boxed area microlithons with preserved S_1 foliation can be recognized; b- Relationship between S_1 and S_2 foliations in the metapelites of KMC. The relics of S_1 are indicated by the black arrow. Parallel polars; c- Composite S_1-S_2 foliation in the metabasites where an asymetric F_2 fold is well developed; d- composite S_1-S_2 foliation in the metabasites of the KMC (actinolite + plagioclase ± biotite ± chlorite). Parallel polars; e- Close-up of a F_3 hinge zone. The relationships among bedding (S_0) and axial plane foliations (S_2 and S_3) are well developed; f- Crenulation cleavage (S_3) in the metapelites of KMC well developed in the hinge zone of a F_3 fold. The previous S_2 foliation is also indicated. Parallel polars.

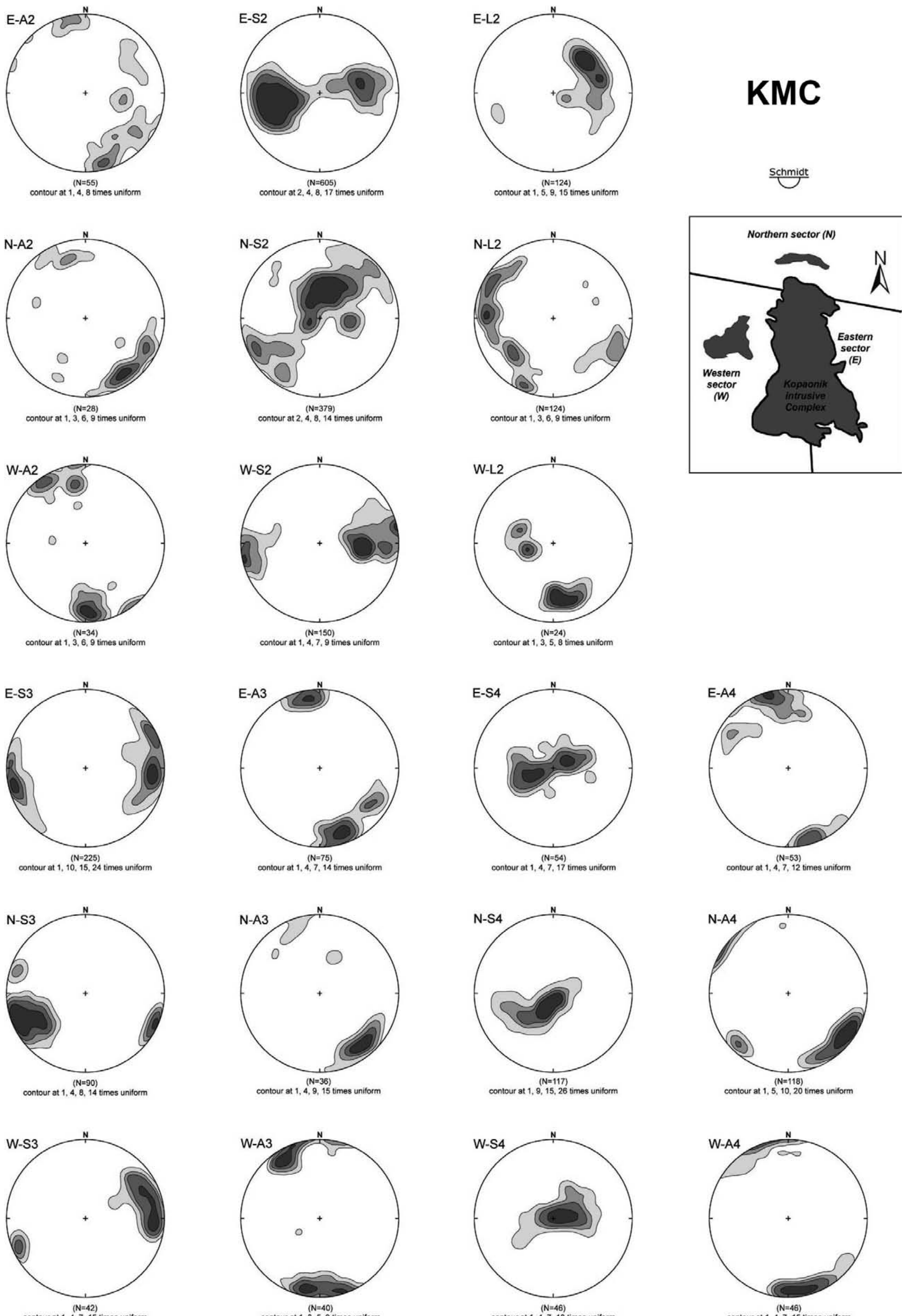

Fig. 9 - Stereographic representation of the main structural elements in the Kopaonik Metamorphic Complex. The three different sectors E, W and N are indicated.

along the D_4 shear zones. The A_4 axes show a change in their strike, that is found being parallel or sub-parallel to the margins of the Kopaonik Intrusive Complex (Fig. 9). West and east of the Kopaonik area, the A_4 axes are oriented generally N-S to NNW-SSE, which is also the orientation of the intrusive complex margins in these areas. To the north and south of the studied area, the A_4 axes display SW-NE and NW-SE trends, respectively. The A_4 axes are very gentle plunging in all domains. The S_4 foliation has been recognized as a crenulation cleavage, with rough to smooth shapes of cleavage domains, showing mainly a gradational transition between the S_4 and the earlier foliations. Associated to the S_4 foliation, recrystallization of quartz, calcite and Fe-oxides was observed.

P-T conditions of the D_3 phase can be proposed also for the D_4 phase.

Brzeće Unit

The structural history of the Brzeće Unit was reconstructed in the turbidite succession, where the deformations are fully recorded.

The D_1 phase was characterized by SE-NW-striking F_1 sub-isoclinal folds with interlimb angles ranging from 10° to 40°. F_1 folds can be described as cylindrical and symmetric with subrounded to subangular hinge zones (Fig. 10a). In the field, the main evidence of F_1 folds is the occurrence of parallel beds with the same attitude but opposite grading, though hinge zones are rare. F_1 folds are characterized by an axial plane S_1 foliation, recognized along the limbs of the folds as parallel to the S_0 bedding and in the pebbly-mudstones as pebble flattening (Fig. 10b). In thin section, the S_1 foliation (Fig. 10c) can be classified as a feeble slaty cleavage, characterized by a synkinematic mineral assemblage of quartz + albite + chlorite + white mica, typical of very low-grade metamorphism.

The F_1 folds as well as the S_0 bedding (Fig. 11) are deformed by symmetrical and cylindrical F_2 folds, showing rounded hinge zones. The F_2 folds are very open with interlimb angles ranging from 160° to 80°. Stereonets of A_2 fold axes show a dominant trend ranging from SE-NW to SSE-NNW, with a very gentle plunge to the SSE (Fig. 11). Their axial planes dip to the east of about 30°-50° (Fig. 11). In thin section, the S_2 axial plane foliation is a crenulation cleavage, showing rough and parallel cleavage domains.

The S_2 axial plane foliations are deformed by cylindrical NNW-SSE trending F_3 folds with subhorizontal axial planes. The S_3 axial plane foliation can be described as a well spaced fracture cleavage. In several outcrops F_3 folds are closely associated to low-angle normal faults.

The Ophiolite Unit

Even if scattered, the metamorphic sole outcrops provide evidence of a complex structural history, well preserved at the meso- and microscopic scale. Generally, foliations and folds are pervasively developed in the fine-grained rocks such as micaschists and fine-grained amphibolites (Fig. 6d), and hardly recorded in the coarse-grained amphibolites.

The oldest deformation (D_1 phase) recognized in the metamorphic sole was observed only in thin sections of micaschists, where relics of S_1 schistosity were preserved in microlithons inside the S_2 foliation as domains made up of lepidoblastic quartz, plagioclase and white mica aggregates. However, the main deformation structure detected in the amphibolites as well as in the micaschists is a well-developed planar S_2 schistosity originated during the D_2 phase. The S_2 schistosity in the metamorphic sole bears clear L_2 mineral lineations, marked by aligned hornblende and plagioclase minerals in the amphibolites, and by aligned white mica and quartz minerals in micaschists. F_2 folds are recognized in the micaschists (Fig. 6d) as well as in the amphibolites. These structures can be classified as similar isoclinal folds, generally intrafolial and rootless, with rounded hinges and axial planes parallel to the S_2 schistosity. In thin section, the most striking feature of the metamorphic sole is a well-developed and widespread S_2 schistosity. In the amphibolites, the S_2 foliation (Fig. 12a) is generally defined by thin layers of oriented plagioclases alternating with bands enriched in syn-kinematic amphibole (horneblende + actinolite) ± clinopyroxene. The micaschists are also characterized by a main S_2 schistosity (Fig. 12b) defined by thin bands of granoblastic plagioclase and quartz alternating with layers of lepidoblastic micas. A top-to-the W/SW shear sense of the metamorphic sole has been determined from the kinematic indicators, mainly C-type shear bands, mica fish and σ-type plagioclase and garnet porphyroblasts in both amphibolites and micaschists (Fig. 12c). As assessed by Carosi et al. (1996) and Gaggero et al. (2009) for the Albanian metamorphic sole, the previously described mineral assemblages, developed during lower to upper amphibolite facies metamorphism, can indicate temperatures ranging from 600°C to 800°C and a pressure lower than 0.7 GPa.

A later D_3 phase can be recognized in the amphibolites and micaschists, but it is poorly developed in the coarse-grained amphibolites. The D_3 phase is characterized by chevron, tight to open folds, associated with a poorly evolved S_3 axial plane crenulation cleavage. During the D_3 phase non-foliated cataclasites with strong grain-size reduction and rounded porphyroclasts of amphibole and clinopyroxene developed in millimetre to centimetre-thick shear zones, generally parellel to the S_2 foliation.

In addition, the boundaries of the Ophiolite Unit with the underlying Kopaonik Metamorphic Complex (Fig. 12d) and Brezće Unit and with the overlying Brus Unit are represented by metre thick, brittle cataclastic shear zones with normal kinematics. These shear zones show different attitudes along the flanks of the Kopaonik dome: west-dipping on the western flank and east-dipping in the eastern one, as reported in the geological map.

Brus Unit

In the Brus Unit the D_1 phase is mainly represented by F_1 isoclinal to sub-isoclinal folds with interlimb angles ranging from 10° to 30°. F_1 folds are cylindrical and symmetric, showing subrounded to subangular hinge zones (Fig. 10d). A_1 axes show N-S to NW-SE trends with gentle dips. The F_1 folds are associated to a well developed S_1 foliation, generally parallel to the S_0 bedding. The S_1 foliation is classifiable as a slaty cleavage (Fig. 10e), composed by a quartz + albite + chlorite + white mica mineral assemblage, typical of very low-grade metamorphism. The S_1 foliation displays a NNW-SSE to NW-SE strike, with moderate to subvertical dips, resulting from the following deformation phases (Fig. 11).

The F_2 folds, developed during the D_2 deformation phase, are symmetric, upright horizontal and moderately inclined horizontal folds, showing subvertical to vertical axial planes. F_2 folds are open to close with interlimb angles

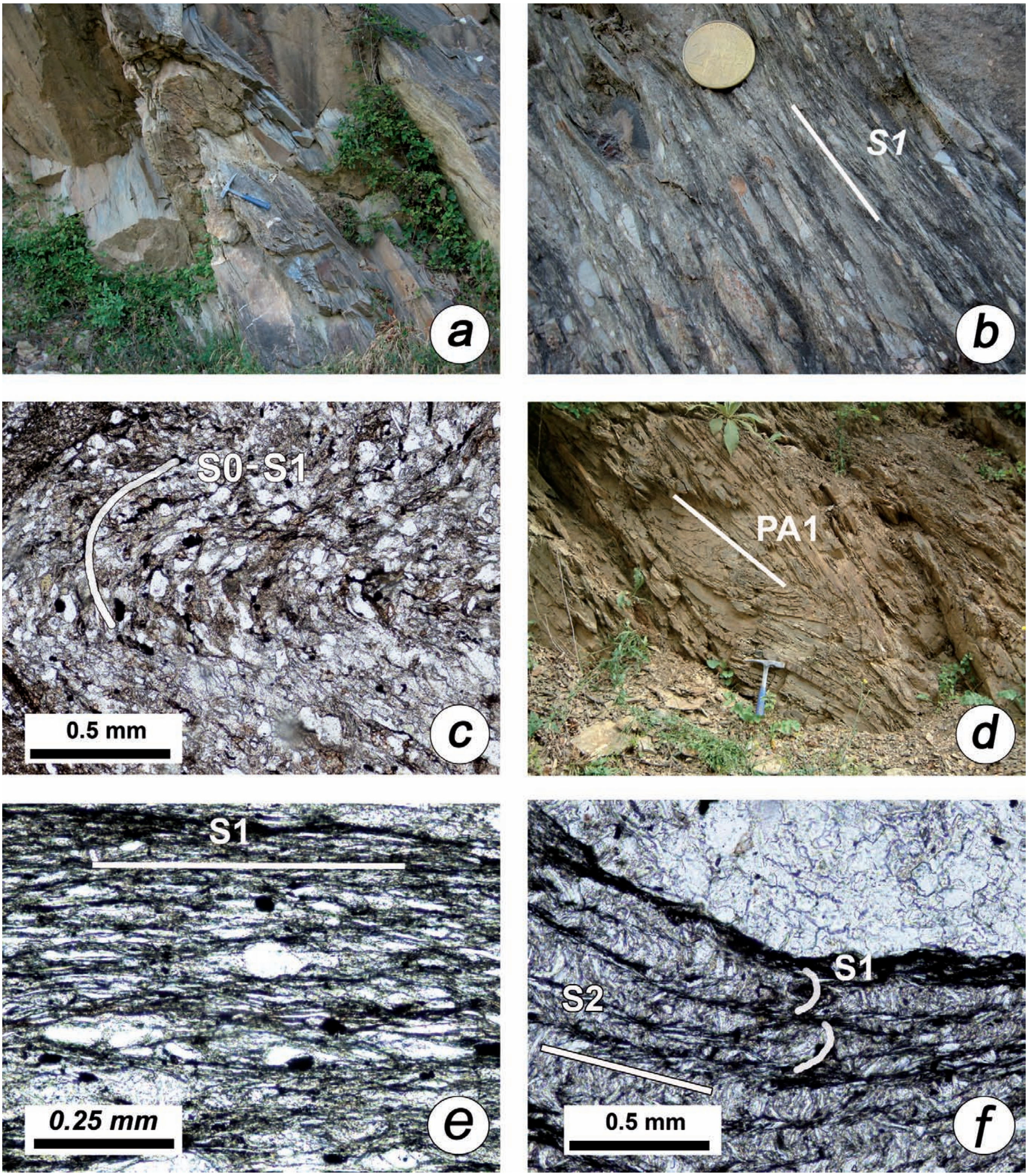

Fig. 10 - Field occurence and photomicrographs of meso- and microstructures in the Brzeće and Brus Units. Brzeće Unit. a- overturned close folds (F_1) developed in the Brzeće Formation; b- S_1 axial plane foliation characterized by pebble flattening. Paraconglomeratic Member (BRZ_3); c- S_1 foliation (S_1-S_2; refolded by the later D_2 event in the Thin Bedded Turbidite Member (BRZ_1). Parallel polars. Brus Unit. d- overturned close folds (F_1) developed in the Brus Formation. The PA_1 axial plane is indicated; e- S_1 foliation classifiable as slaty cleavage in the Brus Formation. Parallel polars; f- relationship between S_1 and S_2 foliations in the Brus Formation. Microlithons with preserved S_1 foliation are indicated. Parallel polars.

ranging from 30° to 100°. A_2 axes have subrounded hinge zones, and NNW-SSE to WNW-ESE trends with low dips (Fig. 11). The S_2 axial plane foliation is a crenulation cleavage, showing rough and parallel cleavage domains (Fig. 10f).

During the D_3 deformation phase the S_2 foliation was folded by F_3 folds, with subhorizontal to horizontal axial surfaces. The F_3 folds, generally associated to low-angle normal faults, are symmetrical, mostly cylindrical and very open, with rounded hinge zones and interlimb angles from

80° to 170°. A_3 axes strike about NW-SE and they have very low dips (Fig. 11). The S_3 foliation is a spaced foliation, smooth to rough.

TENTATIVE RECONSTRUCTION OF THE TECTONIC HISTORY

According to the collected data, all the tectonic units experienced polyphase deformations that can be related to a two-stage tectonic history (Fig. 13). The first stage, developed from Middle to Late Jurassic time, was mainly characterized by shortening during the closure of the oceanic basin located between the Adria and Eurasian Plates and the subsequent continental collision. The second stage developed during extensional tectonics and the related emplacement of intrusive magmatic rocks in Eocene - Oligocene time. Our field and structural data testify strong reworking overprinting? in the second stage of the first stage structures.

In the Kopaonik area the first stage deformations occur mainly in the Kopaonik Metamorphic Complex, but evidence is also found in the Brezće, Ophiolite and Brus Units. The oldest deformations are probably those related to obduction during oceanic closure, as in the metamorphic sole, where syn-metamorphic D_1 and D_2 phases, both in amphibolite facies, have been detected. The available radiometric ages in Serbia, from the metamorphic sole of the Vardar ophiolites (Lanphere et al., 1975; Okrusch et al., 1978; Lugović et al., 2006) indicate ages ranging from 161±4 to 178±14 Ma (recalculation proposed by Schmid et al., 2008). In addition a Sm-Nd isochron obtained from garnet, plagioclase, clinopyroxene, amphibole and whole rock on granulites from Borja, provided an age of 171.4±3.7 Ma (Lugović et al., 2006). The metamorphic sole from the Vardar Ocean ophiolites developed as a result of intraoceanic thrusting during the Middle to Late Jurassic obduction, as proposed in Albania (Dimo-Lahitte et al., 2001) and Greece (Spray et al., 1984). The D_3 deformation recognized in the metamorphic sole may have developed during the subsequent tectonic history, related to the emplacement of the ophiolite nappe, with the Subophiolite Mélange at its base, onto the Adria continental margin in the Late Jurassic.

In contrast, the shortening deformations recognized in the Kopaonik Metamorphic Complex can be related to continental collision that caused the D_1 and D_2 phases at a depth of 10-15 km. The same interpretation can be proposed for the D_1 phase recognized in the Brezće Unit, developed probably during continental collision, when the Adria Plate margin was progressively deformed by the westward migrating deformation front. Also the D_1 and D_2 phases identified in the Brus Unit can be associated to continental collision, probably during a mature stage. However, it is noteworthy that the D_1 phase in Brezće Unit and D_1 and D_2 phases in Brus Unit both developed at very shallow structural levels,

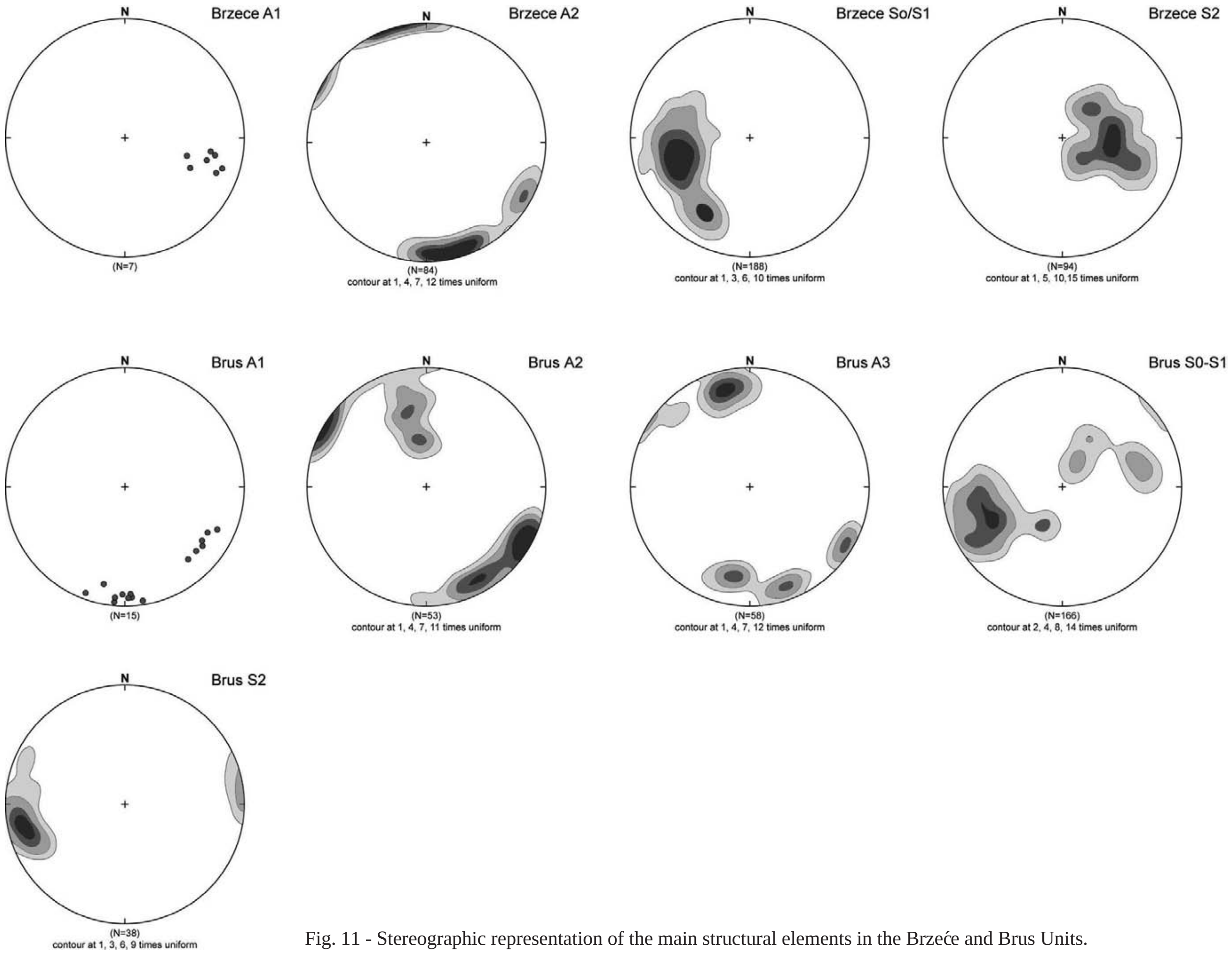

Fig. 11 - Stereographic representation of the main structural elements in the Brzeće and Brus Units.

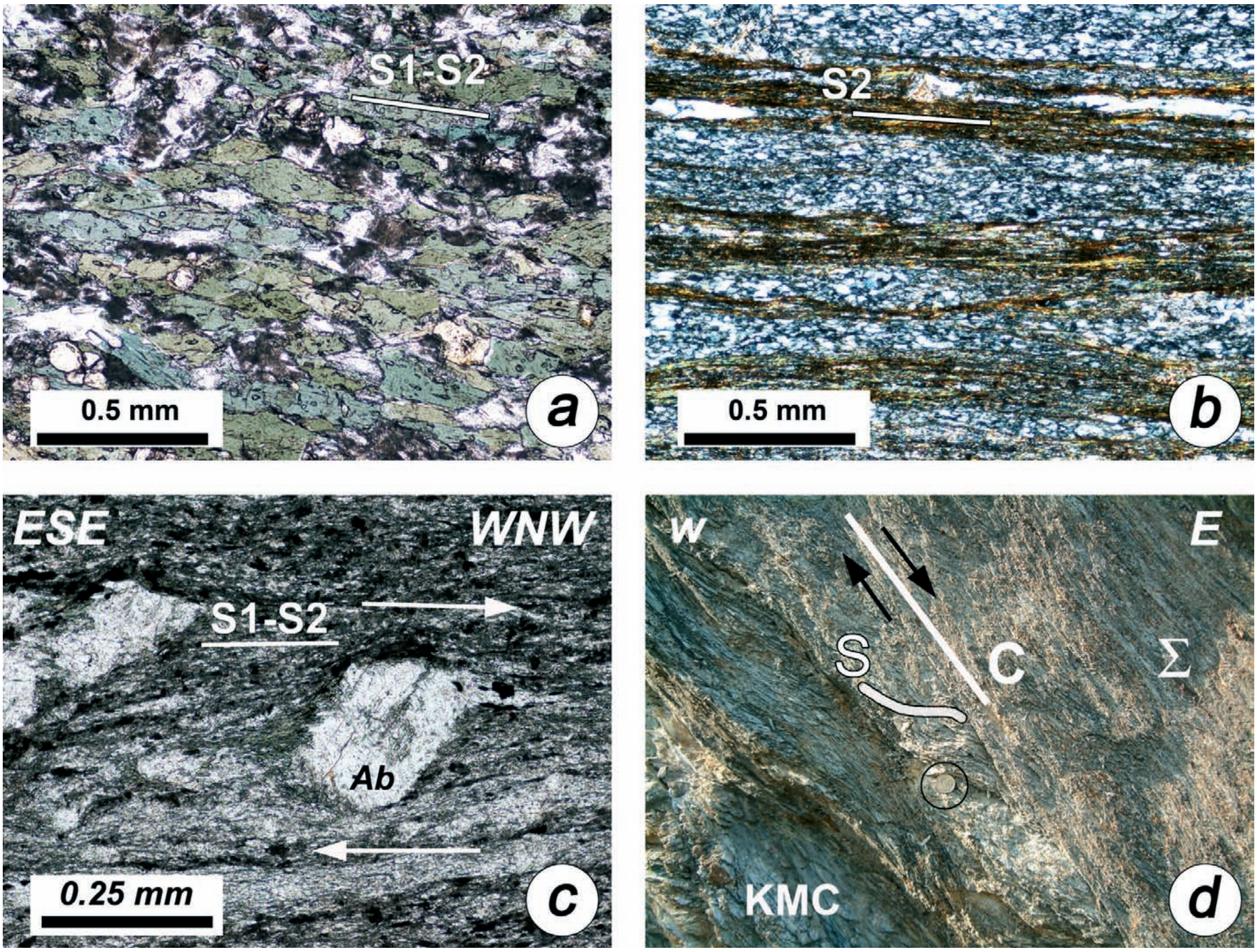

Fig. 12 - Field occurence and photomicrographs of meso- and microstructures in the Ophiolite Unit. a- composite S_1-S_2 foliation (S1-S2) in the Amphibolite Formation. Parallel polars; b- S2 foliation in the micaschists included in the Amphibolite formation. Crossed polars; c- σ-type albite (Ab) porphyroblasts in the Amphibolites Formation. The composite S_1-S_2 foliation (S1-S2) and the shear sense are indicated. Parallel polars; d- brittle cataclastic shear zone, showing normal kinematics, between the Amphibolite Formation (Kopaonik Metamorphic Complex, KMC) and the Serpentinites (Σ) belonging to the Ophiolite Unit. The S and C surfaces are indicated.

whereas the metamorphism associated to D_1 and D_2 phases of the Kopaonik Metamorphic Complex point out to a deeper deformation level. This implies that the first stage deformations identified in the Brus and Brezće Units were acquired before their coupling with the Kopaonik Metamorphic Complex.

The age of the first stage is still matter of debate. In the Vardar Zone, evidence of Late Jurassic - Early Cretaceous contractional deformation related to continental collision has been proposed by Robertson and Karamata (1994), Dimitrijević (1997) and Pamić et al. (2002). Ilić et al. (2005) propose an Early Cretaceous age for the collision-related tectono-metamorphic event by Ar/Ar datings of detrital white micas collected in Campanian to Maastrichtian turbidites from the Vardar Zone. In contrast, Karamata (1994), Robertson and Karamata (1994) and Zelic et al. (2010a) have proposed for the last stage of continental collision-related shortening a younger, Late Cretaceous age. A different picture is proposed also by Schimd et al. (2008), that consider the continental collision age as Late Cretaceous - Early Paleogene, according to the findings of Late Cretaceous magmatic rocks interpreted as ophiolites in the northern areas of the Dinaric-Hellenic Belt (Ustaszewski et al., 2009). However, the different continental collision ages are proposed along different geotraverses. These discrepancies can be explained with a diachronous continental collision along the Dinaric-Hellenic Belt, ranging from Early to Late Cretaceous, respectively from the southern to the northern areas.

Deformations related to the second stage can be detected in all the units cropping out in the Kopaonik area, in particular in the Kopaonik Metamorphic Complex where the D_3 and D_4 phases can be regarded as achieved during this stage. The association of F_3 folds with west-verging thrusts developed under retrograde metamorphic conditions suggests that the D_3 phase is the witness of exhumation of the Kopaonik Metamorphic Complex, that occurred through an extrusion mechanism (Zelic et al., 2010a). In this mechanism, the slice of upper continental crust involved in continental collision underwent buoyancy-driven exhumation along a thrust at the base of the continental slice coeval with a normal fault at its top (e.g., Chemenda et al., 1995; Faure et al., 1999). A model where the exhumed slice is topped by a normal fault can explain the coupling of the Kopaonik Metamorphic Complex with the overlying Brezće, Ophiolite and

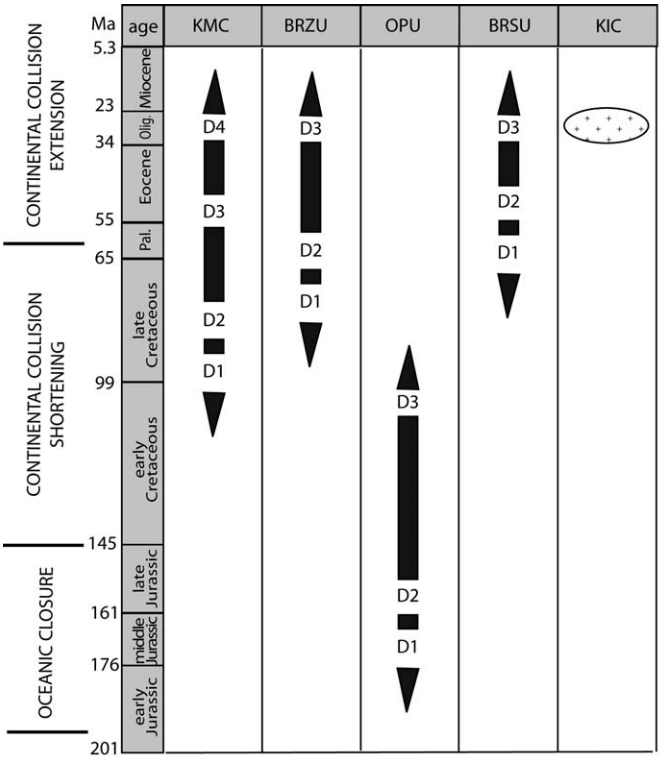

Fig. 13 - Time chart of the deformation in the different units from the Kopaonik area as reconstructed in this paper. Time scale from 2009 Geological Time Scale by the Geological Society of America from Walker et al. (2009).

Brus Units, all devoid of significant orogenic metamorphic imprint. However, the most evident deformations related to extensional tectonics are represented by the D_4 phase structures in the Kopaonik Metamorphic Complex as well as the D_3 phases in the Brezće and Brus Units, all developed at very shallow structural levels. These deformations are not observed in the Ophiolite Unit, probably due to non suitable lithologies. On the whole, all these structures with folds, with flat-lying axial planes and horizontal fold axes, always associated with low-angle normal faults, can be interpreted as originated from vertical shortening and folding of preexisting non-horizontal layers. In our reconstruction, the shear zones that bound these units are reworked?reactivated as low-angle normal faults during this phase. This type of deformation is typical of extensional tectonics, such as recognized in some areas of the Alpine belt (Ratschbacher et al., 1989; Froitzheim, 1992; Wheeler and Butler, 1994; Marroni et al., 2004b). In our interpretation, this deformation was strictly associated with the emplacement of the Kopaonik Intrusive Complex in Early Oligocene. Also the strikes of the structures of this phase, which are subparallel to the boundary of the intrusive body, suggest their close relationships with the intrusion. The close relationships between extensional tectonics and emplacement of intrusive rocks has been detected in other areas of the Dinaric-Hellenic collisional belt (Ricou et al., 1998; Kilias et al., 1999; Kounov et al., 2010). Thus, these deformations as well as the emplacement of the Kopaonik Intrusive Complex can be regarded as the results of extensional tectonics that affected the whole northern area of the internal side of the Dinaric-Hellenic Belt during Oligocene-Miocene times (Dinter and Royden, 1993; Pamić, 1993; Dinter, 1998; Pamić and Balen, 2001; Cvetković et al., 2007a; 2007b). Deformations related to the second stage probably started in the Eocene, as suggested by extension-related magmatism with Early Eocene to Miocene ages (Pamić and Balen, 2001).

IMPLICATIONS FOR THE JURASSIC-CRETACEOUS PALEOGEOGRAPHY

The proposed tectonic history reconstruction allows some considerations about the Jurassic-Cretaceous paleogeography of the Vardar Domain.

As proposed by Rampnoux (1970), Schmid et al. (2008) and Zelic et al. (2010a) a correlation between the Triassic successions of the Kopaonik Metamorphic Complex with that of the Drina-Ivanjica Zone can be suggested because of the common occurrence of calc-alkaline basic rocks associated with a Middle to Late Triassic carbonate sequence. Thus, the Kopaonik Metamorphic Complex can be interpreted as a deformed and metamorphosed slice derived from the same domain as the Drina-Ivanjica Zone (Zelic et al., 2010a). In our reconstruction (see for instance Bortolotti et al., 2005) the Drina-Ivanjica Zone in Serbia, as well as the Korab-Pelagonian Zone in Albania and Greece, are regarded as belonging to the Adria continental margin during Late Jurassic - Early Cretaceous. Accordingly, the Kopaonik Metamorphic Complex can be interpreted as a fragment of the Adria continental margin.

In turn, the Ophiolite Unit can be regarded as derived from the fore-arc basin of the Vardar Ocean that separated the Eurasian and the Adria continental margins during the Middle Jurassic, when continental crust started to be subducted (Marroni et al., 2004a). Thus, the Ophiolite Unit of the Kopaonik area represents a fragment of this oceanic basin emplaced onto the Adria continental margin via obduction. This process resulted in the development of the wide ophiolite nappe that presently characterizes the Dinaric-Hellenic Belt.

In this picture, the Subophiolite Mélange, that includes different slices and coarse-grained deposits derived from the ophiolite sequences (serpentinites, basalts, radiolarites, amphibolites) can be interpreted as developed during the marginal? stage of the obduction process (Michard et al., 1991), leading to the emplacement of the Ophiolite Unit onto the Adria continental margin. The occurrence of tectonic slices and polimict breccias of probable Late Jurassic age can be explained by a tectonic process leading to mélange formation. During this process, the Subophiolite Mélange incorporated fragments of the deposits with progressively different ages on which they pass through, continuing to grow until the last westward movement.

According to their stratigraphic features, the Brzeće Unit deposits can instead be interpreted as turbidites sedimented during the Late Cretaceous in an elongated basin bordered by a continental margin under erosion but also, probably on the opposite side, by an advancing ophiolite nappe. This reconstruction is supported by the characteristics of arenites and pebbles??, that show a mixed carbonatic-siliciclastic sublithoarenitic composition in the lower and middle members of the succession, whereas in the upper one ophiolites fragments are widespread. Thus, the Brezće Unit can be derived from the foredeep basin placed onto the Adria continental margin, and originated by the westward migration of the compressive front. This basin was thus supplied westwards from the Adria continental margin undergoing bending and erosion flexuration? and, on the opposite side, from the orogenic wedge, consisting at this time of obducted oceanic units still being deformed during the first stages of continental collision (Mikes et al., 2008; Luzar-Oberiter et al., 2009; Marroni et al., 2009). From the orogenic wedge can derive also the carbonate fragments, given the growth of a carbonate platform at the top of the obducted oceanic sequence in Late Jurassic-Early Cretaceous (Gawlick et al, 2008).

Very puzzling is the paleogeographic location of the Brus Unit. Based on arenites composition, the source area of the Brus Unit results as a typical continental domain. Taking into account the regional tectonic position of the Brus Unit, i.e. at the top of the unit pile, it seems probable that this domain was located close to the deforming Eurasia passive continental margin. This domain can be identified in the Serbo-Macedonian Massif, presently located east of the Vardar Zone. In this frame, the Brus Unit includes turbidites deposited in a thrust-top basin located in the hinterland of the forming Dinaric-Hellenic Belt. This basin was probably built on a substrate of deformed units belonging to the suture zone, developed since Late Cretaceous as a consequence of the collision between the Adria and Eurasia Plates. A tentative Late Cretaceous reconstruction showing the paleogeographic location of the different Kopaonik units is proposed in Fig. 14.

CONCLUSION

The geological mapping of the Kopaonik area, associated to structural and stratigraphical analyses, has provided a complete dataset on the tectonic setting of the Vardar Zone. The studied area is characterized by a tectonic pile, including oceanic and continental units, intruded by an Oligocene intrusive complex. These units show different structural and metamorphic histories acquired during the long-lived Jurassic to Miocene evolution of the Dinaric-Hellenic Belt. One of the main results of this study is the identification of a polyphase structural history related to extensional tectonics of Eocene-Miocene age that affected the hinterland of the Dinaric-Hellenic collisional belt. This extensional tectonics produced not only ductile deformations inside the different tectonic units, but also modified their relationships. In this frame, the shear zone that separates the tectonics units can be interpreted as a low-angle, brittle normal fault. Even if the structural setting of the Kopaonik area has been acquired mainly by thinning during extensional tectonics and the related emplacement of the granitoid body, this area provides a good section where also the shortening-related tectonic history can be reconstructed. This tectonic history, acquired during the Middle to Late Jurassic closure of the oceanic basin and the subsequent Early to Late Cretaceous continental collision is recorded by the oldest deformations recognized in the tectonic units. According to the collected data, these deformations developed at different structural levels and in different geodynamic settings. This suggests that the shortening-related deformations were acquired before the coupling during the following extensional tectonics.

On the whole, the Kopaonik area can be regarded as a true key-area where the different models proposed for the Vardar Zone can be verified, in order to provide valuable constraints for the geodynamic reconstruction of the Dinaric-Hellenic Belt.

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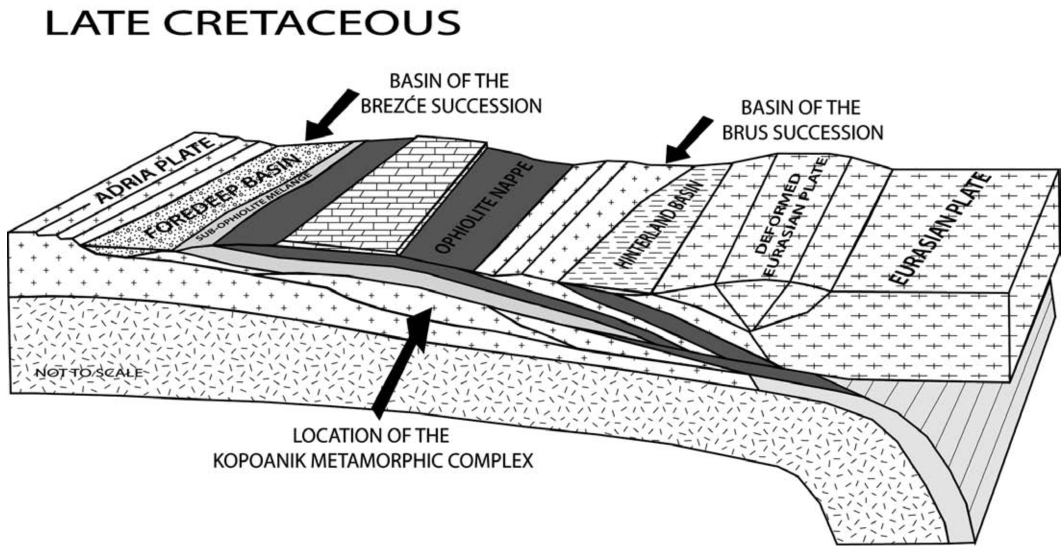

Fig. 14 - Three-dimensional, not to scale paleogeographic reconstruction of the Dinaric-Hellenic Belt during the Late Cretaceous. The proposed location of the units recognized in the Kopaonik area is shown.

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