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Correlation of metabasic rocks from metamorphic soles of the Dinaridic and the Western Vardar zone ophiolites (Serbia): three contrasting pressure-temperature-time paths

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Abstract. The field, petrological-mineralogical, geochemical and geochronological data of the metamorphic sole rocks recorded beneath the Fruška Gora, Povlen (Tejići), Stolovi and Banjska ophiolites in the Western Vardar Zone (WVZ) and beneath the Zlatibor, Bistrica, Sjenički Ozren and Brezovica ophiolites in the Dinaridic ophiolite belt (DOB) in Serbia are compared. The focus has been made on metabasic rocks formed in contact with the oceanic crust members: cumulate gabbro and basalts of SSZ-type with E-MORB and OIB-signature and more evolved tholeiitic basalts of MOR-affinity.

Amphibole, the major phase formed from the mafic sole components, depending on pressure-temperature conditions exhibits compositional variations. According to mineral assemblages, estimated P–T conditions and ages, the potential P–T paths are given: *high pressure – low temperature blueschist facies* assemblage (7–9 kbar and ~400°C and <300–350°C and 4–8 kbar), recorded only in the metamorphic sole at the Fruška Gora (WVZ); *high pressure – high temperature amphibolite to granulite facies* (8–10 kbar and >700–850°C), recorded in both domains, the WVZ (Banjska) and the DOB (Bistrica, Sjenički Ozren, Brezovica) and *medium pressure – medium temperature amphibolite facies assemblages* (~3.5–7 kbar and >350–650°C) recognized in the WZV (Tejići, Devovići) and the DOB (Zlatibor). The peak metamorphic conditions point to depths of the oceanic lithosphere detachment and its initial cooling at 10–30 km, but the ages and tectonic setting of ophiolites remain poorly constrained. The summarized data may be used as an important key in geodynamic evolution of the Mesozoic Tethyan ophiolites.

Key words: Serbia, Western Vardar Zone, Dinarides, ophiolites, metamorphic sole, metabasic rocks, amphibole, PT conditions, correlation.

Апстракт. Постојећи теренски, петролошко-минералошки, геохемијски и геохронолошки подаци о метаморфним стенама развијеним у подини офиолитског појаса Западне Вардарске Зоне (Фрушка гора, Повлен, Столови и Бањска) и Динарида (Златибор, Бистрица, Сјенички Озрен и Брезовица) у Србији корелисани су и допуњени новим минералошким подацима о амфиболитима Бистрице. Разматрани су само метабазити формирани метаморфизмом стена океанске коре тј. кумулатних габрова и базалта из супра-субдукционих зона са геохемијским афинитетом обогаћеног MORB-а и OIB-а или више диференцираних толеитских базалта средњоокеанских гребена.

Разлике у саставу амфибола, главне минералне фаза метабазита, последица су услова метаморфизма и карактера протолита. На основу минералног састава, P–T услова и старости метаморфизма, издвојена су три потенцијална P–T–t метаморфна градијента:

– *високих притисака–ниских температура: асоцијација блушист фације* (7–9 kbar, T ~400°C и <300–350°C, P 4–8 kbar; 123 ± 5 Ma); забележена је једино у метаморфном ореолу Фрушке Горе (Западна Вардарска зона);

– *високих притисака и температура: гранулитска до амфиболитска фација* (8–10 kbar и >700–850°C; 146 ± 4.9 Ma – 174 ± 14 Ma); асоцијација забележена у метаморфном ореолу Бањске (Западна Вардарска зона), Бистрице, Сјеничког Озрена и Брезовице (Динаридски офиолитски појас).

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– *средње високих притисака и средњих температура:* амфиболитска фација (~3.5–7 kbar и >350–650°C; 160–178.3 ± 6.7 Ma), забележена у Тејићима и Девовићима (Западна Вардарска зона) и на Златибору (Динаридски офиолитски појас).

P–T услови метаморфизма указују на „одвајање“ океанске литосфере и почетак хлађења на дубини од 10–30 km, али су тектонске средине и старост метаморфизма за поједине локалности и даље недовољно проучене. Приказани подаци су важни за тумачење геолошке еволуције Мезозојских офиолита Тетиса.

Кључне речи: Србија, Западна Вардарска зона, Динариди, офиолити, метаморфне стене, метабазити, амфиболи, P–T услови, корелација.

Introduction

Numerous ultramafic sequences worldwide comprise high to medium and low grade metamorphic sole rocks formed during the overthrusting of hot lithospheric fragments in intra-oceanic settings or within orogenic belts. Their presence is the clue in clarifying the nature of emplacement processes during intra-oceanic subduction and post-obduction tectonic events. The creation of metamorphic sole is among the earliest event at the end of magmatic construction when tectonic processes take part in ophiolite evolution instead of igneous (JAMIESON 1986; GARFUNKEL 2006). The size of metamorphic sole, its age, thermal evolution and peak metamorphic condition can enable a better insight into the age and thermal properties of the ophiolite sequences during their emplacement. Moreover, it is of key importance in proceedings related to the ocean-realm evolution.

Well to slightly evolved metamorphic sole rocks occur beneath most of the Jurassic Tethyan-type ophiolites in the Western Vardar Zone (WVZ) and in the Dinaridic belt (DOB) in Serbia. The best preserved metamorphic sole rocks crop out within the DOB in association with the Zlatibor, Bistrica, Sjenički Ozren and the Brezovica ophiolites, and in the WVZ in association with the Fruška Gora (FG), Maljen, Povlen (Tejići), Stolovi and the Banjska ophiolites (Fig. 1). The majority of them comprise approximately 100–250 m thick assemblage of metasediments associated with high to medium grade metabasites.

The goal of this contribution is to make correlation sole amphibolites evolved beneath two ophiolite belts i.e. the DOB and the WVZ, on the basis of available geological, geochemical and geochronological data contributed with some new data related to the garnet amphibolites of Bistrica.

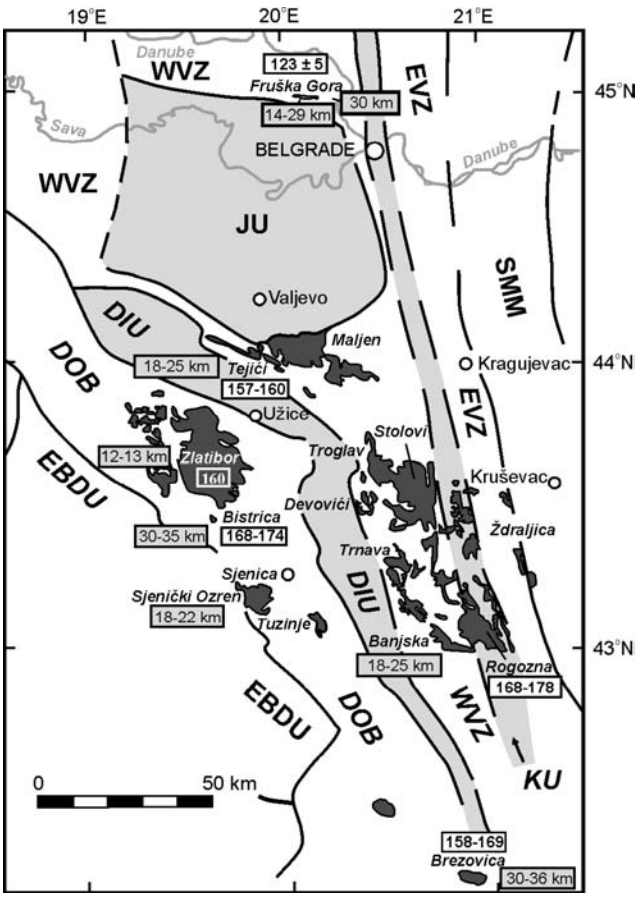

Fig. 1. The ultramafic massifs of Serbia in the geotectonic framework of KARAMATA (2006) with K–Ar radiometric ages of their metamorphic sole rocks and depths realized according to P-T condition of metamorphism. Abbreviation: **EBDU**, East Bosnian Durmitor Unit; **DOB,** Dinaride Ophiolite Belt; **DIU,** Drina Ivanjica Unit; **WVZ,** Western Vardar Zone ophiolite belt; **JU,** Jadar Unit; **KU,** Kopaonik Unit; **EVZ,** Eastern Vardar Zone ophiolite belt; **SMM,** Serbo-Macedonian Massif.

Geological setting

The closure of the Tethyan oceanic realm in the Central Balkan Peninsula since Early Jurassic time was followed by subduction of the oceanic lithosphere along convergent continental margins or within supra-subduction oceanic environments (KARAMATA 2006; ROBERTSON *et al*. 2009, and references there in).

The NNW–SSE trending WVZ represents a large "suture zone" exposed between the Drina–Ivanjica, Kopaonik and the Jadar Units, which continues further northwest (close to Zagreb, Sava Zone of PAMIĆ 2002) and crops out in isolated mountains (Fruška Gora, Pozeška Gora and Prosara) northwest of Belgrade. To the south it extends between the Pelagonian and the Paikon Unit. The WVZ is made of various dismembered ultramafic masses generally harzburgitic (± spinel) in composition with 160 to 123 Ma aged metamorphic sole at their base – mainly amphibolites and subordinated blueschists, gneisses, mica schists and greenschists (KARAMATA *et al.* 2000; MILOVANOVIĆ *et al.* 1995; SREĆKOVIĆ-BATOĆANIN *et al.* 2006; BAZYLEV *et al.* 2009; KORIKOVSKY *et al.* 2000a).

The NW–SE trending DOB is bordered by the Drina–Ivanjica Unit to the east and the WVZ to the northeast and extends to the Dinaridic Carbonate platform to the west and related units to the southwest (Fig. 1). Southwards it enters Metohija Depression and continues to Albania and Greece. The dismembered ultramafic bodies are interpreted as fragments of subcontinental mantle or as supra-subduction (back arc) type. The former is mostly lherzolitic (± garnet) and the latter is lherzolitic (± spinel)-harzburgitic in composition (BAZYLEV *et al.* 2006a, 2009). The metamorphic sole at their base comprises high to medium grade amphibolites (rarely granulite) of 168 ± 1 Ma age (LANPHERE *et al.* 1975).

Material and Methods

Samples of amphibolites (with ± garnet) from Bistrica were investigated under the microscope and afterwards the freshest samples were selected for further study. Morphologies and chemical composition of mineral phases were identified using a JEOL JSM-6610LV Scanning Electron Microscope that was connected to an X-Max large Area Analytical Silicon drift in the Faculty of Mining and Geology in Belgrade. Quantitative mineral analyses were performed under high vacuum conditions, acceleration voltages 20 kV, step sequence 10 mm and external set of standards characteristic for each element. Mineral abbreviation used in text is done after KRETZ (1983).

Metamorphic soles of the WZV and DOB: an overview

In the Vardar Zone Ophiolite Belt the metamorphic sole rocks were noted at its northernmost (Mt. Fruška Gora, MILOVANOVIĆ *et al.* 1995), western (Massif Povlen, the village Tejići; SREĆKOVIĆ-BATOĆANIN *et al.* 2002), central (Massif Stolovi, the village Devovići; POPEVIĆ 1973) and southern parts (Massif Banjska, KORIKOVSKY *et al.* 2000a; Rogozna Massif, PALINKAŠ *et al.* 2008).

The metamorphic soles within the Serbian part of the DOB are evolved in contact with ultramafics at the Mt Zlatibor (ĆIRIĆ, 1968; KORIKOVSKY *et al.* 2000b; BAZYLEV *et al.* 2009), Bistrica (MAJER, 1972; POPEVIĆ & PAMIĆ 1973; POPEVIĆ & KARAMATA 1993; MILOVANOVIĆ, 1988; MILOVANOVIĆ *et al.* 2008; BAZYLEV *et al.* 2006a) and Brezovica (KARAMATA 1968; KARAMATA & MILOVANOVIĆ 1990; KARAMATA *et al.* 2000).

The metamorphic sole rocks beneath the WVZ ultramafics

Mt. Fruška Gora. The metamorphic sole rocks crop out on the southern slope of the mountain inside the mélange composed of large blocks and fragments of sedimentary, igneous and volcaniclastic rocks set in a very low to low grade metamorphosed clayey-sandy matrix. Their age ranges from Triassic to Jurassic–Cretaceous (pre-Maastrichtian). Elongated dismembered ultramafic bodies, spinel harzburgitic (rarely lherzolitic) in composition, form the southern slopes of the mountain in the area Bešenovo–Jazak–Grgurevac. The smaller bodies of serpentinized harzburgite and dunite crop out at the northern slopes in the area between Beočin and Sremski Karlovci, also. Blocks and fragments of terrigenous and volcaniclastic rocks as well as basalts and rarely carbonate rocks from mélange were exposed to various metamorphic grade and transformed into phyllites, sericite-chlorite schists, green schists, metabasalts, metadolerite, calcschists, rarely marbles and blueschists (ALEKSIĆ & ČUČULIĆ-TRIFUNOVIĆ 1972; MILOVANOVIĆ *et al.* 1995; KORIKOVSKY & KARAMATA 2011). The actual size of these blocks cannot be estimated due to insufficient exposure of ultramafics and mélange.

Subduction related high pressure-low temperature metamorphic sole rocks were determined as crossiteschists by MILOVANOVIĆ *et al.* (1995) and later as glaucophane-riebeckite-pumpellyite-actinolite-epidote schists by KORIKOVSKY & KARAMATA (2011). They occur as large blocks on the northeastern slope of Mt. (stream Selište, ~2 km northern of the town Sremski Karlovci,) and on the western slope within the Upper Jurassic–Lower Cretaceous olistostrome mélange (KORIKOVSKY & KARAMATA 2011) as well as pebbles within the Maastrichtian basal conglomerates (e.g. Čitluk stream). The amphibole in the first occurrence is classified as crossite according to the classification of LEAKE *et al.* (1978). MILOVANOVIĆ *et al.* (1995) considered the mineral assemblage epidote + sodic amphibole + quartz to be formed under the epidote-blueschist subfacies or high-T epidote bearing segment of blueschist facies (see EVANS 1990) i.e. at the temperature of approximately 400°C and pressure 7–9 kbar. This pressure corresponds to metamorphism at a depth of about 30 km.

This study reveals the subduction of the oceanic crust of the Vardar Ocean during the Early Cretaceous time (Barremian–Aptian; 123 ± 5 Ma), probably beneath the continental crust situated northeast, which argues the existence of an eastward dipping subduction zone. The second occurrence contains zonal Na-amphibole of the glaucophane–riebeckite series, actinolite, pumpellyite, epidote, chlorite, and rarely quartz. KORIKOVSKY & KARAMATA (2011) suggested that the mélange rocks along with the high-Ti subalkaline basalts and associated K-rich quartz–mica arkoses were buried to depths of 14–29 km by cold subduction. The same authors assumed that at pressure of 4–8 kbar and temperature below 340–350°C the mentioned rocks were transformed into glaucophane (riebeckite)–pumpellyite–actinolite–epidote–chlorite metasandstones and phyllites with high-pressure Mg–Si phengite.

Mt. Povlen (Tejići). The metamorphic sole rocks occur within an olistostrome mélange as fragments or large blocks beneath the ophiolite slab, which is exposed as a narrow, approximately 200 m wide and 800 m long zone. The ophiolite sequence, mainly composed of harzburgite (minor lherzolite) with typical tectonite fabric, gabbro, diabase and pillow-basalt associated with volcanic breccias and tuffaceous rocks, is tectonically emplaced to its present position during the late Upper Jurassic.

The metamorphic sole comprises greenschist to amphibolite facies mineral assemblages created by metamorphism of basic igneous rocks and their volcaniclastics along with sandy-silty (argillaceous) sediments. The low-grade metamorphic rocks are various greenschists, while higher-grade metamorphic rocks (garnet bearing amphibolite, amphibolite sensu stricto and epidote-bearing amphibolite) are exposed at the base of the ultramafic sequence (mostly harzburgite). Amphiboles within higher-grade metamorphic rocks are tschermakite, rarely magnesio-hornblende; primary plagioclase is almost completely replaced by epidote and prehnite whereas garnet porphyroblasts are almandine-rich. Biotite, chlorite, and actinolite are formed at the expense of amphibole due to retrograde metamorphic conditions. Amphibolitic rocks are followed by large blocks or fragments of augen gneisses and garnet mica schists metamorphosed under P–T condition of 435–550°C and 4.5 ± 0.5 kbar (SREĆKOVIĆ-BATOĆANIN & VASKOVIĆ 2000). The P–T conditions of amphibolites estimated for a Grt-Hbl pair using the method of GRAHAM & POWELL (1984), POWELL & HOLLAND (1985) and PERCHUK & LAVRENTEVA (1985) reveal a temperature range of 630 to 680°C and pressure of 6 ± 1.5 kbar (SREĆKOVIĆ-BATOĆANIN *et al*. 2002). The K–Ar age of sole rocks of 160–150 Ma (Tithonian/Callovian) reveals the time when protoliths were overthrusted by the hot ultramafic slab, and the beginning of the closure of the ocean basin (SREĆKOVIĆ-BATOĆANIN *et al*. 2002, 2010). The presence of metaclastic rocks assembled with metabasic rocks reveals the site of emplacement close to a major landmass. The presence of amygdales in pillow basalts and lack of deep water sediments additionally confirm this statement.

Devovići (Ušće). On the southwestern slope of the large Ibar ultramafic mass (Massif Radočelo), 5 km distant from Ušće, the metamorphic sole appears in a narrow tectonic zone (0.3–0.4 km wide and ~1 km long) within the serpentinized spinel harzburgite. A dense alternation of various low and medium to high grade metamorphic rocks derived from rocks of the diabase-chert formation were identified (POPEVIĆ 1973). Based on mineral assemblages in amphibolites next to ultramafics a temperature of about 600°C is suggested. The whole sequence subsequently underwent retrograde metamorphism. Data related to whole rock- and mineral chemistry are lacking.

Banjska. The Banjska Massif (20 × 8 km) is a relatively large body composed of clinopyroxene-poor spinel lherzolite (BAZYLEV *et al*. 2009). The metamorphic sole is developed as a zone of almost 20 m wide and 2 km long. It comprises high grade metamorphic rocks: clinopyroxene and/or hornblende (± clinozoisite) amphibolites with thin bands of garnet-cordierite-sillimanite gneiss (MAJER *et al.* 1979; KORIKOVSKY *et al*. 2000a). Most of them underwent retrograde metamorphism and Fe–Mg–Ca metasomatic processes (KORIKOVSKY *et al*. 2000a). The high-temperature amphibole from amphibolites with up to 1.9% TiO_2 is classified as pargasite-tschermakite-hastingsite. Due to retrograde greenschist facies overprint it is mostly replaced by actinolite ± epidote. Replacements by chlorite ± sericite in garnet and cordierite, and plagioclase by saussurite or prehnite and pumpellyite have been noted. According to the garnet-biotite and garnet-cordierite thermometer of PERCHUCK (1989) and garnet-cordierite-sillimanite-quartz barometer of ARANOVICH & PODLESSKII (1989) gneisses formed within the temperature range of 650°C to 760–780°C at pressure of 6.7–6.9 kbar (KORIKOVSKY *et al*. 2000a). Pressure estimates are compatible with the arrangement of jadeite isopleths in clinopyroxene in the clinopyroxene-plagioclase-quartz assemblage after HOLLAND (1980) indicating the depth of the initial cooling and the onset of tectonic stabilization of the ultramafic mass at 24–25 km.

Troglav. The Troglav Massif mainly consists of spinel harzburgite. Dunite and spinel lherzolite are subordinated. POPEVIĆ (1978) assumed that the Stolovi (east of the Troglav) and the Troglav represent parts of one large massif separated by the Ibar River valley. The metamorphic sole at its base has not yet been studied.

Rogozna. Metamorphic sole at the Rogozna Massif formed from basic igneous and sedimentary rocks mostly comprises schistose amphibolites and greenschists. Rare occurrences of mica schists and marbles are also noted. Rocks are highly hydrothermally altered during the Oligocene Pb–Zn–Ag mineralization processes. Amphibolite samples collected near the Crnac Pb–Zn–Ag mine and along the road section Jošanička creek – Leposavić consist of hornblende (replaced by secondary chlorite and fibrous actinolite) and plagioclase, partly replaced by epidote and prehnite (PALINKAŠ *et al.* 2008). The Ar–Ar ages determined on amphibole and actinolite vary from 168.8 ± 3.9 Ma to 178.3 ± 6.7 Ma; the age of the hydrothermally altered amphibolite is 150.4 ± 10.2 Ma. This age implies the onset of intra-oceanic subduction-obduction processes (Lower to Middle Jurrasic i.e. Toarcian to Bajocian time) synchronous with the formation of Dinaridic and Albanian metamorphic soles (PALINKAŠ *et al.*, loc.cit.).

The metamorphic sole rocks beneath the DOB

Mt. Zlatibor. Metamorphic sole rocks related to the Zlatibor ultramafic mass (20 × 30 km) are found in a few localities: Braneško Polje, Čajetina–Rudine and Rožanstvo. The weakly to moderately serpentinized lherzolitic body of the Zlatibor massif comprises cumulate gabbros at the top of the section (Rzav River), mantle tectonite and subordinated dunite, while the southern and southwestern parts are harzburgitic in composition (POPEVIĆ *et al.* 1996a; PAMIĆ & DESMONS, 1989; BAZYLEV *et al.* 2006a, 2009).

An inverted metamorphic sole (150–200 m thick), mostly composed of metabasic rocks with subordinated gneisses and phyllites is exposed beneath the central part of the Zlatibor massif along the road section Čajetina–Rudine. Three temperature zones are recognized within it: I. hornblende–clinopyroxene–plagioclase, II. hornblende–chlorite–albite and III. actinolite–prehnite–pumpellyite (KORIKOVSKY *et al.* 2000b). Amphibole from metabasic rocks is tschermakite. According to the Grt-Pl thermometer of BLUNDY & HOLLAND (1990) the temperature range of 550–650°C is calculated for the first zone. In the second zone the temperature is estimated at 400–500°C based on the Grt-Phn thermometer of GREEN & HELLMAN (1982). For the third zone a temperature range of 300–350°C is assumed according to the petrogenetic grid for metabasic rocks within an accepted pressure of 3 to 3.5 kbar (after LIOU *et al.* 1987). The roughly estimated pressure according to Jd- concentration in clinopyroxene (after HOLLAND, 1980) is 3–3.5 kbar, too. It seems that this massif was tectonically stabilized and started to cool at much shallower depths (12–13 km) than the other Serbian ultramafic massifs (KORKOVSKY *et al.* 2000b).

Bistrica. A small isometric tectonic block exposed to the south of Zlatibor Mt. is mainly composed of massive coarse-grained spinel lherzolite (northern part), and lherzolites with layers and veins of porphyroblastic harzburgite (southern part). Veins of garnet clinopyroxenite and spinel hornblendite are also common. Ultramafic and underlying metamorphic sole rocks are predominant lithologies. This massif is assumed to be of subcontinental mantle origin (POPEVIĆ & KARAMATA 1993; BAZYLEV *et al.* 2003, 2009). Various high to medium grade metamorphic rocks crop out along the road section Priboj–Prijepolje: garnet bearing mafic granulites, garnet ± clinopyroxene amphibolite, corundum-plagioclase-pargasite amphibolite, and massive to schistose amphibolites sensu stricto (Fig. 2). A number of studies were carried out on these rocks: MARIĆ (1933), PAMIĆ & KAPELER (1970), POPEVIĆ (1970), MAJER (1972), POPEVIĆ & PAMIĆ (1973), LANPHERE *at al.* (1975), MARKOVIĆ & TAKAČ (1985), MILOVANOVIĆ (1988). Recently, CHIARI *et al.* (2011) reported some new data related to the fabric of amphibolite varieties and the chemistry of amphibole, garnet, and clinopyroxene. Garnet-pyroxene amphibolites underwent metamorphism within a temperature range of 828–879°C and pressure of about 10 kbar (MILOVANOVIĆ 1988), while FED'KIN *et al.* (1996) calculated temperatures of 740 to 830°C and pressure of 8 to 10 kbar using the Cpx-Grt equilibrium. MILOVANOVIĆ *et al.* (2008) reported edenitic hornblende from the corundum- bearing amphibolite and cumulate gabbro protoliths (P–T conditions are estimated at >0.8 GPa and >800°C), while CHIARI *et al.* (2011) classified amphibole in the same rocks as pargasite/edenite. BAZYLEV *et al.* (2006b) reported an age of 146.8 ± 4.9 (Nd-Sm isochron age) for a garnet-plagioclase clinopyroxenite (Jurassic–Cretaceous boundary). The K–Ar age of 178 ± 14 Ma is obtained for garnet pyroxene amphibolites and corundum pargasite amphibolites (LANPHERE *et al.* 1975; MAJER & KARAMATA 1979).

Sjenički Ozren. This ultramafic massif (10 × 15 km) consists of spinel and plagioclase lherzolites in a nearly equal amount. The former comprises dunite, depleted spinel lherzolite and harzburgite; while within the latter a small gabbro bodies and thin veins occur (POPEVIĆ 1985; POPEVIĆ *et al.* 1996b; BAZYLEV *et al.* 2006b). The metamorphic sole up to 200 m thick is exposed in a few localities at the mountain's NNE and SE margin: Krajinovići, Brdo, Zmajevac, Gonje and Marina Ravan. Its contact with the ultramafics is tectonic and often followed by blastomylonitization, which led to the formation of low temperature minerals at the expense of primary minerals. In the contact aureole four zones were distinguished (POPEVIĆ, 1985; POPEVIĆ *et al.* 1996b; KORIKOVSKY *et al.* 1996). The fourth zone, next to the contact, is made up of garnet-clinopyroxene amphibolites, while further amphibolites sensu stricto, gabbro-amphibolites and greenschists occur. According to Grt–Cpx geothermometer of AI (1994) amphibolites of the fourth zone formed in the temperature range of 750–830°C at pressure of about 5–6 kbar, corresponding to depths from 18 to 22 km (KORIKOVSKY *et al.* 1996). The peak metamorphic conditions imply the emplacement of the Sjenički Ozren ultramafic mass in a solid-subsolid state (over 1000°C).

Brezovica. The Brezovica massif represents an accretionary complex interpreted as a sub-ophiolitic block-in-matrix type sedimentary mélange or an ophiolitic rock-bearing olistostrome with a peridotite tec-

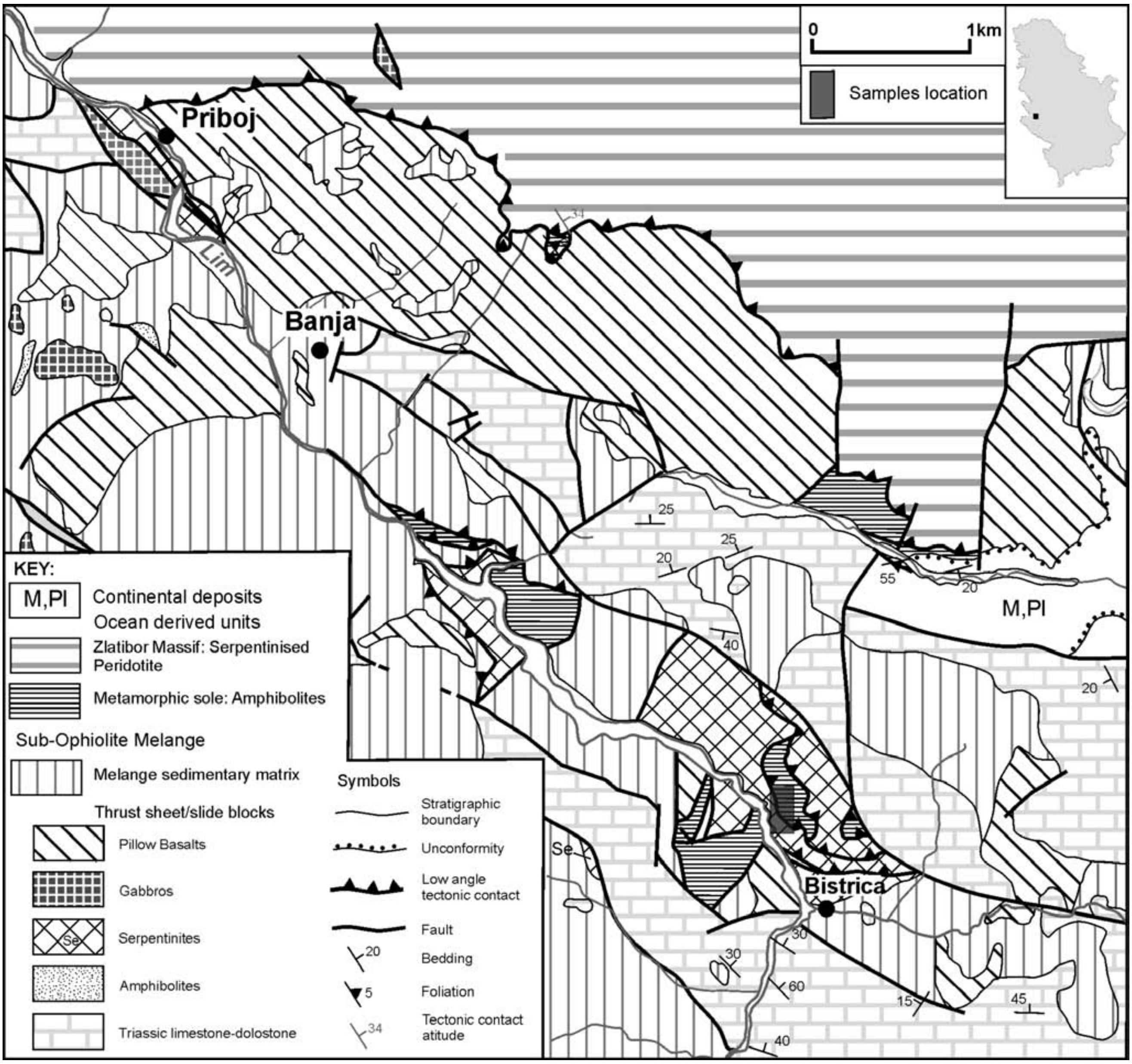

Fig. 2. Geological map of Bistrica–Priboj area: according to Basic Geological Map of former Yugoslavia, scale 1: 100 000 – Sheet Prijepolje (ĆIRIĆ *et al*. 1980) and CHIARI *et al*. (2011).

tonic sheet set up over it (KARAMATA 1968, 1985; KARAMATA *et al.* 1991, 2000; BAZYLEV *et al*. 2003). Blocks and fragments of sediments and basic igneous rocks placed in silty-shaly matrix compose the mélange, up to 1000 m thick. Ultramafics are generally spinel harzburgites, while dunites (± spinel) and layered cumulate rocks are subordinated. A well evolved metamorphic sole (200–500 m wide) occurs beneath. The local study of some of these rocks and minerals dates back to the works of many authors (e.g. MAJER 1956, 1978; KARAMATA 1974, 1979, 1985; SCHREYER & ABRAHAM 1977; ABRAHAM & SCHREYER 1976; MAJER & KARAMATA 1979; KARAMATA & MILOVANOVIĆ 1990; ĆIRIĆ & ERIĆ, 1996).

Within the metamorphic sole KARAMATA *et al.* (2000c) distinguished three zones. The *first zone* (30–50 m wide), next to peridotite, consists of garnet (± clinopyroxene) amphibolites and garnet-kyanite gneisses. Amphiboles in garnet amphibolites are classified as pargasite, hornblende, hastingsite and tschermakite following the classification of LEAKE *et al.* (1997). Using the Grt–Cpx, Grt–Pl and Grt–Bt thermometers (see Table 3 for references) temperatures of 700–750°C and 600–670°C and pressure of 8–9 kbar (employing maximum concentration of jadeite component in clinopyroxene) were estimated. The *second zone* (50–200 m) includes various schistose metamorphic rocks: metabasite with pargasite, tschermakite and edenite; Na-rich pargasite or barroisite garbenschiefer with almandine-rich garnet and phengite (maximum Si content of 3.5 apfu at Mg + Fe = 0.9) which points to pressure of 8–9 kbar; magnetite-bearing metacherts with riebeckite (acmite) needles, chlorite and paragonite; gneisses; talc + phengite metapelites (white schists of ABRAHAM & SCHREYER 1976) an indicator of high pressure (7–9 kbar). Based on the Grt-Hbl, Grt-Phn and Grt-Bt thermometers a temperature of 500–600 °C is estimated (see Table 3 for references). The rocks of this zone underwent retrograde metamorphic imprint reflected in replacement of Bt → Ms + Chl, Grt → Chl, St → Ser, Ky → Ser and by rims of secondary riebeckite around amphibole grains. The *third zone* mostly consists of low temperature metabasites having actinolite (edenite), hornblende or pargasite (winchite)-barroisite amphiboles; metagreywackes and garbenschiefers with Si-rich phengite assembled with barroisite ± pargasite and metacherts with Na-clinopyroxene (acmite-augite-jadeite). Temperatures of 350–500°C were estimated according to Grt–Chl, Grt–Phn, and Grt–Hbl thermometers, while pressure of 7–9 kbar was predicted based on the presence of high-Si phengite (see Table 3 for references). The country rock outside the aureole underwent a very low temperature- high pressure (300–350°C and 7–10 kbar) regional metamorphism before the emplacement of the hot ultramafic slab.

Discussion

The formation of metamorphic soles is directly related to the emplacement of ultramafics implying the overthrusting of hot oceanic lithosphere within intra-oceanic setting or orogenic belts. According to tectonic setting, relationships with adjacent geological units and main tectonic structures, a few models of sole formation have been recently proposed. Some of them for example are low-angle shearing and overthrusting of oceanic lithosphere in an intra-oceanic environment, overlapping mid-ocean ridge crest, obduction caused by roll-back subduction, transform-activated obduction and shearing superimpose onto an older contact aureole (e.g. KARAMATA 1968, 1988, 2006; KARAMATA & LOVRIĆ 1978; WOODCOCK & ROBERTSON 1977; ROBERTSON & KARAMATA 1994; SPRAY 1984; ROBERTSON & DIXON 1985; JONES *et al*. 1991; PARLAK & DELALOYE 1999; ROBERTSON & SHALLO 2000; WAKABAYASHI & DILEK, 2000; ROBERTSON *et al.* 2009). The field, petrological-mineralogical, geochemical and geochronological (K–Ar, Ar–Ar, U–Pb, Sm–Nd) studies of the evolved metamorphic sole rocks reveal valuable data on thermal conditions during intra-oceanic thrusting or during obduction onto passive continental margin.

Comparison of metamorphic sole rocks recorded in the WVZ and the DOB in Serbia offer data on the nature and emplacement of Mesozoic Tethyan ophiolites. However, each metamorphic sole as noted above relies on its own tectonic, structural and metamorphic characteristics. The focus of our comparison has been made only on mafic precursors from which various types of high to medium grade metamorphic rocks were formed.

Comparison of petrography and mineral composition

It can be recognized from the previous section that different species of amphibole are the major phase formed at the expense of the mafic sole components (Fig. 3). Depending on the conditions attained during the ophiolite emplacement a variety of metamorphic rocks were formed close to the contact (e.g. garnet and amphibole bearing granulite, clinopyroxene ± garnet amphibolite, corundum-bearing amphibolite, amphibolite sensu stricto and blueschist). Further from the contact a number of medium to low grade metabasic rocks have formed. Foliation within the last is defined by an arrangement of idiomorphic to sub-idiomorphic amphiboles. At the contact with ultramafics some amphibolite outcrops exhibit an alternation of amphibole- and plagioclase-rich bands (e.g. Tejići, Zlatibor, Bistrica, Brezovica). Generally, grain size ranges from 1–3 mm, although it can be below 0.5 mm. According to the available data the amphibole chemistry shows compositional variations with increasing temperature and pressure, ranging from actinolite to magnesiohornblende, tschermakite to edenite and magnesiohastingsite (Fig. 3), following the classification of LEAKE *et al.* (1997). Exceptions are blueschists from Mt. Fruška Gora - there amphibole corresponds to ferroglaucophane and magnesioriebeckite or to zonal Na-amphibole (glaucophane-riebeckite formed at the expense of older riebeckite) and corundum amphibolites from Bistrica where amphibole is edenite to magnesio-hastingsite and pargasite in (Fig. 3). The individual amphibole grains are commonly compositionally homogeneous.

The insignificant prograde core-rim variations are observed in amphiboles from Fruška Gora, Tejići, Zlatibor, Sjenički Ozren and Brezovica (KORIKOVSKY & KARAMATA 2011; SREĆKOVIĆ-BATOĆANIN *et al.* 2002; KORIKOVSKY *et al.* 1996, 2000b; CHIARI *et al.* 2011).

In the Fruška Gora area the replacement of riebeckite by glaucophane is characterized by an increase in Al, Mg, and Mg/(Mg + Fe^{2+}) ratio due to partial reduction of Fe^{2+} through the prograde reaction *Rbk* + *Chl* + *Ab*→ *Gln* + O_2. According to their composition the Na-amphiboles from those blueschists belong to a single genetic group (KORIKOVSKY & KARAMATA 2011).

The increase of Fe^{3+} values and decrease in Al_{tot} in some zoned amphiboles from the Tejići, Mt. Zlatibor, and Brezovica amphibolites could be related to

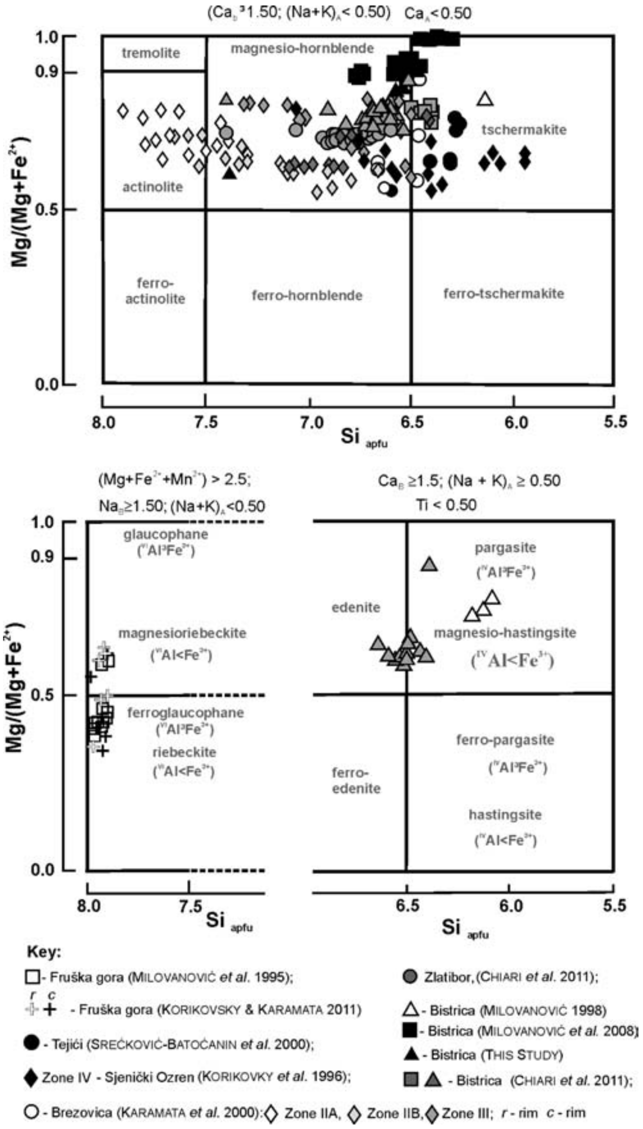

Fig. 3. Classification of amphiboles from the metabasic sole rocks of WVZ and DOB after LEAKE *et al*. (1997).

changes in fO_2 (see SPEAR 1981) during metamorphism. However, the Fe^{3+} content should be taken with caution due to limitation of EPMA to measure Fe^{3+} (see DROOP 1987). The appearance of amphibole within the peripheral parts of the symplectite coronas (cpx + pl) evolved around garnets is noted for the first time in the Bistrica garnet amphibolites (Fig. 4). It is probably related to increase of total Fe content along with decrease of silica as can be seen from the data obtained from the spectrum 3 (Fig. 5). The chemistry of analyzed amphiboles (Table 1) coincides with the data of CHIARI *et al*. (2011): the Si content ranges between 6.52 and 6.72 apfu and $Mg/(Mg+Fe^{2+})$ ratio ranges from 0.782 to 0.793. It must be stressed out that the analyzed amphiboles are compositionally homogenous. The chemistry of amphiboles from the Bistrica garnet amphibolite, presented by MILOVANOVIĆ

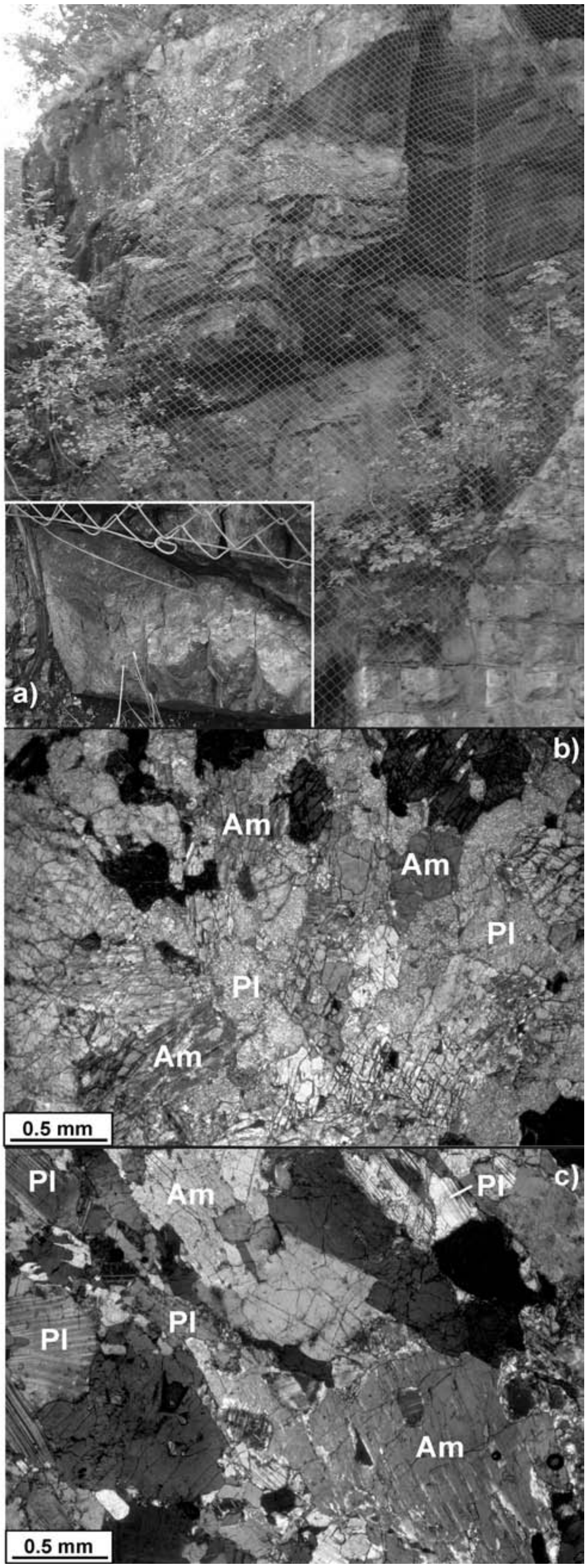

Fig. 4. Outcrop of granulitic amphibolite and garnet amphibolite on the right side of the road, just behind the tunnel (43°28'10.2" N; 19°39'11.4" E) (a); photomicrographs of altered amphibolite having highly saussiritized (b) and fresh plagioclase (c).

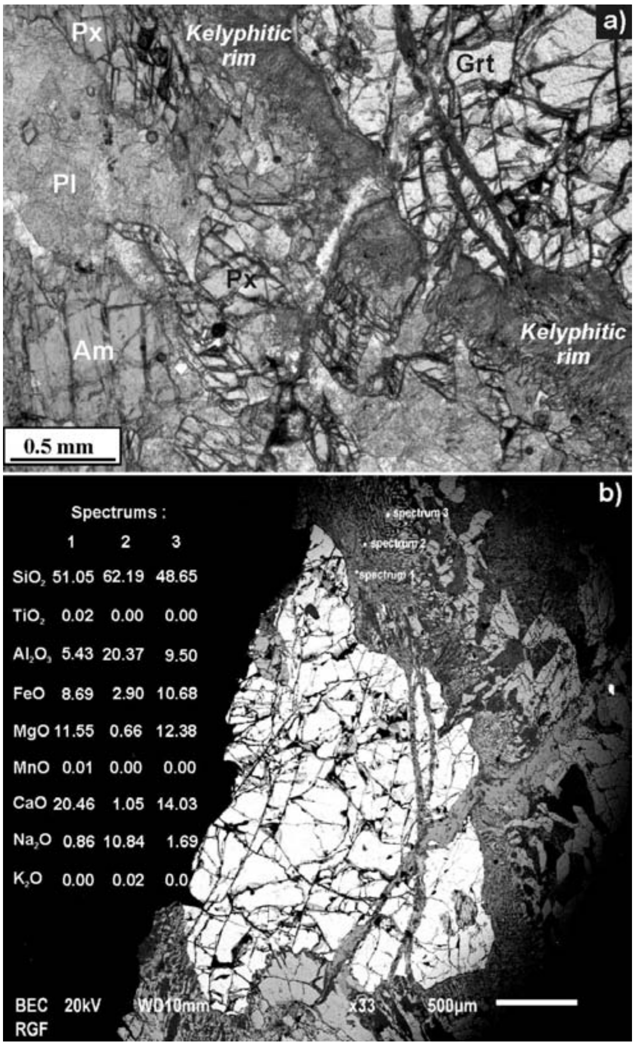

Fig. 5. Microphotograph of the amphibole (Am) with simplectite coronas, clinopyroxene (Px) and garnet (Grt) in granulitic amphibolite from Bistrica (a); Back-scattered image with chemical composition and measured spectrums (1, 2 and 3) within simplectite (b).

(1988), deviates from new obtained data. Only one amphibole has homogenous tschermakitic composition, while the others correspond to magnesio-hastingsite and are characterized by lower Si content per formula unit (6.05–6.14) and higher Al^{VI} (1.88–1.95 apfu), Ti (0.24–0.27 apfu), and Na_A (0.33–0.80 apfu) relative to the previously mentioned ones (Fig. 3). The amphibole grains from the garnet granulitic amphibolites of CHIARI *et al*. (2011) show identical Ti per formula unit (0.22–0.27). The garnet bearing amphibolites have lower Ti concentrations (0.10–0.13 apfu) that correspond to upper amphibolite to lower granulite facies conditions. Amphiboles from the studied amphibolite sensu stricto lack Ti as well as some from garnet clinopyroxene amphibolites of MILOVANOVIĆ (1988). Due to lack of available published data it is not possible to get a real insight into the Bistrica amphibole chemistry. However, an overall impression is that the compositional changes in amphibole are controlled by temperature while the relatively high Al^{IV}/Al^{VI} ratio implies on moderate increase of pressure during metamorphism.

The occurrence of garnet in amphibolites is confined to the upper sections of the metamorphic soles in both ophiolite belts, with the exceptions of garnet-free amphibolites from the metamorphic soles of Rogozna, Devovići, Zlatibor, and Fruška Gora Mt.

The composition of garnet, its distribution and appearance in amphibolites is generally controlled by protolith bulk composition (i.e. Ca content) and by metamorphic conditions. The syn-kinematic and mostly cracked garnet porphyroblasts (<0.5 cm to 1–2 cm across) are commonly assembled with amphibole and often next to plagioclase accumulations or bands (Fig. 4). The appearance of the thin symplectite reaction rim (kelyphitic) in the Bistrica amphibolite taken on the right side of the road section, just behind the tunnel is reported for the first time (Figs. 2, 4, 5). The garnets from Tejići and Bistrica show variable composition ranging between $Alm_{50.5–54.3}Pyr_{18.1–23.3}Grs_{9.2–15}Sps_{10.4–12.1}$ in Tejići to $Alm_{31.5–50}Pyr_{21.5–50.7}Grs_{15.4–24}Sps_{0.9–5}$ in Bistrica (Table 1). The data for garnet chemistry in sole rocks of Sjenički, Ozren and Brezovica are lacking. According to KORIKOVSKY *et al*. (1996) and KARAMATA *et al*. (2000) it is almandine, rich in pyrope component (up to >40 %). All analyzed garnet grains from Tejići are weakly zoned (rims are slightly poorer in pyrope component, 2–4 %) and occasionally occur as inclusions in amphibole. In the Bistrica amphibolites two types of garnet can be recognized: homogenous i.e. unzoned (MILOVANOVIĆ 1988; CHIARI *et al*. 2011), reflecting the compositional equilibration, and zonal with notable increase of pyrope and decrease of almandine and grossularite components from core to rim (FED'KIN *et al*. 1996). The amphibole, clinopyroxene, and plagioclase are found as inclusions in the Bistrica garnets. The observed symplectite coronas around the Bistrica garnets consist of very tiny clinopyroxene, albite and amphibole grains (Fig. 5). The mineral relationships suggest that the garnet mostly grew at the expense of these minerals (higher contents of grossularite).

The clinopyroxene found in the upper part of the metamorphic sole of the Bistrica is diopside, salite and augite following the classification of MORIMOTO *et al*. (1988). It occurs in relic unzoned sub-idiomorphic to xenomorphic grains up to 2–3 mm in size (Fig. 5). Its composition ranges from $En_{37.5–39.9}Fs_{15.2–18.3}Wo_{44.6–47.1}$ to $En_{41.4–42.2}Fs_{7.1–7.9}Wo_{47.4–49.6}$ and $En_{51.7–56.6}Fs_{15.6–19.3}Wo_{27.8–29.0}$ (Fig. 6a; Table 1). The Al_2O_3 content is highly variable, ranging from 3.12 to 6.23 wt.% if we take into consideration the data of MILOVANOVIĆ (1988) and CHIARI *et al*. (2011). The clinopyroxene from analyzed garnet-bearing granulitic amphibolite samples is richer in alumina (7.84 wt.%), but the average of 4.21 wt.% Al_2O_3 (MILOVANOVIĆ 1988) is similar to the value we have obtained in the same rock type (4.83 wt.%).

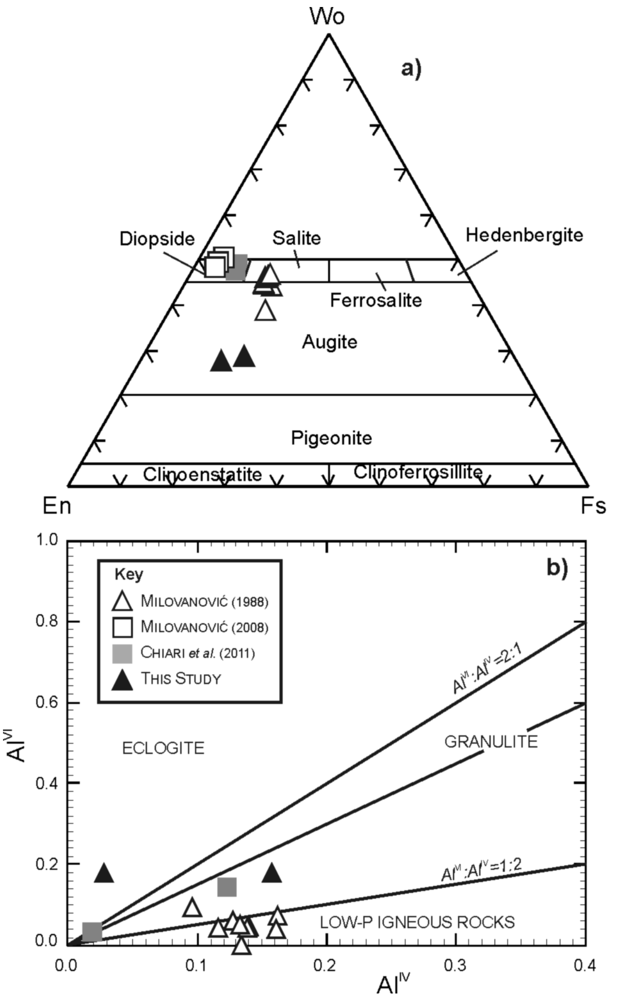

Fig. 6. Composition of clinopyroxenes from garnet bearing granulitic amphibolite and clinopyroxene amphibolite. (a) En-Fs-Wo classification diagram (MORIMOTO *et al.* 1988) and (b) Al^{IV} vs Al^{VI} diagram (MUKHOPADHYAY, 1991).

These differences are probably in close relation with the protolith composition and proximity of the contact zone as can be confirmed by the ratio Al^{IV}/Al^{VI}. This ratio reflects moderate recrystallization of primary clinopyroxene grains within the granulite facies and resulted in Al^{VI} enrichment, i.e. Tschermak component (Fig. 6b). The Jadeite component varies between 9.57 and 8.88 % in average in clinopyroxenes from garnet amphibolites studied by MILOVANOVIĆ (1988). Similar values are found in clinopyroxenes from garnet bearing granulitic amphibolite (9.96 %) while a lower value (6.43 %) is reported by CHIARI *et al.* (2011). MILOVANOVIĆ (1988) has reported also matrix metamorphic clinopyroxene with much lower Al_2O_3 (0.11 wt.%). It should be emphasized that differences in clinopyroxene composition within the Bistrica metamorphic sole could be the result of nonsystematic sampling and use of different analytical techniques. The chemistry of clinopyroxene (associated with garnet) from the Sjenički Ozren amphibolites is similar to the above mentioned – rich in the Tschermak component (i.e. alumina). However, the Al_2O_3 content is higher ranging from 5.8–6.0 wt.% and contain up to 1.3 wt.% Na_2O (KORIKOVSKY *et al.* 1996). The clinopyroxene in the Banjska amphibolite is poorer in Al_2O_3 (1.7–2.1 wt.%) and richer in Jadeite component (6–7 %). The clinopyroxenes in the Brezovica amphibolites are compositionally homogeneous and correspond to high temperature augite with < 8–10 % of Jadeite component (KARAMATA *et al.* 2000). The data of clinopyroxene chemistry for Sjenički Ozren, Banjska, Zlatibor, and Brezovica are not published.

The clinopyroxene is generally associated with plagioclase, amphibole and garnet at the immediate contact with ultramafics and are absent from amphibolite sensu stricto. Therefore, its presence and distribution is a function of bulk rock chemistry and particularly of metamorphic grade. The presence of clinopyroxene in garnet-free assemblages of Zlatibor and Bistrica is probably controlled by protolith Ca abundance. Plagioclase from amphibolites is mostly altered and replaced by prehnite or saussurite (Fig. 4). Albite (0–2 mol.% An), a common constituent of the Tejići garnet amphibolites, is probably formed as a low temperature retrograde phase. Rare unaltered plagioclase found in the Bistrica garnet amphibolite and amphibolite sensu stricto ranges in composition from 58.5–60.2 mol.% An (Fig. 4). MILOVANOVIĆ (1998) reported almost pure anorthite in garnet pyroxene amphibolites, which has been recently classified as garnet bearing mafic granulites (MILOVANOVIĆ *et al.* 2004). FED'KIN *et al.* (1996) found that plagioclase enclosed in garnet has a composition of 30–33 mol.% An while matrix plagioclase is anorthite poor (An 3–4 mol.%) in the garnet clinopyroxene amphibolites. The composition of the plagioclase from the Zlatibor garnet-free amphibolite is 45–50 mol.% An in the contact zone, and 12–15 mol.% An in the mid zone. The plagioclase of the Sjenički Ozren clinopyroxene amphibolite ranges in composition from 50–80 mol.% An (KORIKOVSKY *et al.* 1996). Further from the contact plagioclase is strongly zoned and poorer in An (15–25 mol.%). Generally, in the majority of metabasic rocks occurred further from the contact, the plagioclase have <10–30 mol.% An what enables the determination of P–T conditions.

Correlation of P–T conditions and age of metamorphism

The P–T conditions during metamorphic events are closely related to the thermal properties of the ophiolite sequences and to the rigidity of protoliths. The pressure is directly proportional to the depth. There-

Table 1. Representative mineral chemistry of the Bistrica amphibolites used in thermobarometry.

Amphibole	1	2	3	4	5	6
SiO_2	46.16	46.88	44.21	46.21	46.78	45.98
TiO_2	1.13	1.16	0.00	0.89	0.96	1.05
Al_2O_3	10.88	10.33	11.53	10.95	10.86	11.08
FeO	11.37	11.08	12.71	11.25	11.05	11.65
MnO	0.25	0.00	0.58	0.12	0.21	0.08
MgO	14.66	14.80	13.49	14.58	14.36	14.79
CaO	11.70	11.81	10.73	11.25	11.39	11.38
Na_2O	1.82	1.72	1.86	1.76	1.82	1.77
K_2O	0.19	0.15	0.00	0.08	0.00	0.11
Total	98.16	97.93	95.11	97.09	97.43	97.89
Recalculated on the basis of 23(O)						
Si	6.613	6.719	6.526	6.659	6.720	6.579
Al^{IV}	1.387	1.281	1.474	1.341	1.280	1.421
Sum_T	8.000	8.000	8.000	8.000	8.000	8.000
Al^{VI}	0.450	0.464	0.532	0.519	0.559	0.448
Ti	0.122	0.125	0.000	0.096	0.104	0.113
Fe^{3+}	0.370	0.277	0.731	0.411	0.318	0.507
Mg	3.131	3.162	2.969	3.132	3.075	3.155
Fe^{2+}	0.927	0.972	0.769	0.841	0.944	0.777
Sum_C	5.000	5.000	5.000	5.000	5.000	5.000
Fe^{2+}	0.065	0.079	0.070	0.104	0.066	0.110
Mn	0.030	0.000	0.073	0.015	0.026	0.010
Ca	1.796	1.814	1.697	1.737	1.753	1.745
Na	0.109	0.107	0.161	0.145	0.156	0.136
Sum_B	2.000	2.000	2.000	2.000	2.000	2.000
Na	0.397	0.371	0.372	0.347	0.351	0.355
K	0.035	0.027	0.000	0.015	0.000	0.020
Sum_A	0.432	0.398	0.372	0.362	0.351	0.376
Mg/Mg+Fe	0.76	0.75	0.78	0.77	0.74	0.78

Clinopyroxene	1	2
SiO_2	50.27	54.09
TiO_2	0.87	0.00
Al_2O_3	7.84	4.83
Cr_2O_3	0.18	0.00
FeO	10.71	8.79
MnO	0.00	0.32
MgO	16.04	18.61
CaO	12.53	12.71
Na_2O	1.32	0.49
Total	99.76	99.84
Recalculated on the basis of 6(O)		
Si	1.842	1.953
Al^{IV}	0.158	0.047
Al^{VI}	0.171	0.159
Ti	0.024	
Fe^{3+}	0.018	0.000
Mg (M1)	0.772	0.841
Mg (M2)	0.104	0.160
Fe^{2+}(M2)	0.310	0.265
Mn	0.000	0.010
Ca	0.492	0.492
Na	0.094	0.034
End members		
En	51.7	56.6
Fs	19.3	15.6
Wo	29.0	27.8

Garnet	1	2	3
SiO_2	39.75	38.71	38.65
TiO_2	0.00	0.23	0.00
Al_2O_3	21.70	21.75	21.20
FeO	19.48	19.27	19.08
MnO	1.22	1.32	1.25
MgO	9.66	9.26	6.71
CaO	8.36	8.40	8.34
Total	100.17	98.94	95.23
Recalculated on the basis of 12(O)			
Si	3.000	2.962	3.105
Al^{IV}	0.000	0.038	0.000
Sum_T	3.000	2.962	3.105
Al^{VI}	1.929	1.923	2.006
Ti	0.000	0.013	0.000
Fe^{3+}	0.065	0.083	0.000
Sum_A	1.994	2.018	2.006
Fe^{2+}	1.165	1.151	1.282
Mg	1.087	1.056	0.804
Mn	0.078	0.086	0.085
Ca	0.676	0.689	0.718
Sum_B	3.006	2.982	2.889
End members			
Alm	38.76	38.60	44.38
Andr	3.25	4.00	0.00
Grs	19.25	19.00	24.86
Pyr	36.15	35.43	27.82
Sps	2.59	2.87	2.94

Plagioclase	1	2	3	4
SiO_2	53.49	53.10	52.66	53.01
Al_2O_3	29.92	29.36	30.34	29.96
FeO	0.12	0.25	0.00	0.00
CaO	12.46	12.10	12.27	12.32
Na_2O	4.64	4.74	4.59	4.50
Total	100.63	99.55	99.86	99.83
Recalculated on the basis of 8(O)				
Si	2.406	2.414	2.386	2.401
Al	1.587	1.573	1.620	1.600
Fe	0.005	0.010	0.000	0.001
Ca	0,600	0.589	0.596	0.598
Na	0.405	0.418	0.403	0.395
End members				
Ab	40.3	41.5	40.4	39.8
An	59.7	58.5	59.6	60.2

Explanations:

Amphibole: site assignment and ferric iron contents were calculated using the scheme of SCHUMACHER in LEAKE *et al.* (1997).

Garnet: Fe is recalculated on Fe^{2+} and Fe^{3+} after KNOWLES (1987); End members after DEER *et al.* (1992); End members mineral abbreviation after KRETZ (1983).

Clinopyroxene: site assignment and ferric iron contents were calculated using the scheme of MORIMOTO *et al.* (1988). End members mineral abbreviation after KRETZ (1983).

fore various pressures can indicate various depths of detachment of the oceanic lithosphere as well as the depth of initial cooling. A gradual increase of P–T conditions with advancing movement of the ophiolite slab was recorded in some minerals through changes in their chemistry (e.g. Tejići, Bistrica, Fruška Gora). WAKABAYASHI & DILEK (2000) assumed considerable thinning of ophiolites after the sole formation, in cases when the estimated depths greatly exceed the thickness of ophiolites.

Based on P–T estimates for mineral assemblages in metabasic rocks of the WVZ and the DOB three types of metabasic soles can be distinguished (Fig. 7a, Table 2, 3):

a) high pressure – low temperature blueschist facies assemblage, only recorded in the metamorphic sole at the Fruška Gora (WVZ). A temperature of approximately < 300–350°C and ~400°C and pressure of 4–8 kbar and 7–9 kbar respectively, corresponding to depths of about 14–29 km and 30 km, are estimated. These estimations are based on the petrogenetic grid for low-temperature metabasic rocks of moderate and high pressures of LIOU *et al*. (1987) for the glaucophane-riebeckite + pumpellyite assemblage. This assemblage is controlled by the reactions: *Pmp* + *Chl* + *Qtz* = *Czo* + *Act* + H_2O and *Pmp* + *Gln* +*Qtz* = *Czo* + *Act* + *Ab*+H_2O (see NAKAJIMA *et al*. 1977) and by the stability field of natural glaucophane (MARESH 1977), which is in the upper limit range of 6–9 kbar and 400–450°C. The stability field for Na-amphibole is well constrained at pressure range of 5–9 kbar for the temperature range of 300–600°C (e. g. HOLLAND & POWELL 1988; HOLLAND 1988; HOFFMAN 1972; MARUYAMA *et al*. 1986; BROWN 1974, 1977; BROWN & FORBES, 1986). Generally, in this stability field the composition of Na-amphibole is pressure dependent. Accordingly, the estimation of MILOVANOVIĆ *et al.* (1995) for the assemblage ferroglaucophane (former crossite) + phengite + epidote can be considered realistic. Crossite is pressure dependent and very useful as it divides low-P riebeckite from high-P ferroglaucophane. Although the term crossite is not used anymore for the amphibole nomenclature of LEAKE *et al.* (1997) it was used due to its above described nature.

The K–Ar age of 123 ± 5 Ma for the blueschist implies the Early Cretaceous subduction of the oceanic crust beneath the northeastern continental crust (MILOVANOVIĆ *et al*. 1995).

b) high pressure – high temperature granulite to amphibolite facies characterize the metamorphic soles in both, the WVZ (Banjska) and the DOB (Bistrica, Sjenički Ozren and Brezovica) domains.

At the Banjska domain the chemistry of amphiboles from the metabasic members, (belong to the pargasite-tschermakite-hastingsite series, with up to 1.9 wt.% TiO_2) imply temperature conditions which coincide with the maximum temperature of 760–780°C calculated for the garnet-cordierite-sillimanite gneisses, which occur as thin layers within the immediate contact with ultramafics (KORIKOVSKY *et al*. 2000a). The pressure of 6–7 kbar, estimated according to the jadeite isopleths in clinopyroxene from the clinopyroxene + plagioclase + quartz assemblages is also in accordance with the pressure calculated for the gneisses using the Grt-Crd-Sil-Qtz geobarometer of ARANOVICH & PODLESSKII (1989). This pressure corresponds to a depth of 24–25 km.

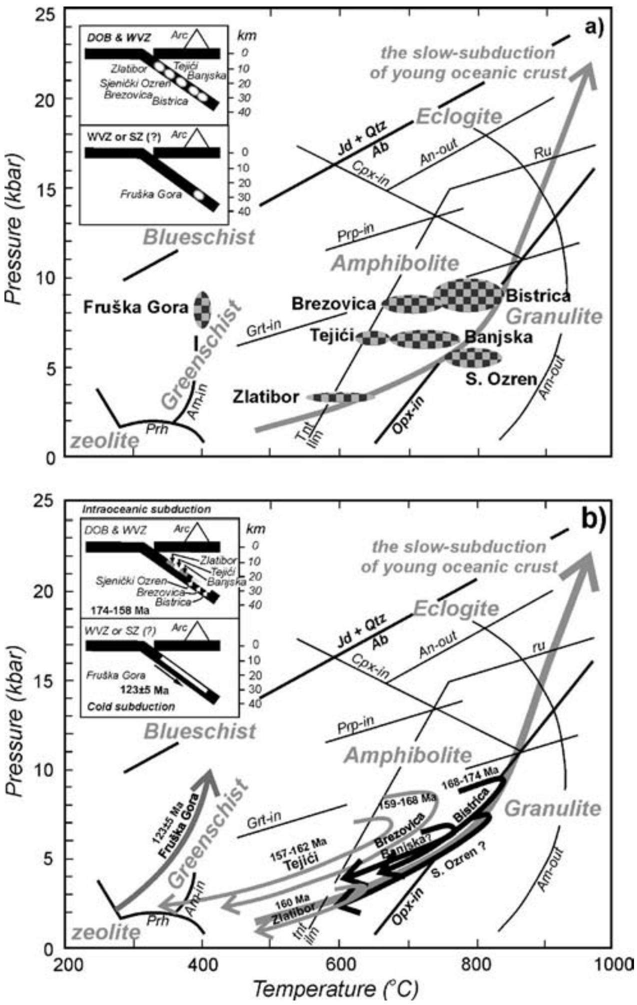

Fig. 7. a) P-T ranges of the metabasic rocks from the WVZ and DOB metamorphic sole. Reaction curves: Am-in, Am-out and Grt-in (ERNEST & LIOU 1998); Prp-in, Jd+Qtz and An-out (GREEN & RINGWOOD 1967); Cpx-in, Opx-in (MUKHOPADHYAY & BOSE 1994); titanite-ilmenite and rutile (LIOU *et al.* 1996); Prh (FREY *et al.* 1991); b) Assumed P-T-t paths for the DOB and WVZ metamorphic sole rocks operated during the intra-oceanic subduction and cold subduction within the northern part of the WVZ or Sava Zone (SZ) – Fruška Gora. Inlet in the upper left corner shows the depth of metamorphism (a) and (b) begining of subduction related to scrutinized domains with different rock types. The P–T–t path of slow-subduction of young oceanic lithosphere is after PEACOCK *et al*. (1994).

Table 2. Overview of P–T conditions for the metabasic rocks of the WVZ metamorphic soles in Serbia

Location	Rock Type	P kbar	T °C	Geothermometar Geobarometar	Depth km	K-Ar Age (Ma)	Reference
Fruška Gora	Blueschist	7–9 4–9	400 <300–350	PT stability of Na-Am and pumpelyite*	~30 14–29	123 ± 5	MILOVANOVIĆ *et al.* (1985) KORIKOVSKY & KARAMATA (2011)
Tejići	Grt Amphibolite	5.5 ± 1	620–670	T: Grt-Pl (HB) P: Al-in Hbl (HZ)	18–25	160 ± 6.2 157.6 ± 10 160.3 ± 8	SREĆKOVIĆ-BATOĆANIN *et al.* (2002)
Devovići	Amphibolite	no data	600	no data		no data	POPEVIĆ (1973)
Banjska	Cpx amphibolite,	6–7	650–780	P: Jdin Cpx (H) T: Grt-P l(HB);	18–25	no data	KORIKOVSKY *et al.* (2000a)
	Grt-Crd gneiss	6.7–6.9	760–780	T: Grt-Crd & Grt-Bt (P) P: Grt-Crd-Sil-Qtz (AP)			
Troglav	no data						
Rogozna	Amphibolite s.s. Greenschist	no data				168 ± 3.9 178 ± 6.7	PALINKAŠ *et al.* (2008)

Abbreviations: HB – HOLLAND & BLUNDY (1994); A – AI (1994); HZ – HAMARSTROM & ZEN (1986); J – JAQUES (1982); KS – KOHN & SPEAR (1990); P – PERCHUK (1989); 1990; AP – ARANOVICH & PODLESSKII (1989); H – HOLLAND (1980). * – LIOU *et al.* (1987); MARESH (1977); NAKAJIMA *et al.* (1977).

The amphibolites from the Bistrica domain (DOB) were the subject of a few researches. The P–T estimates for garnet-clinopyroxene granulitic amphibolite, garnet amphibolites and corundum-bearing amphibolites are almost consistent and range from 740 to 830°C and 8–10 kbar. The amphibolites sensu stricto are metamorphosed under T–P of 600–650°C and 3.5 to 7 kbar. FED'KIN *et al.* (1996) pointed out that the retrograde stage of the thermal evolution of the Am+Cpx+Pl amphibolite was probably periodically interrupted by tectonic movements caused by the rapid ascent of the Bistrica complex. According to the Am–Cpx–Pl geothermobarometry and estimated P–T changes four phases or depth levels are distinguished. The peak metamorphic condition for the Bistrica garnet-bearing granulitic amphibolite, garnet clinopyroxene amphibolite, and amphibolite sensu stricto is estimated according to the amphibole – plagioclase geothermometer of HOLLAND & BLUNDY (1994). The temperature was calculated for the assumed pressures of 6 to 12 kbar and the pressure estimates were based on the Grt–Am–Pl–Qtz geobarometer of KOHN & SPEAR (1990) for the temperature range of 600 to 900°C. The average P–T value resulted from the intersection of lines for calculated temperatures and pressures (taking into consideration the average error of the applied method). The obtained temperature of 808°C ± 40°C and pressure of 9.5 ± 0.9 kbar corresponds to the lower part of the granulite facies (Fig. 7a). These results are in accordance with the data of MILOVANOVIĆ (1988) and FED'KIN *et al.* (1996).

The K–Ar age of the Bistrica amphibolite ranges from 168 to 174 ± 14 Ma (Table 3). The high PT conditions of the Bistrica garnet pyroxenite and its age of 146 ± 4.9 Ma (Nd–Sm) imply the subduction of oceanic crust ensued by exhumation and cooling in a subduction channel (BAZYLEV *et al.* 2006a): the exhumation can arise during SSZ-spreading and rollback of the subducting oceanic slabs and culminate in tectonic emplacement over a continental margin prior to the Tithonian–Berriasian time (see ROBERTSON *et al.* 2009).

The P–T conditions of the amphibolites comprising Cpx+Am+Pl (up to 80 % An) assemblage from the Sjenički Ozren (DOB) were calculated following the Hbl-Pl thermometer of JAQUES *et al.* (1982). The estimated peak metamorphic conditions of 750–830°C and 5–6 kbar (according to Al-in Hbl geobarometer and high pyrope content in garnet) imply a depth of 18–22 km (Table 3). The age of those amphibolites and of the Banjska metamorphic sole remains unknown.

The inverted zonal metamorphic sole at the subduction-accretion complex of Brezovica (DOB) is characterized by metamorphic imprint of igneous basic rocks to amphibole schists and amphibolite varieties in the temperature range from 350–500°C in the third zone to 500–600°C in the second zone. The maximum metamorphic peak of 600–670°C is attained in the first A zone to 700–750°C in the first B zone at almost isobaric condition (7–9 kbar). On the basis of P–T calculations two subdomains are recognized: the southwestern part with upper amphibolite facies (Borov Vrh, Malo Borče and Jezerina) and the northeastern part with greenschist to medium amphibolite facies conditions (locality Krst). Both show evidence of localized retrogressive reactions related to the subsequent uplift, cooling and thrusting of ultramafics: clinopyroxene and hornblende → actinolite and epidote; garnet → chlorite and epidote; plagioclase → saussurite.

The difference in the temperature imprint of these two subdomains, originally metamorphosed at almost the same depth, suggests that the ultramafic part of a single harzburgite mass had a different temperature. It should be stressed out that garnet, the usual source of information about prograde metamorphism, shows

Table 3. Overview of P-T conditions for the metabasic rocks of the DOB metamorphic soles in Serbia.

Location	Rock Type	P kbar	T °C	Geothermometar Geobarometar	Depth km	K-Ar Age (Ma)	Reference
Zlatibor	Zone I: Cpx Amphibolite	3–3.5	550–650	**T**: Grt–Pl (HB) **P**: Jd-in Cpx (H, G)	12–13	[1]160	KORIKOVSKY *et al.* (2000) [1]KARAMATA & LOVRIĆ (unpublished)
	Zone II: Amphibolite s.s		400–500	**T**: Grt–Phn (GH)			
	Zone III: Greenschist, Act-Prn-Pmp schist		300–350	According to LIOU *et al.* (1987) and SPRINGER *et al.* (1992)			
Bistrica	Grt-Cpx Amphibolite	10	800–1000	**T**: Grt–Hbl (GP; P**); Am–Cpx (P**) **P**: Grt–Cpx (P*)	30–35		MILOVANOVIĆ (1988)
	Grt-Cpx Granulitic amphibolite; Grt Amphibolite	8–10	740–830	**P**: Am–Grt–Pl (KS); Cpx–Pl (P) **T**: Grt–Cpx (A); Am–Pl (HB); Am–Grt (LP)		[1]174±14 170±11 168±8.2 [2]146±4.9 (Nd-Sm)	[1]LANPHERE *et al.* (1975); FED'KIN *et al.* (1996) [2]BAZYLEV *et al.* (2006)
	Amphibolite	3.5–7	600–650				
	Grt-Cpx Granulitic amphibolite	9.5±0.9	808±40	**T**: Hbl–Pl (BH) **P**: Grt–Am–Pl (KS)			this study
	Corund bearing Amphiibolite	> 8	> 800	not specified			MILOVANOVIĆ *et al.* (2008)
Sjenički Ozren	Cpx Amphibolite Amfibolite s.s. Greenschists	5–6	750–830 400–430	**T**: Grt–Px (A) **P**: Al in Hbl (HZ)	18–22		KORIKOVSKY *et al.* (1996)
Brezovica	Zone IB:Grt-Cpx Amphibolite	8–9	750	**T**: Grt–Hbl (J); Grt–Phn (GH), Grt–Bt (FS); **P**: Jd-in Cpx (H)	30–36	[1]169.0±3.2 162.6±3.4 161.5±1.6 162.8±1.9	[1]OKRUSCH *et al.* (1978)
	Zone IA: Grt Amphibolite; amphibolite, garbenschiefer		600–670				
	Zone II: metabasat, amphibolite		500–600	**T**: Grt– Hbl (J) Grt–Phn (GH), Grt–Bt (FS)			
	Zone III: metabasalt, greenschist	7–9	350–500	**T**: Grt–Chl (DH); Grt–Phn (GH); Grt–Hbl (GP; P**); **P**: Si–Phn		[2]158–168	[2]KARAMATA *et al.* (2000)
	Zone IV: Blueschist-metabasite	7–10	300–350				

Abbreviation: HB - HOLLAND & BLUNDY (1994); A – AI (1994); HZ – HAMARSTROM & ZEN (1986); J – JAQUES (1982); KS – KOHN & SPEAR (1990); P** – PERCHUK (1967, 1969, 1970); P – PERCHUK (1989, 1990); AP – ARANOVICH & PODLESSKII (1989); H – HOLLAND (1980), G – GASPARIK (1985); GH – GREEN & HELLMAN (1982); GP – GRAHAM & POWELL (1984); P* - POWELL (1985); DH – DICKENSON & HEWITT (1986) MODIFIED BY LAIRD (1989); FS – FERRY & SPEAR (1978); **T** – geothermometer; **P** – geobarometer.

evidence of prograde zoning growth. It is reflected in an increase of Mg and decrease in Ca component from core to rim. It is almandine rich with up to 24 % of pyrope component in the outer shells in the second to nearly 40 % in the first distinguished zone. Textural and chemical evidence suggest that garnet grew at medium to high temperature and continuously re-equilibrated up to peak conditions.

The K–Ar age measured on the Brezovica amphibolites gave 159–168 Ma (KARAMATA & LOVRIĆ, 1978) and 162–169 Ma (OKRUSH *et al.* 1978).

c) medium pressure – medium temperature amphibolite facies assemblages is found in WVZ (Tejići, Devovići) and DOB (Zlatibor).

At the Tejići domain (WVZ) the Am-Grt geothermometer (Table 2) gave an average temperature range of 620–670°C at an assumed pressure of 5.5 ± 1 kbar. This P–T range is similar to that obtained for the garnet-free clinopyroxene amphibolites in DOB (Table 3). The garnet mica schist displays lower P–T range (500 ± 50°C at 3–5 kbar) and could be assigned to uplift of hot ultramafic body (SREĆKOVIĆ-BATOĆANIN & VASKOVIĆ 2000).

The K–Ar age measured on amphibole and mica ranges from 157.6 ± 10 to 160.1 ± 7.1.

Based on mineral assemblages in amphibolites next to the ultramafic body at the Devovići domain a temperature of about 600°C is reported by POPEVIĆ (1973).

An inverted contact metamorphic aureole underneath the large Zlatibor ultramafic mass comprises three metamorphic zones. A temperature range of 300–350°C and pressure of 3–3.5 kbar for the third marginal zone (actinolite + pumpellyte + prehnite) is assumed using the petrogenetic grid for low temperature metabasites of LIOU *et al.* (1987). The remarkable progressive change in mineral assemblages within metabasites is realized in the transition to the second zone. It is characterized by the break down of pumpellyite and prehnite, replacement of actinolite rim by tschermakite, appearance of phengite (Si up to 3.38–3.41 apfu, MgO up to 3.3 wt.%, FeO up to 2.9 wt.%), and an increase of anorthite component in plagioclase (7–15 %). The presence of rare intercalations of phyllites and paragneisses in metabasic members with mica and garnet (4–16 % of pyrope component from core to rim and decrease of grossular from 21–8 % and spessartine component from 15–7 %) allowed the Grt – Phn thermometer of GREEN & HELLMAN (1982) to be used. A temperature range of 400–500°C was estimated (KORIKOVSKY *et al.* 2000b). The first zone with almost homogenous magnesiohornblende and tschermakite having a slightly elevated Ti concentration, plagioclase (20–50 % An) and rare augite with less than 2–3 % of jadeite component implies shallower depths when compared to the Brezovica aureole. The Grt-Pl thermometer of BLUNDY & HOLLAND (1990) gave temperatures of 550–650°C. The low concentration of jadeite component in clinopyroxene enabled rough estimation of pressure of 3–3.5 kbar at a temperature of ~650°C (Table 3). According to all these estimations KORIKOVSKY *et al.* (2000b) summarized that the Zlatibor massif was tectonically stabilized and started to cool isobarically at depths of approximately 12–13 km.

The K–Ar age of the Zlatibor metabasites is 160 Ma (KARAMATA & LOVRIĆ, personal communication) what is consistent with the ages obtained for the Tejići and the Brezovica metamorphic sole.

Based on mineral assemblages, estimated P–T conditions, zoning in mineral phases and obtained ages, the potential *P–T*–t paths are given for metabasic rocks from the WVZ and the DOB metamorphic sole (Fig. 7b). The retrograde assemblages indicating the overprint of high- to medium grade metabasites are low-temperature mineral phases of greenschist facies.

The tectonic settings that could be parental to the Serbian southwestern part of DOB (e. g. Bistrica) are assigned to the ocean thrusting and subsequent intra-oceanic subduction. At the beginning the metamorphism operated at a depth ≥30 km (≥10 kbar and ~800 ± 50 °C). The appearance of corona texture and medium-PT mineral phases imply a short-lived high-PT event and subsequent fast exhumation of the ophiolitic sequence; at another domain the intra-oceanic subduction of SSZ-type, operating in various depths, was responsible for the development of metamorphic soles. Thus, the garnet clinopyroxene bearing metabasites of the Bistrica represent the deepest subducted slab (~30 km). Further northwest, the peak metamorphic condition of various types of amphibolites imply the shallower burial of subducted slabs – ranging from 18–25 km (Sjenički Ozren and Banjska) over 18–15 km (Tejići) until 12–13 km (Zlatibor).

Composition and Correlation of protoliths and tectonic implication

Generally, the ocean units of the Dinaridic and the Western Vardar Zone belt comprise sub-ophiolite mélange thrust by an ophiolite unit with a metamorphic sole at its base. Within them the different types of basaltic rock and rarely gabbros were metamorphosed under various metamorphic conditions.

The blueschists of the Fruška Gora are considered to be a relic of the subducted oceanic unit (MILOVANOVIĆ *et al.* 1995). Recalculation of data reflects on prevailing of basaltic trachyandesitic composition instead of trachybasaltic (Fig. 8b). The ratios of incompatible elements (Ti, Zr, Y) suggest an MORB- and CAB-affinity (Fig. 8a). The latter was reported by MILOVANOVIĆ *et al.* (1995) as VAB-affinity (due to lack of data for Nb it is not possible to discriminate between Nb–Zr–Y). The Zr/Y ratio ranges from 4.01 to 5.95. The REE patterns normalized to chondrite values after SUN & MCDONOUGH (1989) show medium

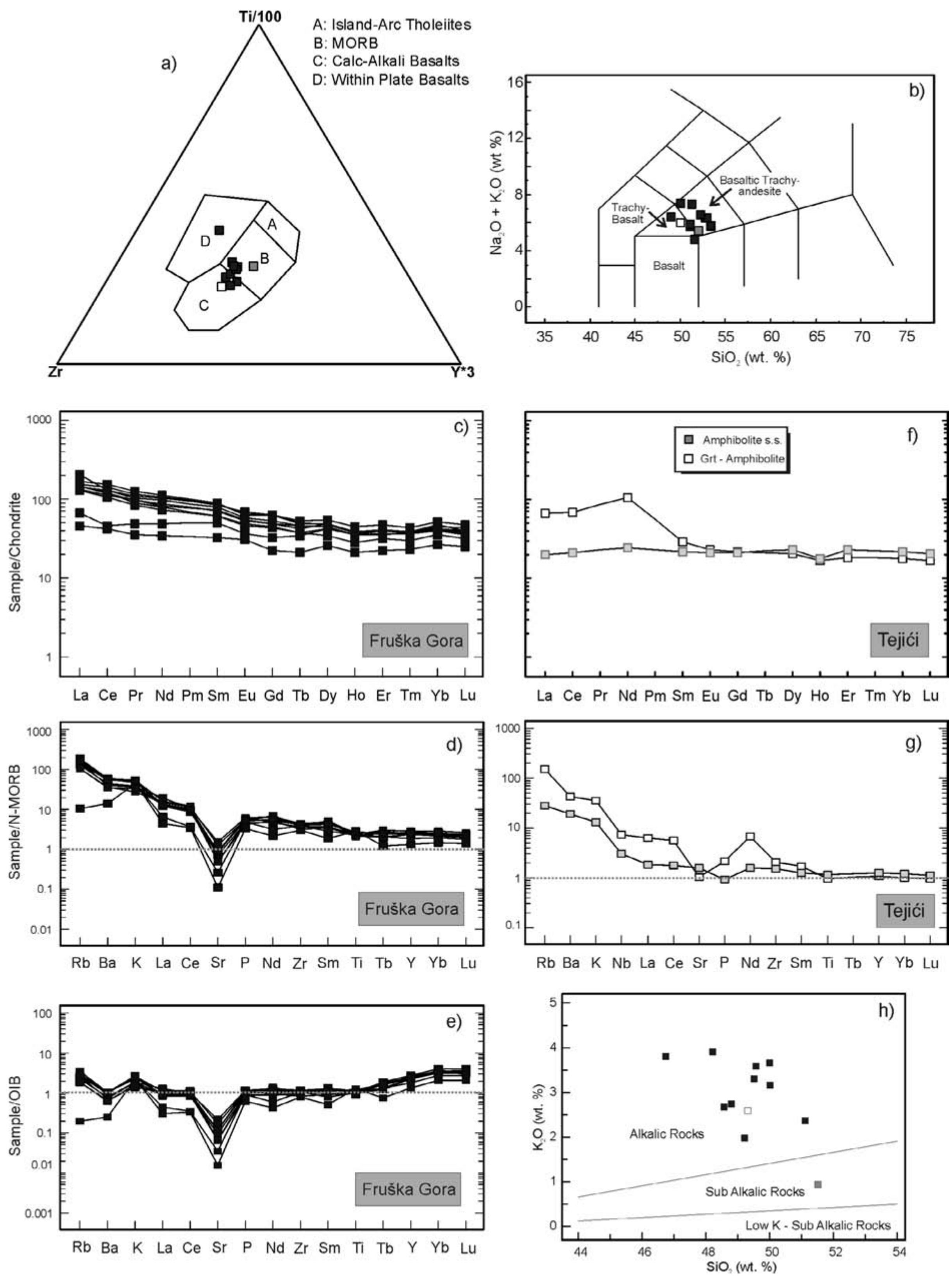

Fig. 8. Geochemistry of the Fruška Gora blueschists and Tejići amphibolites according to recalculated data of MILOVANOVIĆ *et al*. (1995) and SREĆKOVIĆ-BATOĆANIN *et al*. (2002): a) Ti-Zr-Y discrimination diagram (after PEARCE & CANN, 1973); b) SiO_2–Na_2O+K_2O classification diagram (after LEBAS *et al*. 1986); c) Fruška Gora chondrite – normalized REE patterns, d) N-MORB normalized and e) OIB normalized trace element spider diagrams of the Fruška Gora blueschists, f) Chondrite – normalized REE and g) N-MORB normalized trace element spider diagrams of the Tejići amphibolites; g) SiO_2 vs K_2O classification diagram (after MIDDLEMOST 1975); normalizing values are after SUN & MCDONAUGH (1989).

LREE enrichment (La_N/Yb_N = 1.41–3.43), no marked Eu-anomaly (Eu/Eu* = 0.84–1.13) and high ΣREE content (187.7–253.3) with two exceptions (85.8 and 116.6). All analyzed rocks are high-TiO_2, Zr and Y type basaltic rocks enriched in alkalis (Fig. 8b, h). The relations between compatible and incompatible elements presented on spider diagrams normalized to the average N-MORB and average OIB (Fig. 8e) indicate a very strong negative Sr-anomaly relative to adjacent elements. In respect to the average N-MORB they are much more enriched in LILE and slightly in HFSE as compared with the average OIB (Fig. 8d). Actually, the reexamination of blueschist geochemistry has shown characteristics very similar to OIB (Fig. 8d; Fig. 8e). The strong negative Sr-anomaly as has been many times encountered in MORB and OIB environments (see HOFMAN 1997) could be a result of seawater- basic magma interaction i.e. alteration prior to subduction. During the high-P low-T metamorphism the LILE elements behave as immobile (e.g. BEBOUT 1995, 2007; BEBOUT *et al.* 1999). Therefore, the blueschists probably originate from rocks whose composition is similar to OIB.

The metabasic rocks from the Tejići show the tholeiitic trachybasaltic to basaltic trachyandesitic composition (Fig. 8b). According to the ratio of Ti, Zr and Y they plot within MORB and CAB field (Fig. 8a). The Zr/Nb ratios (5.59–1.91) are lower than in the typical N-MORB (~32). The chondrite normalized REE patterns for garnet amphibolite (GA) and amphibolite sensu stricto (A) differ in LREE abundance (Fig. 8f). The former is much more enriched in LREE (70–100× chondrite values; La_N/Sm_N = 1.93) than the latter (~10× chondrite values; La_N/Sm_N = 0.77) with almost flat REE. The Eu-anomaly is absent (Eu/Eu* = 0.91–1). The La_N/Yb_N is 3.15 (GA) and 0.77 (A). The slight to moderate enrichment in LREE could be assigned to pre-metamorphic basalt-seawater interaction. The N-MORB normalized trace element patterns (Fig. 8g) are characterized by a negative slope from Rb to Sr and nearly smooth pattern from Zr–Y: the more mobile elements i.e. LILE are variably enriched; whereas, the HFSE have an N-MORB abundance. The $(Nb/La)_{PM}$ ratio (1.04–1.45) precludes sediment contribution. The Nb/Y is 0.46 (GA) and 0.19 (A). The Zr/Nb of 5.59 for the GA and 1.51 for the A and Ce/Y of 1.38 (GA) and 0.36 (A) ratios and Ti/Y vs. Zr/Y relation (see PEARCE & GALE 1977) indicate an E-MORB affinity as summarized also by SREĆKOVIĆ-BATOĆANIN *et al*. (2002).

The texture, mineral chemistry and geochemical composition (high Mg#, low SiO_2/Al_2O_3 values, REE pattern, and positive Eu anomalies) of the Bistrica metabasic sole rocks are consistent with a cumulate gabbro and evolved tholeiitic basalts originated in MOR-type setting (BAZYLEV *et al*. 2003, 2009; MILOVANOVIĆ *et al.* 2008). The geochemical data of the Bistrica and the Zlatibor metabasic sole rocks are not published.

According to data of CHIARI *et al.* (2011) three types of basaltic rocks are recognized in the Zlatibor aureole. The first two have N-MORB, E-MORB or P-MORB affinities and their origin is assigned to partial melts derived from depleted mantle that was variably influenced by an OIB-component erupted in seamount or off-axis tectonic settings. The third one of CAB affinity originates in an island or a continental arc orogenic setting – the enrichments in Th and Yb are recognized as indicators of the SSZ-imprint.

The protoliths of the sole metabasic rocks of the Brezovica are identified as moderate to high-Mg, low-Ti and moderate to high-Ti low-K tholeiitic basalts (KARAMATA *et al*. 2000). Among them three sub-types are distinguished: strongly LREE depleted (La_N/Sm_N = 0.44 ± 0.22), moderately LREE depleted (La_N/Sm_N = 0.73 ± 0.13) and LREE enriched (La_N/Sm_N = 1.51 ± 0.36). The first two sub-types have geochemical feature similar or close to N-MORB while the third is transitional between enriched MORB (T-type) and OIB. Following their age (Table 3) the N-MORB basalts are recognized as products of an early oceanic stage or later paleo-oceanic products, whereas the third (T-MORB–OIB), the oldest one closely linked to the initiation of oceanic basin and continental fragmentation, is SSZ-type. They show similar features with those within the northwest and southern continuation of DOB (Krivaja–Konjuh, Borja, Mirdita–Pindos) concerning their LREE abundance, TiO_2, P_2O_5 as well as with metabasalts of E-MORB affinity in WVZ (e.g. Tejići).

Conclusions

The correlation of data collected from the available literature related to the metabasic sole rocks developed at the base of the ophiolites of DOB and WVZ with contribution of new data for the Bistrica metabasic rocks allow to summarize and conclude that:

1. Spatial relation and comparison of mineralogical, petrological and geochemical data as well as P–T conditions of metabasic sole rocks between the WVZ and the DOB ophiolites, with the exception of Fruška Gora, confirmed their common origin;

2. The different types of metabasic sole rocks occur at the base of obducted ophiolites as thrust or collided sheets, large blocks and fragments within the sub-ophiolitic mélange;

3. Metamorphic structures (i.e. foliation) of the majority of metabasites are parallel to basal thrust faults beneath the overlying peridotites; the same feature is confirmed in the metasediment interlayers occurring within;

4. The zonal composition of amphiboles and garnets from some metamorphic soles (e.g. Tejići, Zlatibor, Sjenički Ozren and Brezovica) are controlled by temperature; the relatively high Al^{IV}/Al^{VI} ratios in amphiboles imply mostly the moderate increase of

pressure during metamorphism; due to pressure drop and a subsequent short thermal increase the garnet from the Bistrica granulitic amphibolite show corona textures;

5. The metamorphic peak conditions recognized based on mineral assemblages and chemistry of minerals, determined: a) a high-P – low-T epidote-blueschist facies at 4–8 kbar and <300–350°C to 7–9 kbar and ~400°C (Fruška Gora); b) a high-PT amphibolite-granulite to amphibolite facies at 8–10 kbar and >700–850°C (Banjska, Bistrica, Sjenički Ozren and Brezovica); c) a greenschist to medium-PT amphibolite facies at ~3.5–7 kbar and >350–650°C (Tejići, Devovići and Zlatibor).

6. Major, trace and rare earth element distribution and elemental ratios within metabasic rocks bear geochemical affinities of cumulate gabbro and basalts of SSZ-type (E-MORB and OIB signature) or more evolved tholeiitic basalts of MOR-affinity (e.g. Bistrica); the E-MORB – OIB affinity can be linked to the rifting in an oceanic spreading center, partially affected by a plume-mantle component in both domains (WVZ and DOB); the east-dipping intra-oceanic subduction (SCHMID *et al*. 2008; CHIARI *et al*. 2011) was responsible for the evolution of the metabasic sole rocks at different metamorphic grades; according to available data it probably started at the end of Early Jurassic (178 Ma) leading to development of back-arc SSZ oceanic basins in the Middle–Late Jurassic;

7. The depth of metamorphism, i.e. the depth of detachment varies from 10 to 30 km.

8. The still hot overlying ultramafics were responsible for the creation of an inverted metamorphic sole during intra-oceanic obduction (KARAMATA *et al*. 2000; ROBERTSON *et al*. 2009 and reference therein);

9. At the Fruška Gora domain the different rock-types from the olistostrome mélange including subalkaline basalts were buried to the depths of 14–30 km by cold subduction. The generated blueschists are represented by two different mineral assemblages: glaucophane(riebeckite) + pumpellyite + actinolite + epidote at its west slope and ferro-glaucophane (earlier crossite) + riebeckite + albite + epidote + phengite at its eastern slope;

10. The reported K–Ar age range is between 174 and 146 Ma and spans almost 30 Ma.

11. The estimated P–T conditions and mineral assemblages depicted in metabasic sole rocks in the Serbian Dinaridic and the Western Vardar ophiolites are mostly in accordance with the majority of metamorphic sole metabasites developed in their north-western and western continuation in Bosnia (e.g. Krivaja–Konjuh, Borja, Ozren, Kozara) and Croatia ("Sava Zone" or WVZ) where blueschist facies metabasic rock occur as remnant of cold subduction within the sub-ophiolitic mélange (Medvednica & Motajica, see BELAK & TIBIJAŠ 1998) along with its eastern occurrence at Mt. Fruška Gora. Additionally, the metabasic sole rocks are spatially related with those exposed further south in Albania (Mirdita zone) and in Greece (Pindos zone).

This correlation reveals the need to further clarify various aspects of metamorphic sole formation, particularly for those which have not yet been studied and whose age remains uncertain.

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Резиме

Корелација метабазита из метаморфних серија у подини офиолита Динарида и Западне Вардарске Зоне (Србија): три различита P–T–t градијента

Метаморфне стене у подини офиолита указују на време метаморфизма који је изазван још загрејаном ултрамафитском масом на самом почетку затварања океанског простора. У Србији су откривене на Фрушкој Гори, Маљену, Повлену (Тејићи), Столовима и Бањској у Западној Вардарској зони (WVZ), односно на Златибору, Бистрици, Сјеничком Озрену и Брезовици, у Динаридском офиолитском појасу (DOB). На основу минералног састава, P–T услова и старости метаморфизма, издвојена су три различита P–T– t градијента.

Постојећи теренски, петролошко-минералошки, геохемијски и геохронолошки подаци о метаморфним стенама у подини офиолита WVZ и DOB-а допуњени су новим минералошким подацима о амфиболитима Бистрице. У раду су разматране само метабазичне стене чији протолити су стене океанске коре: кумулатни габрови и базалти из супра-субдукционих зона (SSZ) са одликама обогаћеног MORB-а, OIB-а или више диференцираних толеитских базалта средњоокеанских гребена. Овакве стене се редовно налазе на самом контакту са ултрамафитима. Ултрамафитски масиви, претежно лерзолитског (± гранат) састава су дефинисани као фрагменти субконтиненталног омотача (Бистрица, Сјенички Озрен) док су лерзолити (± спинел)-харцбургити Златибора и Брезовице сврстани у офиолите супра-субдукционих зона (басени иза лука). У њиховој подини су, зависно од услова метаморфизма и карактера протолита, образоване метаморфне стене веома различитог састава: гранатски и амфиболски гранулити, гранат-клинопироксенски амфиболити, клинопироксенски амфиболити, амфиболити са корундом, амфиболити и блушисти. Већина је претрпела накнадне ретроградне измене при чему су образоване различите асоцијације нискотемпературних минерала.

Метаморфити високих притисака и ниских температура, везани за субдукцију, налазе се на Фрушкој Гори: асоцијација глаукофан-рибекит-пумпелит-актинолит-епидот образована је у условима епидот-блушист субфације температурама од ~400°C и притисцима 7–9 kbar тј. на дубинама од око 30 km. Сматра се да је ту океанска кора некадашњег Вардарског океана субдукована под континенталну кору на североистоку почетком креде (барем-апт; 123 ± 5 Ma). Други тип метаморфита на Фрушкој Гори, односно другачија минерална парагенеза, образована је на температурама испод 340–350°C и притисцима од 4–8 kbar. Њихови протолити су стене из меланжа, које су процесом хладне субдукције потиснуте на дубину 14–29 km где су метаморфисане у глаукофан (рибекит)–пумпелит–актинолит–епидот–хлоритске метапешчаре и филите са фенгитом.

Метаморфити Тејића обухватају различите стене образоване у условима амфиболитске и гриншист фације. Протолити су базичне магматске стене и њихови вулканокластити, као и песковито-алевритски (пелитски) седименти. Стене вишег ступња метаморфизма (амфиболити са и без граната и епидотски амфиболити) налазе се у подини ултрамафита (претежно харцбургити из омотача). Чести су и фрагменти или блокови окцастих гнајсева и микашиста са гранатом који су образовани на температурама од 435–550°C до 630–680°C и притисцима од 4.5 ± 0.5 kbar до 6 ± 1.5 kbar. Титон/Келовејска старост метаморфита Тејића (160–150 мил. год.) утврђена је K-Ar методом. Присуство метакластита у асоцијацији са метабазитима може указати на близину копна што је потврђено појавом мандоласте текстуре у „pillow“-базалтима и одсуством дубоководних седимената.

Амфиболити на контакту са ултрамафтима у селу Девовићи (југозападни обронци Ибарског ултрамафитског масива) су формирани на температурама око 600°C од стена дијабаз-рожначке формације, односно меланжа.

Амфиболити из подине ултрамафитске масе Бањске, метаморфисани у температурном интервалу од 650°C до 760–780°C и притисцима од 6.7–6.9 kbar, указују да се почетак хлађења и тектонске стабилизације ултрамафитске масе дешавао на дубинама од 24–25 km.

Метаморфити Рогозне су углавном представљени амфиболитима и зеленим шкриљцима (микашисти и мермери су мање заступљени). Старост мерена на зрнима амфибола из свежих стена је између 168.8 ± 3.9 и 178.3 ± 6.7 милиона година, а старост хидротермално алтерисаних амфиболита 150.4 ± 10.2 милиона година (Ar–Ar метода). Добијене вредности времена почетка интраокеанске субдукције/обдукције (доња до средња јура; тоарски и бајески кат) су у складу са вредностима добијеним за метаморфите из подине офиолита Динарида и Албаније.

Метабазити развијени око Златиборског ултрамафитског масива (550–650°C и 3–3.5 kbar) показују да се тектонска стабилизација и почетак хлађења овог масива дешавао на знатно мањој дубини (12–13 km) у поређењу са другим масивима Србије. Тектонски блок Бистрице на јужном ободу Златиборског масива састоји се углавном од спинел лерзолита и лерзолита са жицама и слојевима порфиробластичних харцбургита, гранатских клинопироксенита и спинелских хорнблендита, које указују на порекло из субконтиненталног омотача. Метаморфне стене у подини ултрамафита су образоване у условима амфиболит-гранулитске, амфиболитске и гриншист фације. Гранат-пироксенски амфиболити настали су на температурама између 828–879°C и 740–830°C при притисцима од 8–10 kbar. Старост гранат-пироксенских амфиболита и корунд-паргаситских амфиболита од 178 ± 14 милиона година утврђена је K–Ar методом.

Опсег услова метаморфизма гранат-пироксенских амфиболита Сјеничког Озрена јесте 750–830°C при притисцима 5–6 kbar што је еквивалентно дубинама од 18 до 22 km. Амфиболити, габро амфиболити и зелени шкриљци, који се налазе даље од контакта са ултрамафитима, метаморфисани су на температури између 400–430°C. Максималне израчунате вредности метаморфизма указују да је масив Сјеничког Озрена смештен у данашњи положај као већ очврсла или делимично очврсла маса (изнад 1000°C).

У контактном ореолу Брезовице издвојене су три зоне. У првој зони, на самом контакту са перидотитима, налазе се гранат (± клинопироксен) амфиболити и гранат –дистенски гнајсеви, образовани на температурама између 700–750°C и 600–670°C и притисцима од 8–9 kbar.

У свим испитиваним метаморфним стенама амфибол је главна минерална фаза. Образује се од мафитске компоненте из протолита, а варијације у хемизму су последица промене P–T услова. У већини напред приказаних типова стена они по саставу одговарају Mg – хорнбленди, едениту, магнезијском хастингситу и актинолиту. Изузетак су блушисти Фрушке Горе у којима је то феро–глаукофан и Mg–рибекит или зонарни Na–амфибол глаукофан рибекитског типа, као и амфиболити Бистрице са еденитом и Mg–хастингситом и паргаситом.

Гранати су запажени у амфиболитима развијеним на самом контакту са ултрамафитима и то у оба офиолитска појаса. Амфиболити Рогозне, Девовића, Златибора и Фрушке Горе не садрже гранат. Симплектитски, реакциони руб, запажен први пут око зрна граната у гранатским амфиболитима Бистрице, изграђен је од врло ситних зрна клинопироскена, албита и амфибола, што говори да је гранат углавном и растао на рачун ова три минерала.

Температурни услови метаморфизма и карактер новостворених фаза су тесно везани за топлотни капацитет офиолита и карактер протолита. Притисак је директно пропорционалан дубини, па његове различите вредности указују на различите дубине одвајања океанске литосфере и дубину иницијалног хлађења. Метаморфити у подини офиолита Србије су образовани на притисцима којима одговарају дубине од 10 до 30 km. Постепен пораст притиска са напредовањем океанске плоче је у неким случајевима забележен кроз промене хемизма минерала (на пр. Тејићи, Бистрица, Фрушка Гора).

На основу минералног састава, израчунатих P–T услова метаморфизма, зонарности минерала и старости метаморфизма, издвојена су три потенцијална *P–T–t* градијента:

– висок-P – ниска-T – 123 ± 5 мил.год. (7–9 kbar, T ~400°C и <300–350°C, P 4–8 kbar). Ова асоцијација метаморфних минерала је забележена једино у метаморфном ореолу Фрушке Горе (WVZ);

– висок-P – висок-T – 146 ± 4.9 и 174 ± 14 мил. год. (8–10 kbar, >700–850°C) утврђена у Бањској (WVZ) и у Бистрици, Сјеничком Озрену и Брезовици (DOB) и

– средњи- P – средњи-T – 160–178.3 ± 6.7 мил. год. (3.5–7 kbar и >350–650°C), утврђена у оба појаса: Тејићи и Девовићи (WVZ) и Златибор (DOB).

Тектонска средина која би одговарала делу DOB у Србији (на пр. Бистрица) одговара подручју обдукције океанске плоче и касније изазване унутар океанске субдукције. Метаморфизам се у почетку одвијао на великим дубинама ≥30 km (P≥10 kbar и T ~800 ± 50°C). Појава реакционих рубова и минералних фаза средњих P–T указују да су овакви услови кратко трајали и да је дошло до брзе ексхумације офиолитске секвенце.

У другим деловима океанског подручја се унутар-океанска субдукција SSZ-типа одвијала на различитим дубинама и дала различите метаморфне стене. Продукт најдубље субдукованог офиолитског блока (~30–36 km) су гранат–клинопироксенски метабазити Бистрице. Одатле ка северозападу постепено опадају вредности P–T, односно дубине субдукције на 18–25 km (Сјенички Озрен и Бањска) и 18–15 km (Тејићи). Минимална вредност, од 12–13 km је забележена на Златибору.

Просторни распоред и поређење минералошко-петролошких и геохемијских података, као и P–T услова у којима су образоване метабазичне стене у бази офиолита ЗВЗ и ДОП са изузетком метаморфита Фрушке Горе, указују на образовање у сличном тектонском режиму, на шта су указали и SCHMID *et al*. (2008) и CHIARI *et al*. (2011).