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Evidence of the spreading culmination in the Eastern Tethyan Repno oceanic domain, assessed by the petrology and geochemistry of N-MORB extrusive rocks from the Mt. Medvednica ophiolite mélange (NW Croatia)

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ABSTRACT

The Eastern Tethyan Repno oceanic domain (ROD), from the Zagorje-Mid-Transdanubian Shear Zone, borders the Meliata-Maliak and Dinaric-Vardar oceanic realms. The domain lacks ophiolite complexes and oceanic rocks are restricted to four Early Callovian to Late Valanginian ophiolite mélange sectors integrated in the Kalnik Unit. Previous research on ophiolitic rocks from the Kalnik Unit provided a detailed tectonomagmatic evolution of crust formation at different settings from the Late Anisian to the Cretaceous. N-MORB-type crust with peculiar supra-subduction signatures formed on a spreading ridge from the Late Carnian (~225 Ma) to the Late Pliensbachian (~185 Ma), and the first intraoceanic subduction rocks were dated as Late Bathonian (165 Ma). The newly discovered basaltic rocks, in coherent slices with the Latest Bajocian-Early Bathonian (~169 Ma) radiolarin cherts from the Mt. Medvednica ophiolite mélange sector, completed the Late Pliensbachian-Late Bathonian chemostratigraphic gap in the domain. The analysed unfractionated extrusive rocks lack any influence of a subduction related component, $[(Nb/La)_n = 1.16–1.34$; $Th/Ta = 0.99–1.05]$ and are akin to proper N-MORB compositions $[(Nd/Lu)_{N\text{-}MORB} \sim 1.1$; $(La/Lu)_{cn} = 0.82–0.92]$ that were derived from a slightly depleted mantle source $[\varepsilon_{Nd(T=170\ Ma)} = +6.21$ to $+6.27$; $(^{87}Sr/^{86}Sr)_i = 0.703365$ to $0.703511]$. The rocks are interpreted as vestiges of the middle oceanic ridge crust formed during the culmination of spreading in the ROD.

Keywords: petrology, geochemistry, N-MORB extrusives, ophiolite mélange, Bajocian-Bathonian, Zagorje-Mid-Transdanubian Zone, Mt. Medvednica, Croatia

1. INTRODUCTION

Fragments of ancient oceanic lithosphere are terrestrially exposed in an orogenic belt, due to relative coherent thrust sheets that form an ophiolite complex that is generally associated with underlying ophiolite mélange. Most of the oceanic lithosphere, with a geochemical affinity highlighted by proper (normal) middle ocean ridge basalts (N-MORB), was formed at the mid oceanic ridge during several tens of millions of years of spreading. The major part of the mid oceanic ridge succession has been subducted, and only a minor part has been preserved by being removed from the subducting slab, in trench sediments of the accreationary prism in front of the overriding plate. However, a significant proportion of the youngest N-MORB lithosphere related to the spreading ridge has been obducted and created an example of pristine crust of the intraoceanic upper plate, which was replaced by ongoing formation of true SSZ crust derived from a depleted and metasomatized mantle wedge, that experienced a long term complex history of partial melting. Consequently, the amount of proper N-MORB lithologies is relatively low in the ophiolite mélange. The culminating stage of ocean spreading, represented by the youngest N-MORB crust, may therefore be poorly documented in an ophiolite mélange and only a systematic petrological and geochemical study of magmatic inclusions of the mélange may provide more opportunity to characterize oceanic tectomagmatic evolution at this stage.

This work provides more detailed knowledge of the tectonomagmatic evolution of an Eastern Tethyan oceanic domain, colloquially termed the Repno Oceanic Domain (ROD; BABIĆ et al., 2002), which borders the Meliata-Maliak and Dinaric-Vardar ocean systems. The domain lacks ophiolite complexes and ophiolitic rocks are exposed in only four separate ophiolite mélange sectors, integrated in the Kalnik Unit by HAAS et al., (2000). The various magmatic blocks and juxtaposed fragments of sedimentary rocks, vary in both age and lithology, and are mostly tectonically included within the matrix of mélange, thus obscuring their original geological setting of formation (HALAMIĆ, 1998; SLOVENEC & PAMIĆ, 2002). Previous research on the magmatic blocks in the Kalnik Unit, provided constraints on the detailed geodynamic and tectonomagmatic evolution of the ROD, based exclusively on geochemical and petrological data. The evolution commenced in the Anisian by intra-continental rifting, via formation of proto-oceanic crust in the Ladinian and the onset of crust formation at a spreading ridge until the Middle Jurassic. Initial SSZ crust formed in the Late Bathonian, with formation of infant forearc-proto-arc crust in the Callovian-Oxfordian, and formation of the youngest crust in a Cretaceous back-arc basin (LUGOVIĆ et al., 2007; SLOVENEC & LUGOVIĆ, 2008, 2009; SLOVENEC et al., 2010, 2011; KISS et al., 2012; LUGOVIĆ et al., in rewiev). The peculiar characteristic of MORB-type crust in the ROD that commenced in the Middle Carnian and was prolonged to the Late Pliensbachian is its SSZ geochemical flavour. The evolutionary stage of the ROD that may be reflected by proper N-MORB lithosphere remained unsolved by previous research. Relatively rare occurrences of the relevant rocks were recently encountered only in the Mt. Medvednica ophiolite sector near Poljanica (*locus tipicus)*. Petrological and geochemical research on these rocks and particularly on the coherent blocks composed of N-MORB pillow lavas and radiolarian cherts, provided age determination of the culminating phase of spreading in the ROD, thus improving knowledge of the high-resolution tectomomagmatic evolution of the domain.

2. OUTLINE OF REGIONAL GEOLOGY

Mt. Medvednica along with Mts. Ivanščica and Kalnik is located at the southwestern tip of the SW-NE trending Zagorje-Mid-Transdanubian Zone (ZMTDZ; PAMIĆ & TOMLJENOVIĆ, 1998), within the triple junction zone between three complex tectonic units represented by the Southern-Eastern Alps Unit, Internal Dinarides, and the Tisia continental block (Fig. 1A). The ZMTDZ approximately corresponds to the Sava Unit defined by HAAS et al. (2000) and comprises a 100 km wide and 400 km long area between the Periadriatic-Balaton lineament to the north and the Zagreb-Zemplin lineament to the south. Although the structural pattern of these intra-Panonnian *inselbergs* is obscured by Tertiary displacements and Neogene sedimentary cover, a Dinaride characteristic has been recognized (e.g. HAAS & KOVÁCS, 2001). The true Dinarides which are traditionaly divided into the External (Outer) and Internal (Inner) Dinarides, stretch southeastwards from the Zagreb-Zemplin lineament as 700 km long tectonostratigraphic units bounded by the Skutari-Peć transform fault to the southeast (Fig. 1A). Dinaric tectonostratigraphic units extend further into the Albanides and continue southwards into the Hellenides. The External Dinarides mainly consist of Mesozoic carbonate platform that is structurally overlain by allochthonous, continentally derived units showing Palaeozoic–Triassic stratigraphic successions; the Internal Dinarides comprise several zones that regularly reflect the transition from platform sediments to the Mesozoic oceanic realm, with the outermost zone sutured to the Eurasian continental lithospheric plate, (see compilation in PAMIĆ et al., 2002 and ROBERTSON et al., 2009). Most internal zones are dominated by ophiolite units and are sensu PAMIĆ (2002) subdivided into the Central Dinaridic Ophiolite Zone (CDOZ) and more internal Sava-Vardar Suture Zone (SVSZ).

Structural and palaeomagnetic data indicate that the tectonic block comprising the Medvednica, Ivanščica and Kalnik Mts. experienced ca. 130° clock-wise rotation and eastwards escape during the Oligocene-earliest Miocene, (TOMLJENOVIĆ et al., 2008) that resulted in a structural trend almost perpendicular to the NW-SE Dinaric trend. Despite this dramatic change of trend in respect to the overall Dinaric structural trend, SCHMID et al. (2008) included the ZMTDZ in the Western Vardar Ophiolite Unit, based on the similar tectonostratigraphic evolution, particularly for the ophiolitic rocks. Ophiolite mélanges from the southwestern ZMTDZ exposed in these three mountain sectors, and possibly those in the Mt. Samoborska Gora sector, are integrated into a combined tectonostratigraphic unit termed the Kalnik Unit (HAAS et al., 2000). The Kalnik Unit incorporates various ophiolitic, lithic vestiges related to the ROD, that according to BORTOLOTTI & PRINCIPI (2005) may represent the westernmost oceanic segment of Eastern Tethys. Therefore, the ROD is an important oceanic domain that borders the Meliata-Maliak oceanic segment located to the northeast and the Dinaric-Vardar oceanic system to the southeast.

3. GEOLOGY OF MEDVEDNICA MT.

The geographic position of the locations relevant for this work and a simplified geological map of the northwestern part of Mt. Medvednica are displayed in Fig. 1B–C.

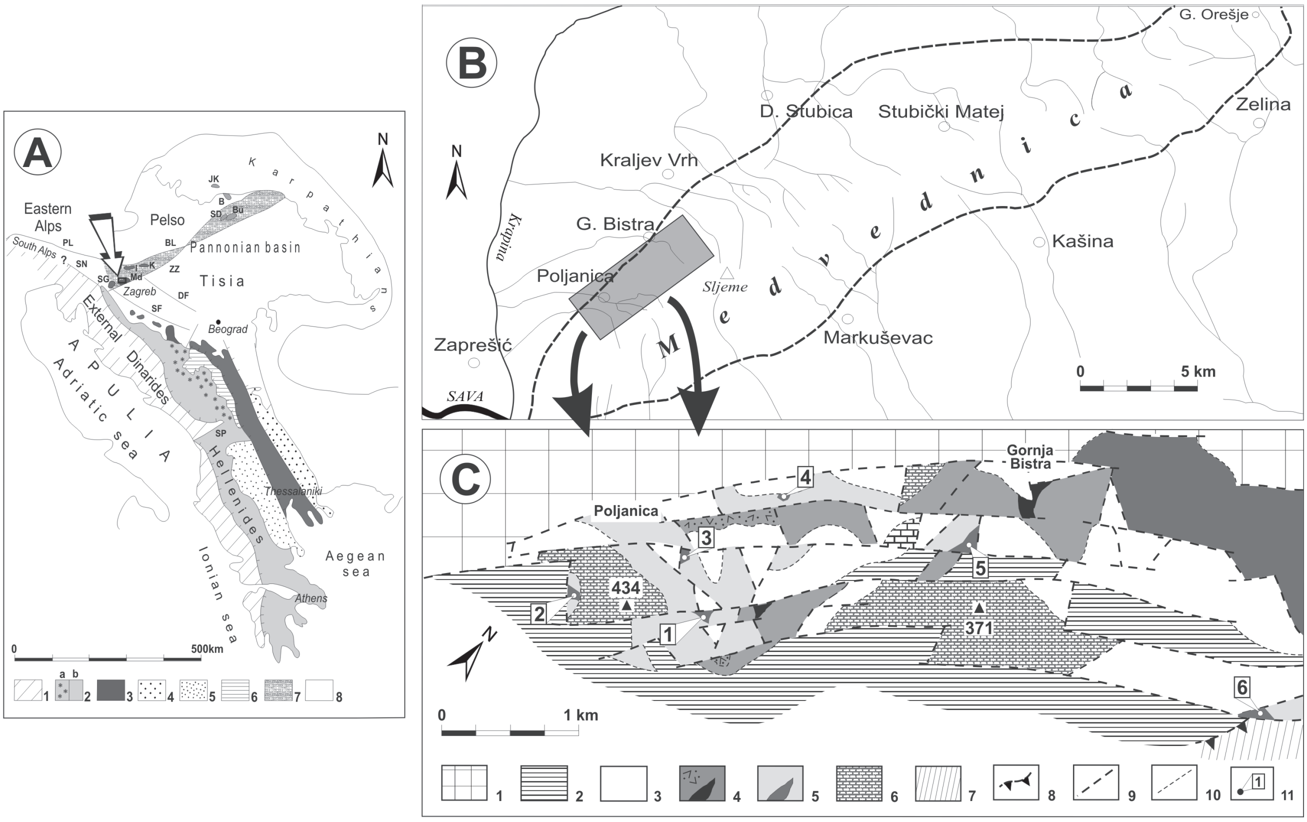

Figure 1: **(A)** Geotectonic sketch map of Alps, Dinarides and Hellenides showing the position of the Periadriatic-Sava-Vardar suture zone (modified after PAMIĆ, 2000). Legend: 1 – External Dinarides and Alps; 2 – Internal units [a: Central Dinaride Ophiolite Belt (CDOB); b: Passive continental margin and Mirdita Zone]; 3 – Periadriatic-Sava-Vardar Zone; 4 – Serbo-Macedonian Massif; 5 – Pelagonide metamorphic complex; 6 – Golija Paleozoic Zone; 7 – Zagorje-Mid-Transdanubian Zone; 8 – Panonian Basin. Faults: BL – Balaton; DF – Drava; PL – Periadriatic; SF – Sava; SP – Scutari-Peć; SN – Sava Nape; ZZ – Zagreb-Zemplin. Mountains: I – Ivanščica; K – Kalnik; Md – Medvednica; SgŽ – Samoborska gora and Mts. Žumberak; SD – Szarvaskö-Darnó. B – Bódva valley; JK – Jaklovce**.** **(B)** Geographical location of the study area (gray shaded). **(C)** Simplified geological map of Mt. Medvednica (modified after HALAMIĆ, 1998). Legend: 1 – Neogene and Pleistocene sedimentary rocks; 2 – Late Cretaceous-Paleocene flysch including Senonian carbonate breccias; 3 – ophiolite mélange with blocks of: 4 – Middle Triassic radiolarites, shales, limestones, pyroclastites and basalts (black fields), 5 – Middle Jurassic radiolarites, shales and basalts (dark gray fields), 6 – Alb-Cenomanian limestones and clastic rocks (shale, siltite and sandstone); 7 – Lower Cretaceous metamorphic complex; 8 – reverse or thrust faults; 9 – normal faults; 10 – geological contact line; 11 – sample locations: 1 = vs-113/2, vs-113A4; 2 = vh-49B; 3 = vs-94/1; 4 = vs-85/2; 5 = vh-1001/1; 6 = vs-307/1.

Structurally, the lowermost tectonic unit of Mt. Medvednica consists of lower greenschist facies para- and orthometamorphic rocks represented by slate-phyllites, quarzites, marbles metasandstones and greenschists, respectively (ŠIKIĆ et al., 1978, 1979; BASCH, 1981, 1983), that correspond to the ZMTDZ metamorphic complex or Medvednica Unit (HAAS et al., 2000). The Medvednica Unit comprises a thick sedimentary succesion deposited from the Silurian to the Ladinian, that was metamorphosed in the Lower Aptian (BELAK et al., 1995) by emplacement of a Late Jurassic island-arc onto the Adria continental margin (LUGOVIĆ et al., 2006). The Medvednica Unit is thrusted by an ophiolite mélange, that is, by the Mt. Medvednica sector of the Kalnik Unit. The accretionary age of the Kalnik Unit can be constrained from the Early Callovian to the Late Valanginian (BABIĆ et al., 2002) and represents the period of accumulation of lithostratigraphically different materials in the intraoceanic trench (SLOVENEC et al., 2011). Both units are unconformably overlain by a Late Cretaceous-Palaeocene Gosau-type sedimentary sequence, composed of clastic-carbonate and flysch sediments (ŠIKIĆ et al., 1979). Neogene and Pleistocene sedimentary sequences unconformably overlie pre-Neogene basement rocks along the southern slopes of the mountain, whilst on the northwestern slopes they are tectonically superimposed.

The Kalnik Unit in the Mt. Medvednica sector is characterized by block-in matrix fabric, typical for chaotic complexes from subduction-related tectonic mélanges (FESTA et al., 2010). The primary depositional structural features are obliterated during emplacement and incorporation of large fault-bounded olistoliths (Fig. 1C), that resulted in strongly sheared pelitic-silteous continent derived matrix. However, the matrix of the ophiolite mélange does not show any metamorphic overprint after diagenetic equilibration (JUDIK et al., 2008).

The Mt. Medvednica ophiolite mélange incorporates fragments of various Mesozoic sedimentary rocks, (greywacke, minor shale, red and grey cherts and scarce limestones), that are randomly mixed, along with fragments of igneous plutonics (peridotite cumulates and gabbros) and extrusive basalts and mafic dyke rocks (SLOVENEC & LUGOVIĆ, 2008, 2009; SLOVENEC et al., 2010 and references). Fragments of basaltic rocks are fairly dominated by magmatic components in this ophiolite mélange. Excluding fragments of Illyrian-Fassanian pre-oceanic within-plate alkali basalts, all other magmatic rocks display oceanic supra-subduction affinity, i.e., are scraped from an upper plate. In Mt. Medvednica, the oceanic crust fragments show a wide range of geochemical signatures consistent with their geotectonic setting, but show a relatively narrow range of corresponding ages of formation (SLOVENEC & LUGOVIĆ, 2009). The oldest oceanic rocks in the Mt. Medvednica ophiolite mélange are the latest Bathonian N-MORB-like basalt, related to the initial intraoceanic subduction rocks that were followed by true subduction IAT-type basalts of the Early Oxfordian. Despite age or geotectonic provenance, these MORB-type or MORB-like lithologies show peculiar subduction related components, or, in another words, correspond to "MORBs with arc-signatures" sensu SHERVAIS (2001).

However, only six blocks of proper N-MOR basalts were found in the Poljanica area of the Mt. Medvednica ophiolite mélange (Fig. 1C) which is a unique occurrence of this rock type in the entire Kalnik Unit. These hectometre large blocks consist of pillow lavas and massive extrusives (Fig. 1C, locations 1, 4, 5, 6 and 2–3, respectively). Pillow lavas at location 1 and location 5 form a coherent slice along with radiolarian cherts, sometimes mixed with silicified shales which were (on account of the radiolarian assemblage) dated to the Latest Bajocian-Early Bathonian (HALAMIĆ et al., 1999). These extrusive rocks are the subject of this work.

4. ANALYTICAL TECHNIQUES

Minerals were analyzed at the Mineralogisches Institut, Universität of Heidelberg, using a CAMECA SX51 electron microprobe equipped with five wavelength-dispersive spectrometers. Measurements were performed using an accelerating voltage of 15 kV, beam current of 20 nA, beam size of ~ 1 μm (for feldspars 10 μm) and 10 s counting time for all elements. Natural minerals, oxides and silicates were used for calibration. Raw data for all analyses were corrected for matrix effects with the PAP algorithm (POUCHOU & PICHOIR, 1984, 1985) implemented by CAMECA. Formula calculations were

Table 1: Selected microprobe analyses and structural formulae of clinopyroxene from the N-MORB extrusive rocks in the Mt. Medvednica ophiolite mélange

Sample	vs-113/2							
Anal. nr.	6	8	11	13	17	18	21	23
SiO_2	49.94	47.98	49.56	48.98	51.77	50.60	49.44	49.54
TiO_2	1.31	2.29	1.57	1.64	1.09	1.44	1.31	1.53
Al_2O_3	2.55	4.26	3.13	3.68	2.06	2.11	2.93	3.11
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
FeO	12.69	12.56	10.12	10.65	9.58	13.90	13.73	9.97
MnO	0.60	0.45	0.31	0.33	0.30	0.43	0.43	0.23
MgO	12.05	11.37	14.61	13.67	14.83	12.19	11.75	13.92
CaO	19.83	20.38	19.73	20.23	20.09	19.06	19.59	20.42
Na_2O	0.45	0.43	0.68	0.41	0.32	0.19	0.40	0.46
Total	99.42	99.72	99.73	99.59	100.04	99.92	99.65	99.23
Si	1.900	1.824	1.846	1.838	1.926	1.925	1.882	1.862
Ti	0.037	0.065	0.044	0.046	0.030	0.041	0.038	0.043
Al^{IV}	0.100	0.176	0.137	0.162	0.074	0.075	0.118	0.138
Al^{VI}	0.014	0.015	0.001	0.001	0.016	0.020	0.014	0.001
Cr	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.001
Fe^{3+}	0.043	0.062	0.131	0.098	0.020	0.000	0.058	0.085
Fe^{2+}	0.360	0.338	0.184	0.236	0.278	0.442	0.379	0.229
Mn	0.019	0.014	0.010	0.010	0.009	0.014	0.016	0.006
Mg	0.683	0.644	0.811	0.765	0.882	0.692	0.667	0.780
Ca	0.808	0.830	0.787	0.813	0.801	0.777	0.799	0.822
Na	0.033	0.032	0.049	0.030	0.023	0.014	0.030	0.034
Total	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000
Mg#	65.5	65.6	81.5	76.4	74.7	61.0	63.8	77.3
Al^{VI}/Al^{IV}	0.14	0.09	0.01	0.01	0.21	0.27	0.12	0.01
Wo	42.21	43.96	40.93	42.30	41.48	40.37	41.64	42.76
En	35.69	34.13	42.17	39.77	42.60	35.93	34.75	40.56
Fs	22.09	21.91	16.89	17.93	15.93	23.70	23.62	16.68

Formulae calculated on the basis of 4 cations and 6 oxygens. Mg# = 100*Mg/($Mg + Fe^{2+}$).

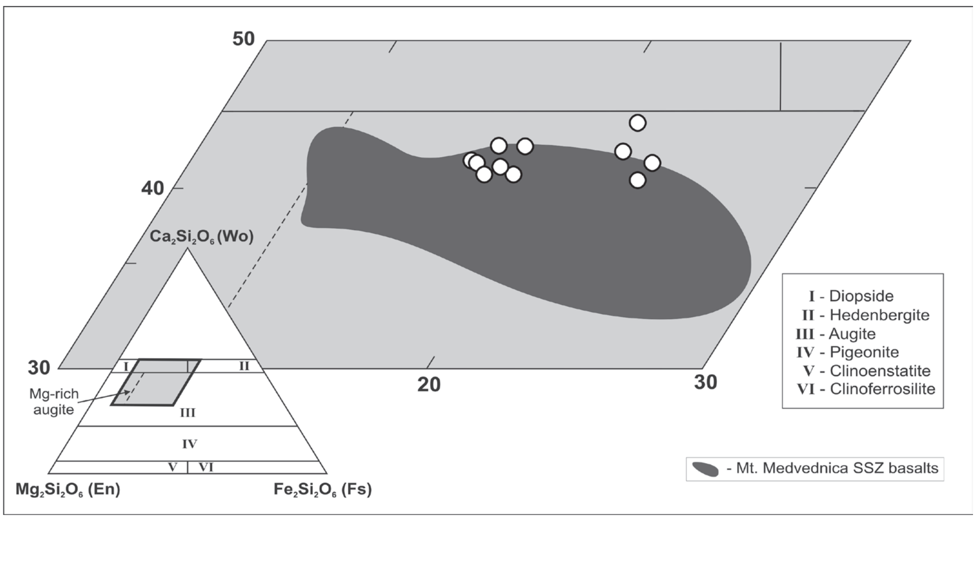

Figure 2: Plot of clinopyroxene compositions in the En–Wo–Fs ($Mg_2Si_2O_6$–$Ca_2Si_2O_6$–$Fe_2Si_2O_6$) diagram with the nomenclature fields of MORIMOTO (1988) for N-MORB volcanic rocks from the Mt. Medvednica ophiolite mélange. Field of clinopyroxene compositions (dark gray shaded) from high-, medium- and low-Ti tholeiitic SSZ basalts in the Mt. Medvednica ophiolite mélange (SLOVENEC & LUGOVIĆ, 2009) plotted for correlation constraints.

done by using a software package designed by Hans-Peter Meyer from the Mineralogisches Institut, Universität of Heidelberg, Germany.

Bulk-rock powders for chemical analyses of seven samples were obtained from rock chips free of veins and amygdales. The samples were analysed by ICP for major elements, and ICP-MS for all trace elements at Actlab Laboratories in Ancaster, Canada. International mafic rocks were used as standards. Major element and trace element concentrations were measured with accuracy better than 1% and 5%, respectively.

Isotopic compositions of 2 bulk rock samples were measured in CRPG in Vandoeuvre, France, on a Triton Plus mass spectrometer. Normalizing ratios of $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$ were assumed. The $^{87}Sr/^{86}Sr$ ratio for the NBS 987 Sr standard for the period of measurement was 0.710242 ± 0.000030 (2σ). The $^{143}Nd/^{144}Nd$ ratio for the La Jolla standard was 0.5118451 ± 0.000010 (2σ). Total procedural blanks were ~500 pg and ~150 pg for Sr and Nd, respectively.

5. PETROGRAPHY AND MINERAL CHEMISTRY

The analysed rocks are represented by green to red basaltic massive or amygdaloidal pillow lavas, characterized by irregular fracturing. Monomineralic vesicle infillings are composed of calcite, chlorite or fine-grained quarz. Near the contact with the shale, the pillows exhibit a fine-grained haematite pigmented zone with divergent-radial texture. Both types of lavas are severely altered but still preserve fine- to medium-grain ophitic, or intergranular texture occassionally with minor plagioclase phenocrysts. Magmatic plagioclase is replaced by albite ($An_{0.2–3.1}$) and peristerite ($An_{\sim 8}$) and contains small inclusions of chlorite, aggregated sericite-pumpellyite and zoisite-group minerals. Small relics of skeletal clinopyroxene are rare, usually pseudomorphosed by pycnochlorite-diabantite and epidote. Fe-Ti oxides (magnetite and skeletal ilmenite) are accessory minerals. Such altered rocks are usually called spilite. Petrographic evidence suggests the following order of crystallization: plagioclase → clinopyroxene + plagioclase ± Fe-Ti oxides, that is traditionally assumed as typical for volcanic rocks formed at an ocean ridge (e.g. BECCALUVA et al., 1980). Microtextures of an alteration assemblage with prehnite, pumpellyite, chlorite and calcite indicate ocean floor metamorphism. The clinopyroxene from the Poljanica rocks shows an augite composition ($Wo_{40.4–43.9}En_{34.1–42.6}Fs_{15.93–23.7}$; Table 1) that is significantly different compared to the clinopyroxenes from the Mt. Medvednica SSZ volcanic rocks (Fig. 2). They are characterized by a comparatively higher content of non-quadrilateral elements (Fig. 3) and their Ti/Al ratio (0.28–0.43). The TiO_2 content is generally high but variable in individual grains (1.09–2.29 wt.%), whilst the range of Mg# is limited to 81.5–61.0 (Table 1) reflecting the lack of significant Fe-enrichment in the analyzed clinopyroxenes (Fig. 2). The clinopyroxene Al^{VI}/Al^{IV} ratio ≤ 0.27 suggests low pressure crystallization consistent with the observed order of crystallization.

6. BULK ROCK CHEMISTRY

Chemical compositions of the analyzed rocks are shown in Table 2. High LOI (up to 8.32 wt.%) combined with petrographic evidence confirm the severe alteration of the rocks that might have affected the magmatic content of certain elements. The relative mobility of elements was proven by plotting their concentration against Zr as a differentiation index (not shown). Large ion lithophile elements (= LILE) Cs, Rb, K, Ba and Sr revealed random and selective migration caused by alteration and were consequently excluded from petrogenetic constraints. However, high field strength

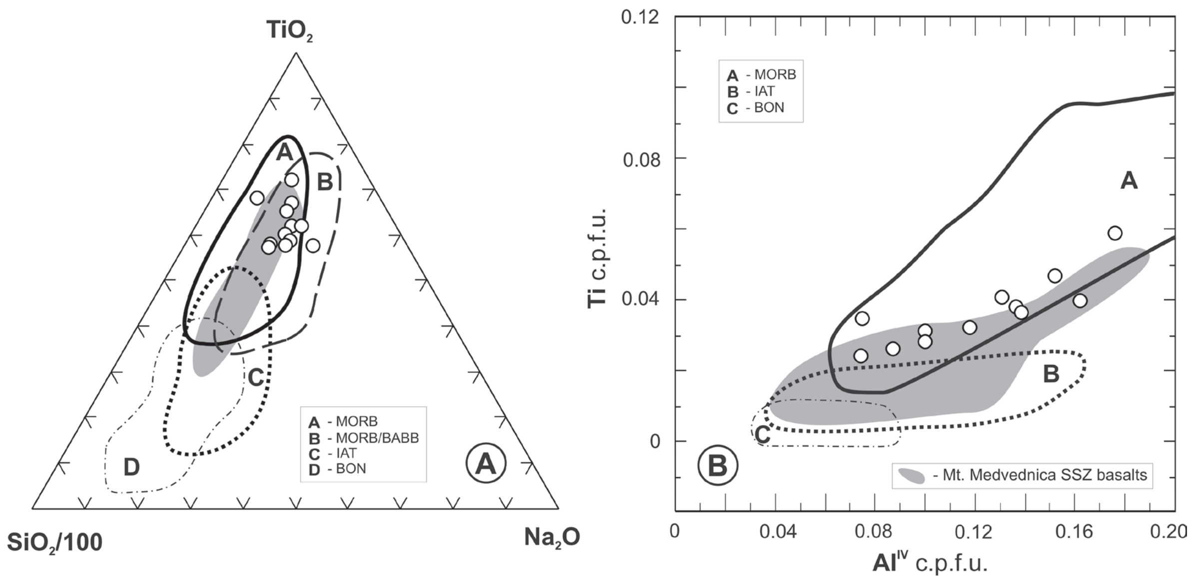

Figure 3: **(A)** Diagram $SiO_2/100 – Na_2O – TiO_2$ and **(B)** $Ti – Al^{IV}$ (simplifed after BECCALUVA et al., 1989) for clinopyroxene from the Mt. Medvednica N-MORB volcanic rocks. MORB – mid-ocean ridge basalts; BABB – back-arc basin basalts; IAT – island-arc tholeiites; BON – boninite. Fields of clinopyroxene compositions (gray shaded) from high-, medium- and low-Ti tholeiitic SSZ basalts in the Mt. Medvednica ophiolite mélange (SLOVENEC & LUGOVIĆ, 2009) plotted for correlation constraints.

Table 2: Chemical analyses of N-MORB extrusive rocks from the Mt. Medvednica ophiolite mélange.

Sample	vs-113/2	vs-113A4	vh-49B	vs-94/1	vs-85/2	vh-1001/1	vs-307/1
Rock type	PB	PB	MB	MB	PB	PB	PB
SiO_2	51.32	46.43	49.62	47.12	48.23	47.89	47.06
TiO_2	1.20	1.34	1.24	1.38	1.42	1.57	1.64
Al_2O_3	16.68	15.67	17.46	15.02	15.94	14.96	13.78
$Fe_2O_{3\,total}$	8.32	9.05	6.84	12.43	9.21	13.05	13.88
MnO	0.32	0.71	0.15	1.26	0.29	0.33	0.25
MgO	6.65	7.06	7.13	8.01	6.92	7.63	7.78
CaO	5.92	6.98	7.91	4.03	6.28	5.39	5.99
Na_2O	4.75	3.99	4.51	3.35	3.56	3.21	2.83
K_2O	0.32	0.15	0.65	0.16	0.32	0.18	0.16
P_2O_5	0.10	0.10	0.11	0.12	0.11	0.13	0.15
LOI	3.96	8.32	3.93	6.89	6.64	5.31	5.94
Total	99.54	99.80	99.55	99.77	99.92	99.65	99.46
Mg#	62.9	61.1	67.9	56.5	60.7	55.3	53.6
Cs	0.5	1.2	0.7	1.6	1.4	2.1	1.8
Rb	12	7	12	15	11	10	9
Ba	225	108	257	203	192	202	187
Th	0.24	0.21	0.26	0.27	0.23	0.34	0.37
Ta	0.24	0.20	0.25	0.27	0.22	0.33	0.36
Nb	4.0	3.4	4.1	4.5	3.7	5.5	5.8
Sr	92	101	131	105	112	101	132
Zr	72	70	83	92	75	98	111
Hf	2.0	1.8	2.2	2.5	1.9	2.7	3.0
Y	25	24	27	31	25	34	38
Sc	35	34	40	32	39	41	48
V	206	196	226	214	218	221	254
Cr	575	598	497	372	524	126	187
Ni	191	294	195	210	233	122	156
La	3.47	3.14	3.76	3.98	3.25	4.51	4.63
Ce	9.92	8.78	10.51	11.16	9.02	12.48	12.65
Pr	1.38	1.22	1.55	1.64	1.31	1.73	1.85
Nd	7.24	6.67	7.89	8.99	6.98	9.20	10.28
Sm	2.56	2.21	2.65	3.04	2.31	3.25	3.54
Eu	0.981	0.872	1.010	1.139	0.940	1.219	1.412
Gd	3.31	3.08	3.38	4.03	3.21	4.23	4.74
Tb	0.59	0.55	0.62	0.73	0.59	0.79	0.92
Dy	3.84	3.61	4.07	5.02	3.78	5.51	6.14
Ho	0.89	0.83	0.94	1.11	0.88	1.21	1.36
Er	2.55	2.40	2.79	3.39	2.62	3.58	3.89
Tm	0.390	0.371	0.419	0.478	0.389	0.542	0.591
Yb	2.66	2.58	2.80	3.41	2.63	3.68	3.98
Lu	0.399	0.389	0.421	0.490	0.402	0.552	0.588

Major elements in wt.%, trace elements in ppm. LOI = loss on ignition at 1100 °C. MB = massive basalt, PB = pillow basalt. Mg# = 100*molar MgO/(MgO + FeO_{total}).

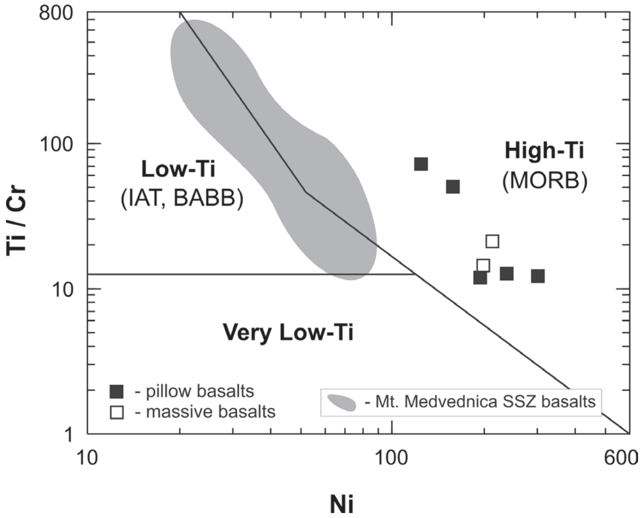

Figure 4: Ni – Ti/Cr diagram (BECCALUVA et al., 1983) for the N-MORB volcanic rocks from the Mt. Medvednica ophiolite mélange. Field (gray shaded) for high-, medium- and low-Ti tholeiitic SSZ basalts from the Mt. Medvednica ophiolite mélange (SLOVENEC & LUGOVIĆ, 2009) plotted for correlation constraints.

elements (= HFSE) Ti, Th, Hf, Nb, Ta, P and Y and rare earth elements (= REE) from La to Lu showed magmatic correlation and therefore were utilized as suitable tools for geochemical and petrogenetic considerations, as previously used for analogue rocks elsewhere (e.g. PEARCE & NORRY, 1979; SHERVAIS, 1982; BECCALUVA et al., 1983). This also holds true for the transitional metals V, Cr, Mn, Fe, Ni and Zn, though their measured concentrations are strongly dependent on the amount of related mineral phase in a rock.

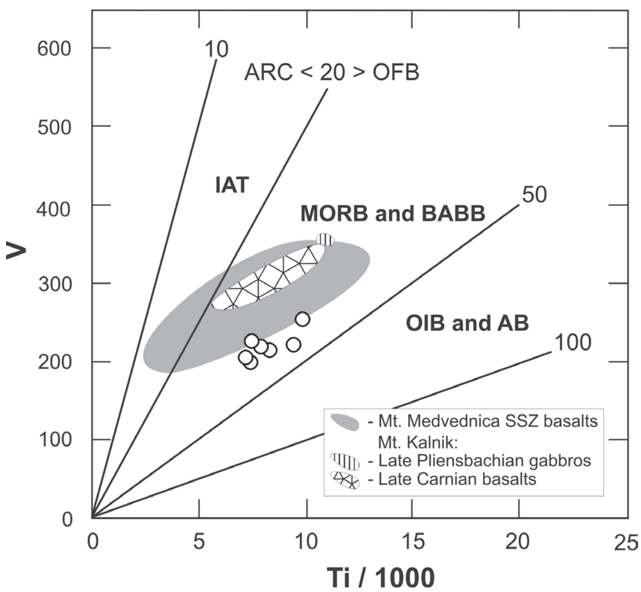

Figure 5: V – Ti/1000 diagram (SHERVAIS, 1982) for the N-MORB volcanic rocks from the Mt. Medvednica ophiolite mélange. IAT – island-arc tholeiites, MORB – mid-ocean ridge basalts, BABB – back-arc basin basalts, OIB – ocean-island basalts and AB – alkali basalts. Fields for high-, medium- and low-Ti tholeiitic SSZ basalts from the Mt. Medvednica ophiolite mélange (SLOVENEC & LUGOVIĆ, 2009), Late Pliensbachian gabbros (LUGOVIĆ et al., in rewiev) and Late Carnian basalts (SLOVENEC et al., 2011) from Mt. Kalnik plotted for correlation constraints.

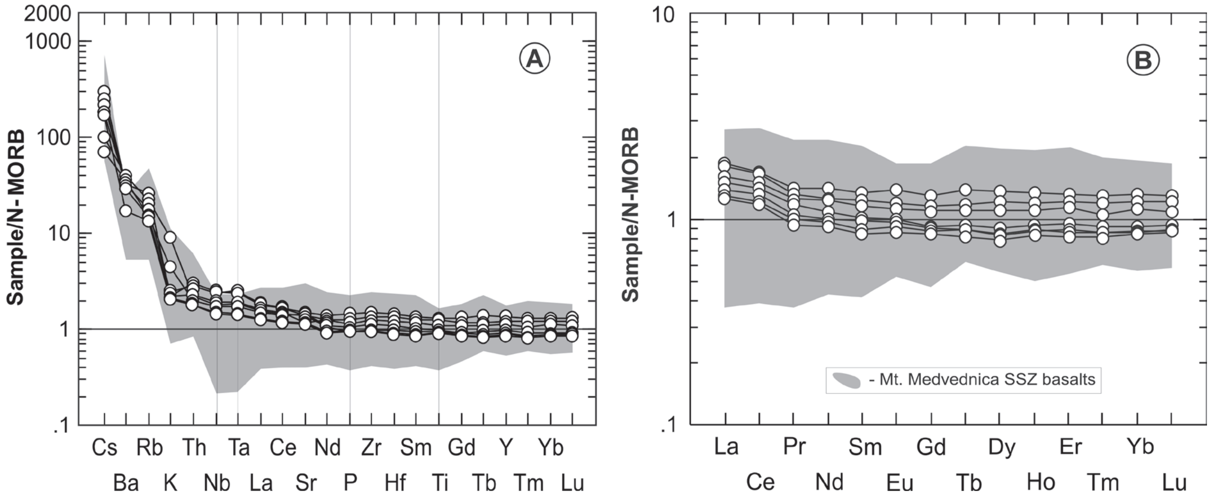

Figure 6: (A) N-MORB normalized multielement patterns (SUN & McDONOUGH, 1989); **(B)** N-MORB normalized REE patterns (SUN & McDONOUGH, 1989) for the Mt. Medvednica N-MORB volcanic basaltic rocks. Gray shaded area represent compositional field of high-, medium- and low-Ti tholeiitic SSZ basalt suite from the Mt. Medvednica ophiolite mélange (SLOVENEC & LUGOVIĆ, 2009) plotted to stress their distinctive geochemical signatures.

In the Zr/TiO_2 vs. Nb/Y diagram (WINCHESTER & FLOYD, 1977) for classification of altered extrusives, the analysed rocks with low Zr/TiO_2 (0.006–0.007) and Nb/Y (0.14–0.16) plot in the field of subalkaline, tholeiitic andesite/basalt, and in this respect they are not distinguished from the Mt. Medvednica SSZ basalts (not shown). However, they are strongly geochemically separated in the Ti/Cr vs. Ni diagram (Fig. 4) whereas in the Poljanica rocks, they plot exclusively in the field of high-Ti basalts of MORB affinity, whilst SSZ extrusives trend from high-Ti to low-Ti basalts of IAT and/or BABB signatures. The ocean ridge affinity of the Poljanica rocks is also deduced from their high Ti/V ratio (32.9–42.6), that is typical for MORB rocks derived from a slightly depleted mantle reservoir (Fig. 5).

The multi-element abundance patterns normalized to N-MORB values for Poljanica volcanic rocks are displayed as a spider diagram in Fig. 6A. The rocks display a wide range of selective LILE enrichment consistent with their polyphase alterations. The unique feature of these rocks is their smooth and flat patterns in the profile from Nd to Lu which range from 0.8 to 1.3 times relative to N-MORB and, moreover, show a very slight HFSE positive anomaly $[(Nb/La)_n = 1.16–1.34; (Ti/Gd)_n = 1.00–1.16]$. In that respect, six blocks of Poljanica basalts represent a geochemical exception concerning the whole suite of oceanic exstrusive rocks archived in the Kalnik Unit (compare with SLOVENEC et al., 2011).

N-MORB normalized REE patterns of analysed rocks are displayed in Fig. 6B. Excluding a slight La-Ce enrichment, (most likely due to alteration), the REE show smooth and flat profiles in the Pr-Lu segment of pattern $[(Pr/Lu)_n = 1.08–1.26]$ at 0.8–1.4 times relative to N-MORB. Three out of seven samples (vs-94/1, vh-1001/1 and vs-307/1, Table 1) show fractionated patterns (> 1.2 times relative to N-MORB). This signature combined with a lack of negative HFSE anomalies in the spider diagram (Fig. 6A) show that the Poljanica basalts formed at an oceanic setting far away from the influence of any subduction related source, that is, at an evolved spreading ridge centre. A slight Eu anomaly (Eu/Eu* = 1.03–0.96) in the samples is typical for low accumulation, or fractionation, of plagioclase, suggesting that the four unfractionated rock samples may represent near primary melts.

The Nd and Sr isotopic compositions of two pillow basalts are shown in Table 3. Measured $^{143}Nd/^{144}Nd$ ratios are concordant in both samples (0.512975 and 0.512979) whilst the $^{87}Sr/^{86}Sr$ ratios show slight variations between 0.704057 and 0.704423, most likely due to different intensity of alterations. The initial ε_{Nd} and Sr isotopic ratios calculated for an arbitrary age of 170 Ma vary from +6.21 to +6.27 and from 0.703365 to 0.703511, respectively, and plot within the mantle array in the field of recent MORB close to the PREMA (Fig. 7).

Table 3: Nd and Sr isotope data of N-MORB extrusive rocks from the Mt. Medvednica ophiolite mélange.

Sample	Location	Rock group	$^{143}Nd/^{144}Nd^a$	$^{147}Sm/^{144}Nd$	$^{87}Sr/^{86}Sr^a$	$_{Nd(t)}{}^b$	$^{87}Sr/^{86}Sr_{(t)}{}^c$	Age (t)*
vs-113/2	1	PB; high-Ti	0.512975 (8)	0.213788	0.704423 (9)	+6.21	0.703511	170 Ma
vh-1001/1	5	PB; high-Ti	0.512979 (6)	0.213589	0.704057 (10)	+6.27	0.703365	170 Ma

Location number corresponds to the locations in Fig. 1C. PB = pillow basalt. [a] Errors in brackets for Nd and Sr isotopic ratios are given at the 2-level. $^{147}Sm/^{144}Nd$ ratios calculated from the ICP-MS concentrations of Sm and Nd following equation: $^{147}Sm/^{144}Nd = (Sm/Nd)*[0.53151 + 0.14252*^{143}Sm/^{144}Nd]$. [b]Initial $\varepsilon_{Nd(t)}$ calculated assuming $I°_{CHUR} = 0.512638$, $(^{147}Sm/^{144}Nd)°_{CHUR} = 0.1966$, and $\lambda_{Sm} = 6.54*10^{-12}\ a^{-1}$. [c] Initial $^{87}Sr/^{86}Sr_{(t)}$ calculated using ICP-MS Rb and Sr concentrations and assuming $\lambda_{Rb} = 1.42*10^{-11}\ a^{-1}$. *Coresponding age for the initial ε_{Nd} and initial Sr isotopic ratios.

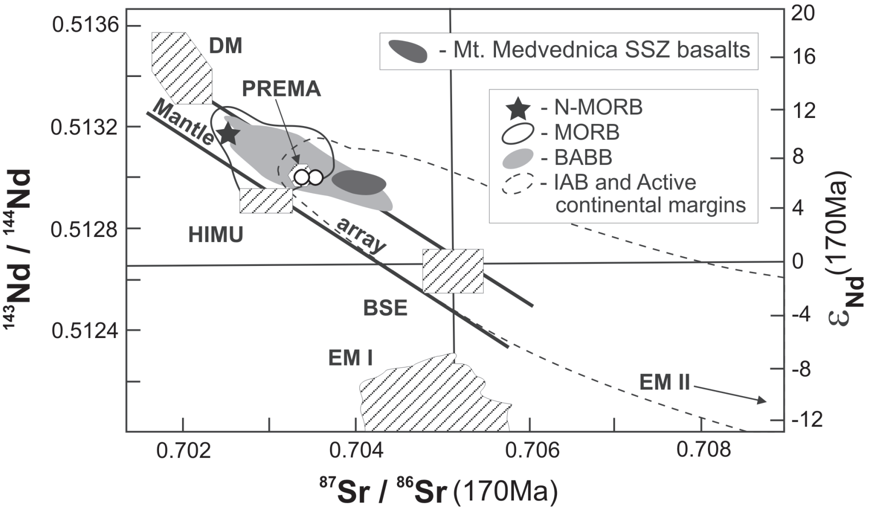

Figure 7: Initial $^{143}Nd/^{144}Nd$ – $^{87}Sr/^{86}Sr$ isotope ratios diagram for Mt. Medvednica N-MORB volcanic rocks and tholeiitic SSZ basalts (gray shaded; SLOVENEC & LUGOVIĆ, 2009) showing the main oceanic mantle reservoirs of ZINDLER & HART (1986). DM – depleted mantle, BSE – bulk silicate Earth, EMI and EMI II – enriched mantle, HIMU – mantle with high U/Pb ratio, PREMA – frequently observed PREvalent MAntle composition. The mantle array is defined by many oceanic basalts and a bulk Earth value for $^{87}Sr/^{86}Sr$ can be obtained from this trend. Data for back-arc basin basalts – BABB (gray shaded field) compiled from WILSON (1989) and references therein, COUSENS et al. (1994) and references therein, PEARCE et al. (1995) and EWART et al. (1998). Data for mid-ocean ridge basalts – MORB (solid line) compiled from WILSON (1989) and references there in and COUSENS et al. (1994), references therein and PEATE et al. (1997). Data for average N-MORB are from SUN & McDONOUGH (1989). Data for oceanic island arcs and active continental margins – IAB (broken line) compiled from WILSON (1989) and references therein, COUSENS et al. (1994) and references therein, PEARCE et al. (1995) and PEATE et al. (1997).

7. DISCUSSION AND CONCLUSIONS

Ophiolite mélanges that contain fragmented rocks similar to the lithologies of a coherent lithostratigraphic pile of an ophiolite complex, formed in an accretionary wedge in front of an overriding oceanic plate (e.g. FESTA et al., 2010). Rock fragments derived from the overriding plate were incorporated in the accretionary wedge mainly through sedimentary processes, whilst the materials from the subducting slab were included by pealing off from a MORB-type subducting slab (e.g. SACCANI & PHOTIADES, 2005). Ophiolite mélanges are finally formed as tectonic mélanges during ophiolite emplacement, whereby various rocks from continental crust are ordinarily also included in the mélange as fault-bounded blocks. A systematic petrological and geochemical study of materials incorporated in mélanges provides opportunity for detailed reconstruction of the geodynamic evolution of an oceanic realm, or its particular segment, as has been successfully done for the Repno oceanic domain of the Meliata-Maliac-Dinaric-Vardar oceanic system (see Fig. 10 in SLOVENEC et. al., 2011). This work refers to terminal Jurassic spreading in the ROD and will improve the overall tectonomagmatic cartoon of the domain at its culminating spreading stage.

As in the other two ophiolite mélange sectors (Mts. Samoborska Gora and Kalnik) of the Kalnik Unit, the oldest magmatic rocks in Mt. Medvednica are Illyrian-Fassanian alkali basalts, related to the terminal phase of intracontinental rifting that prograded to opening of an ensialic back-arc basin in the ROD (SLOVENEC et al., 2011). The crustal succession formed by onset of an ocean spreading ridge is completely lacking in the Mt. Medvednica and Samoborska Gora ophiolite mélange, but was well documented in the Mt. Kalnik by fragments of E-MORB-type proto-oceanic crust formed during the Early and Late Ladinian, followed by Middle Carnian T-MORB-type crust; the oldest N-MORB-type crust formed in the Late Carnian (SLOVENEC et al., 2011) and the youngest in the Late Pliensbachian (LUGOVIĆ et al., in rewiev), both related to an evolving oceanic spreading centre. As a rule, the N-MORB-type crust show supra-subduction signatures inherited from a subducting Palaeotethyan oceanic slab that diminish from Late Carnian to the Late Pliensbachian crustal rocks. It was inferred that slab break-off in the ROD might already have occurred in the Latest Pliensbachian.

The initiation and onset of intraoceanic subduction is recorded in the Mt. Medvednica and Samoborska Gora sectors by abundantly distributed Late Bathonian high-Ti N-MORB-like extrusives, and Callovian medium- and low-Ti IAT lavas and composite fragments of SSZ upper crustal sequences (SLOVENEC & LUGOVIĆ, 2008; 2009; SLOVENEC et al., 2010). However, in Mt. Kalnik, ophiolite mélange fragments of SSZ crust are rare and marked by Late Bathonian medium-Ti basalts and Tithonian IAT-type amphibole gabbro, that is by now the youngest Jurassic SSZ crustal lithology in the ROD. Such a regular chemostratigraphic progression (WHATMAN & STERN, 2011) of Late Bathonian to Tithonian SSZ upper crustal rocks in the ROD, clearly reflects progressive depletion of the mantle wedge involved in melting, influenced by enriched fluids released from the subducting plate. Assuming that this first SSZ crust in the ROD formed in the Late Bathonian the most evolved or, in other words, the youngest stage of Middle Jurassic ocean spreading evolution of the domain remains unsolved.

The stratigraphic gap of ocean crust formation arising in the ROD between the Late Pliensbachian and the Late

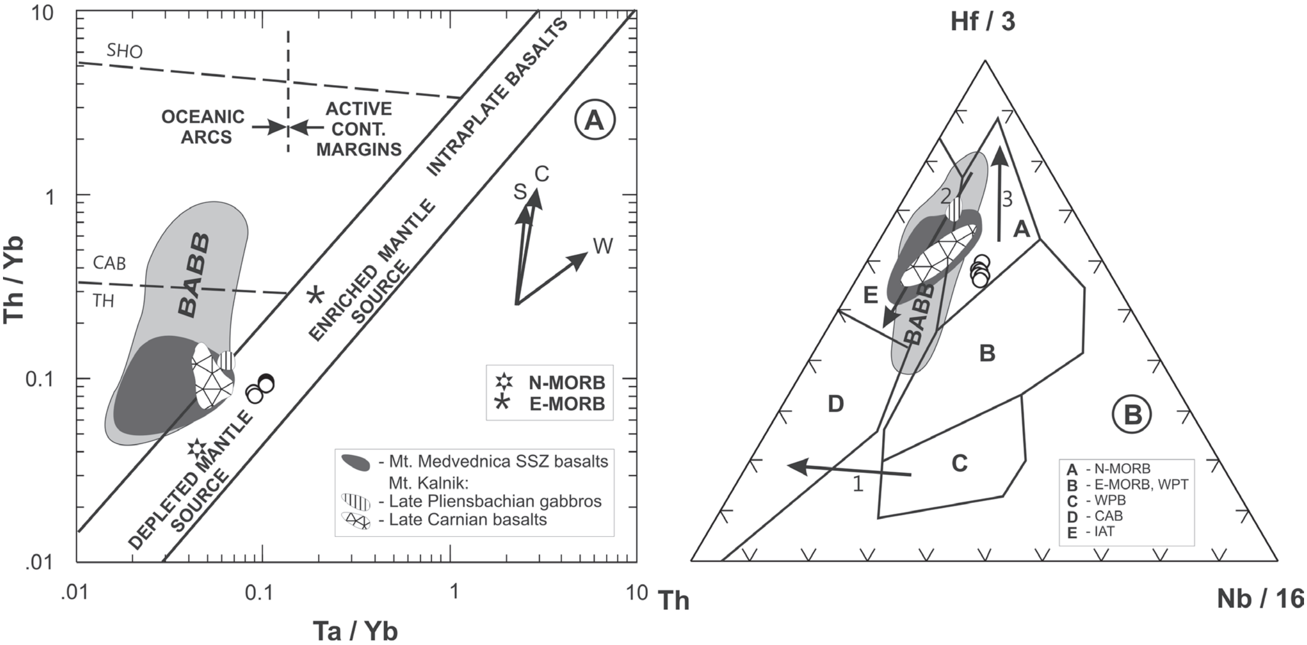

Figure 8: Discrimination diagrams for the N-MORB volcanic rocks from the Mt. Medvednica ophiolite mélange. **(A)** Ta/Yb – Th/Yb diagram (PEARCE, 1983). S – subduction zone enrichment; C – crustal contamination; W – within-plate enrichment. N-MORB and E-MORB are from SUN & MCDONOUGH (1989). Data for back-arc basin basalts (BABB) fields (Mariana, Lau-Tonga, Oman, East Scotia Ridge) are from PEARCE et al. (1984) and LEAT et al. (2000). **(B)** Th – Nb/16 – Hf/3 diagram (WOOD, 1980). A – normal mid-ocean ridge basalts (N-MORB); B – enriched MORB (E-MORB) and within-plate tholeiites (WPT); C – alkaline within-plate basalts (AWPB); D – calc-alkali basalts (CAB); E – island-arc tholeiites (IAT); 1 – crustal contamination; 2 – SSZ ophiolites trend; 3 – MORB ophiolites trend. Data for back-arc basin basalts – BABB (light gray shaded field) compiled from SAUNDERS & TARNEY (1979), WEAVER et al. (1979), JAHN (1986), IKEDA & YUASA (1989), GRIBBLE et al. (1998), LEAT et al. (2000). Fields for high-, medium- and low-Ti tholeiitic SSZ basalts from the Mt. Medvednica ophiolite mélange (SLOVENEC & LUGOVIĆ, 2009), Late Pliensbachian gabbros (LUGOVIĆ et al., in rewiev) and Late Carnian basalts (SLOVENEC et al., 2011) from Mt. Kalnik plotted for correlation constraints.

Bathonian, is now completed by the Latest Bajocian-Early Bathonian lavas from coherent slices with radiolarian cherts near the Poljanica locality (Fig. 1C). These volcanic rocks are geochemically more akin to Late Pliensbachian isotropic N-MORB-type gabbros, that were formed at a spreading ridge (LUGOVIĆ et al., in rewiev), than to Late Bathonian

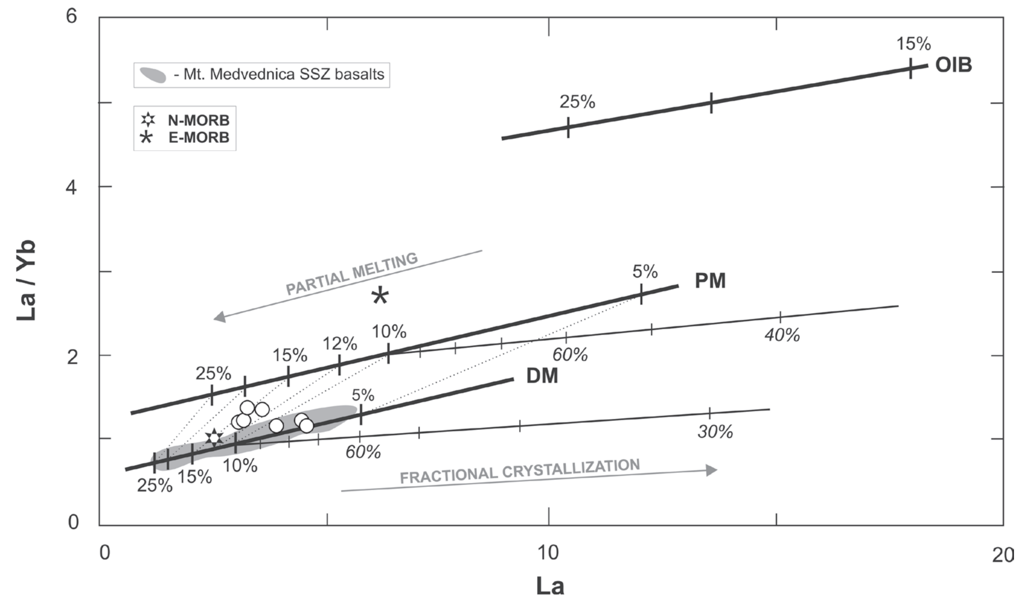

Figure 9: Petrogenic model for N-MORB volcanic rocks from the Mt. Medvednica ophiolite mélange. Partial melting lines: DM – depleted mantle source, PM – primitive mantle source (KOSTOPOULOS & JAMES, 1992), OIB – enriched mantle source (CLAGUE & FREY, 1982). Model parameters = spinel-lherzolite source (ol_{57}–$opx_{25,5}$–cpx_{15}–$sp_{2,5}$), melting proportion = $ol_{1,21}$–$opx_{8,06}$–$cpx_{76,37}$–$sp_{14,36}$, distribution coefficients are from KOSTOPOULOS & JAMES (1992). Fractional crystallization lines: initial magma = 10% melting of DM and PM mantle source, respectively, fractionated mineral assemblage = ol_{30}–cpx_{40}–pl_{30}, distribution coefficients are from CHEN et al. (1990). Field (gray shaded) for high-, medium- and low-Ti tholeiitic SSZ basalts from the Mt. Medvednica ophiolite mélange (SLOVENEC & LUGOVIĆ, 2009) plotted for correlation constraints.

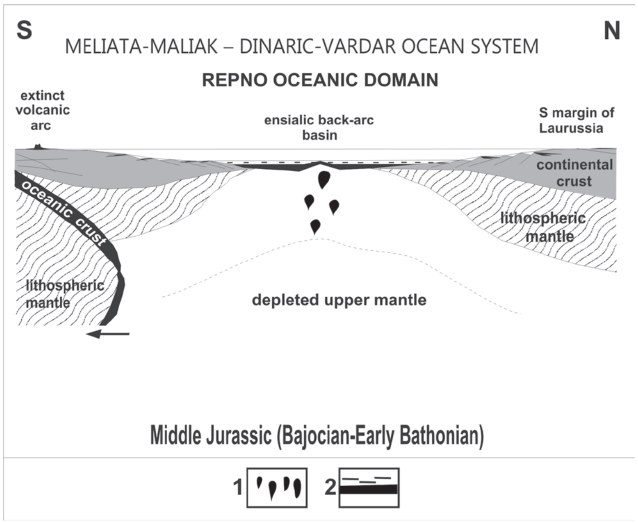

Figure 10: Schematic geodynamic sketch of the tectonic setting of the investigated Mt. Medvednica N-MORB extrusive rocks in the Repno oceanic domain as part of Meliata-Maliak-Vardar oceanic system. 1 – mantle diapires, 2 – oceanic crust topped by radiolarian cherts.

SSZ high-Ti N-MORB-like extrusives (SLOVENEC & LUGOVIĆ, 2009) (Fig. 5 and 8A–B). The Late Pliensbachian rocks show *inherited* negative HFSE anomalies, whilst these anomalies in the Late Bathonian extrusives are *re-established* during intraoceanic subduction (SLOVENEC et al., 2011). However, Poljanica extrusive rocks display very slight positive HFSE anomalies, which, combined with other geochemical parameters, suggest a different mantle source and comparatively peculiar geotectonic setting of formation. Their normalized element concentration patterns (Fig. 6A, 6B), high-Ti content (Fig. 4) and hosted clinopyroxene composition (Fig. 3A–B) are accepted as being representative of melt generation at an N-MOR setting of the Eastern Tethyan ophiolites (e.g. SERRI, 1981; BECCALUVA et al., 1983).

These mineralogical and geochemical signatures suggest that only suboceanic mantle, unaffected by subduction-related components, contributed to the formation of ROD crust during the Latest Bajocian-Early Bathonian. This is also supported by the Nd-Sr isotopic composition that is strictly akin to MORB (Fig. 7), and corresponds to the isotopic composition of prevalent mantle composition (PREMA). The plot in the diagram Th-Yb vs. Ta/Yb reveals MORB signatures of the analyzed rocks that reflect a mantle source ranging in composition between enriched and depleted (Fig. 8A). The different mantle sources for Late Pliensbachian and Late Bathonian MORBs, that are obviously contaminated by subduction-related components (mantle wedge), compared to the subduction uncontaminated Latest Bajocian-Early Bathonian spreading ridge suboceanic mantle, are best illustrated from this diagram. In Figure 8B, Th-Hf/3-Nb/16 is utilized for discrimination of geotectonic settings of mafic extrusive rocks, the Poljanica basalts plot in the field of N-MORB and form the trend typical of basalts from MOR relatad ophiolites.

The Poljanica basalts are undoubtely formed at a spreading ridge, from melts derived from uncontaminated suboceanic mantle (Figs. 7 and 8A). Different geochemical variables were used to infer the amount of partial melts extracted from a parental mantle source (e.g. PEARCE, 1983). The model implemented by KOSTOPOULOS and JAMES (1992), on relative concentrations of REE, revealed most reliable results in our case. In the La/Yb vs. La diagram wherein three potential mantle sources are considered (Fig. 9), analysed unfractionated rock samples plot between primitive mantle (PM) and depleted mantle (DM) sources. According to the model, the Poljanica basalts are compatible with approximately 13–17% partial melting of a mantle source transitional between primitive and depleted MORB-type mantle. Jurassic mantle peridotite of such fertile composition, typical for Jurassic Central Dinaric ophiolite lherzolites (LUGOVIĆ et al., 1991; BAZYLEV et al., 2009), was never found in the ROD.

In conclusion, based on geochemical and petrological data, the analysed Latest Bajocian-Early Bathonian basalts from the Mt. Medvednica ophiolite mélange sector of the Kalnik Unit, represent vestiges of the youngest Jurassic proper N-MORB crust formed at middle ocean ridge centre during culmination of spreading in the ROD as a part of the Meliata-Maliak-Dinaric-Vardar ocean system (Fig. 10). This terminal phase of spreading lasted around 20 Ma, from the Late Pliensbachian to the Early Bathonian, and postdated the major phase of ridge magmatism resulting in MORB-type crust with SSZ signatures around 55 Ma, from the Late Carnian to the Late Pliensbachian (185 Ma).

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