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Triassic Magmatism in the Area of the Central Dinarides (Bosnia and Herzegovina): Geochemical Resolving of Tectonic Setting

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Abstract

Triassic magmatic rocks in the Central Dinarides in Bosnia and Herzegovina are known from two separate geotectonic units: (1) the Adriatic Carbonate Platform (Outer Dinarides) and (2) the Palaeozoic–Triassic allochthonous complex. They are assigned to the same regional, genetic and geochemical unit. Their emplacement age is inferred from contacts with the surrounding marble and sedimentary rocks (post-Anisian for intrusives and Ladinian for effusives).

The magmatic rocks display different levels of emplacement and crystallization (intrusive, effusive and dyke rocks). They represent different stages of magmatic differentiation, from gabbro/basalt via diorite/andesite to granodiorite/dacite and granites. The most frequent dyke rock is diabase. Pillow basalts indicate eruption under subaquatic conditions. Pyroclastic rocks within the volcano-sedimentary unit point to the temporary explosive character of orogenic magmatic activity. Most rocks are affected and modified by post-magmatic alteration and hydrothermal fluids. This led to the formation of spilite, keratophyre, quartz keratophyre and rarely K spilite.

New geochemical data support the opinion that subduction was the main process which triggered the Triassic magmatic activity in the Central Dinarides. Although some of the investigated rocks reveal MORB characteristics (in the selected geochemical discriminations), most samples are enriched in all elements which are reported as characteristic for arc magmatism at convergent margins including incorporation of sediments.

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1. INTRODUCTION

In the Central Dinarides of Bosnia and Herzegovina, Triassic magmatic rocks are associated with platform carbonate sediments and also occur frequently within Palaeozoic–Triassic allochthonous series (mountains of Central Bosnia, Sana–Una Palaeozoic complex, southeast Bosnia near Čajniče, Foča, Tjentište and Kalinovik – Fig. 1). Towards the southeast, the Triassic magmatism continues into the territory of Montenegro. The same formations can also be found in Slovenia, Croatia, and Serbia.

Previous investigations resulted in two different conclusions about the tectonic setting and origin of the Triassic magmatic rocks:

(1) BEBIEN et al. (1978) classified the rocks as a product of subduction-initiated magmatism, while

(2) PAMIĆ (1984) explained them as a product of the rifting of continental crust.

A new investigation by KNEŽEVIĆ et al. (1998) yielded ambiguous results: within plate magmatism combined with volcanic arc influence. TRUBELJA et al. (2000) came to a conclusion similar to Pamić's explanation, as they described contamination of the magmatic rocks with a continental crust component which can be best explained by magmatic activity in the course of opening of a continental rift.

The aim of this work is to contribute new microscopic and geochemical data to the clarification of the tectonic setting of the Triassic magmatism in Bosnia and Herzegovina. Microscopic studies were performed for the classification of the rocks but they served mainly for estimating the intensity of alteration with possible changes of the original chemical composition, and from this the selection of appropriate geochemical discrimination diagrams (with elimination of elements which could be mobile in the course of alteration). 'Classic' and newly developed geochemical diagrams were used for determination of the geotectonic setting of the magmatic rocks including highly evolved members. Rare earth elements patterns were also investigated and included in the discussion.

Fig. 1 Sketch map of selected occurrences of Triassic magmatic rocks in Bosnia and Herzegovina. Legend: 1) pyroxene andesite – river Doljanka; 2) keratophyre – Trešanica, Bradina; 3) basalt – Vareš; 4–6) gabbro-norite – Jablanica; 7) olivine-bearing gabbro-norite – Novi Travnik; 8) andesite or dacite – Trnova, Sanski Most; 9) sodium rhyolite – Fojnica; 10) quartz-diorite – Ćusine, Jajce; 11) basalt – Babino Selo, Vrbas river valley; 12) basalt, Vrbas river valley; 13) basalt (spilite) – Tjentište; 14) basalt – Kalinovik; 15) basalt – Dobro polje.

2. OVERVIEW OF GEOLOGY AND PETROGRAPHY

Triassic magmatic rocks in the Dinarides form a spatial, genetic(?) and geochemical unity with a wide range of rocks varying from basalt/gabbro to rhyolite/granite. All levels of solidification are present, i.e. intrusive, effusive and hypabbysal rocks. The most frequent dyke type is of diabase composition. Effusive and dyke rocks are partly modified to spilites, keratophyres and quartz keratophyres. K-spilites with adularia as their main constituent are also present, but quite rare (TRUBELJA, 1978).

The Jablanica gabbro is the most investigated rock with its halo in the surrounding sediments (Fig. 2). In the northwestern part this intrusive body is in contact with an Anisian limestone which was thermally metamorphosed to marble. The first description of the contact, the developed contact-metamorphic silicates (garnet, albite, chlorite, sericite, titanite, epidote), and the skarn deposit of Tovarnica with magnetite ore was published by CISSARZ (1956). After ČELEBIĆ (1967), the intrusion age of this gabbroic complex is post-Anisian. In the same region a corresponding contact-metamorphic zone was found on the left side of the river Crima (Fig. 3).

Another huge basic intrusion occurs in the Radovan Mt. (Novi Travnik), rather similar to the Jablanica gabbro. Rb/Sr isotopic data of this rock determined an age of 223–232 million years (PAMIĆ & LOVRIĆ, 1980).

Effusive rocks include basalts, andesites and dacites and their modified equivalents spilite, keratophyre and quartz keratophyre. They are mostly in concordant position within volcanic–sedimentary associations of Middle Triassic ages (palaeontological determinations; Fig. 4). The most intense volcanic activity was of Ladinian age. Pyroclastic rocks (tuffs) are common within the volcanic-sedimentary association, showing that the volcanic activity was partly explosive. Also pillow lavas have been observed indicating underwater volcanic activity.

In some localities (Vareš, Hrčavka river on Tjentište, valley of the Vrbas river) mixing of lava with sedimentary material can be observed. Limestone xenoliths within lava flows frequently occur. The effusive rocks in these locations display typical amygdaloidal fabric. The amygdules with diameters reaching more than 10 centimetres are filled predominantly with calcite.

3. METHODS OF INVESTIGATION

With respect to their general classification, qualification of samples for chemical analysis and applicability of discrimination methods, 15 rocks were selected covering the range of Triassic magmatism in Bosnia and

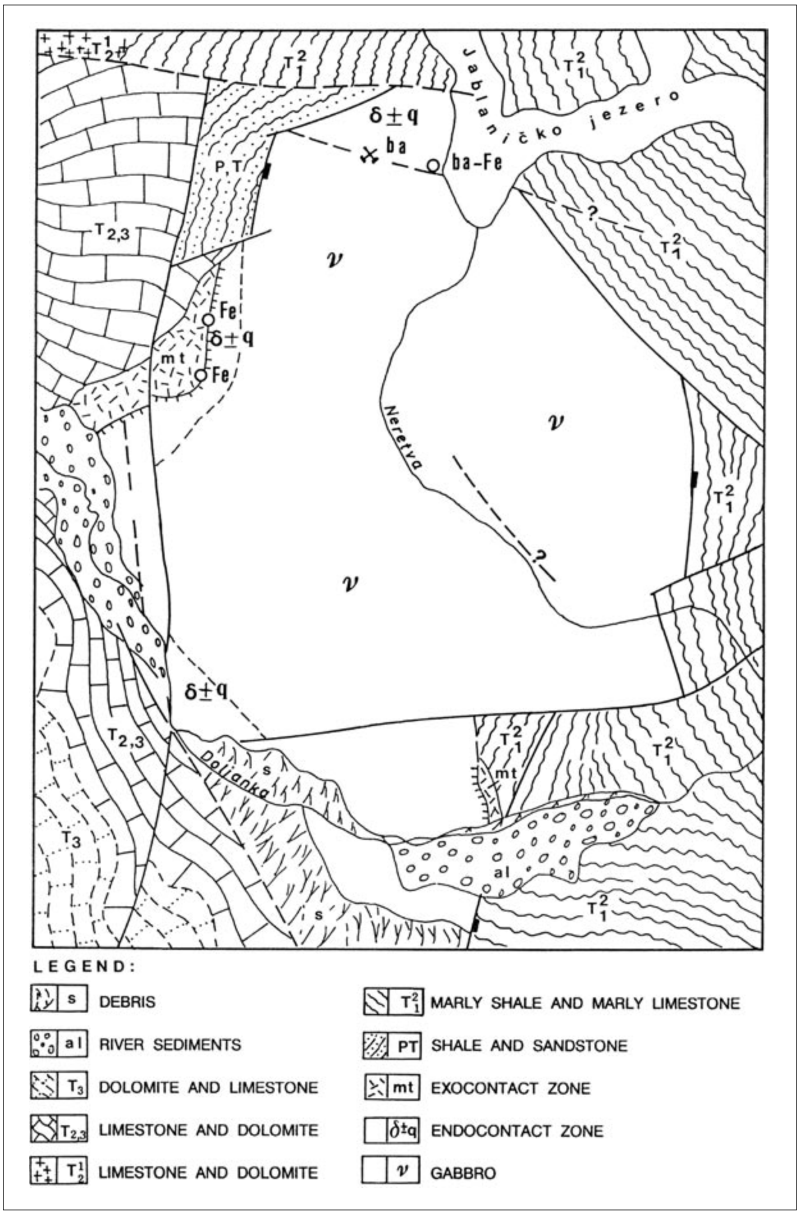

Fig. 2 Geological map of the Jablanica gabbro massif with sedimentary country rocks (from ČELEBIĆ, 1967).

Herzegovina. Polished thin-sections of these rocks were prepared and studied microscopically.

The aliquots of selected samples were crushed in a shatter box with agate inlay for chemical analyses. One gram of powder was mixed and melted with 5 g $LiBO_2$ at 1200°C for 20 minutes. The obtained glass was analysed by X-ray fluorescence; Phillips PW 1400 and PW 1480 wavelength dispersive spectrometers were used. Analytical precision was better than 0.5% (relative) for major elements and 1–10 ppm for trace elements. The quality of the results was controlled with certified reference materials (CRM) (i.e. BCR, Community Bureau of Reference, Brussels).

After being used in XRF the glass was crushed and dissolved in an acid mixture ($HCl–HNO_3$) in a microwave oven. From this solution trace elements below the detection limit of XRF were determined, including rare earth elements. The instrument used was an inductively coupled plasma-mass spectrometer (ICP-MS) Perkin Elmer Sciex Elan 5000. Analytical precision was controlled using CRM, and was better than 5% (relative).

4. PETROGRAPHIC DESCRIPTION OF SAMPLES

The selected representatives of Triassic magmatism in Bosnia and Herzegovina were classified as follows according to their mineralogical composition:

1 – porphyric pyroxene andesite, weakly altered, Doljanka river valley (sample T99/1);

2 – keratophyre, strongly altered, Trešanica, Bradina (sample T99/2);

3 – (tholeiitic?) basalt, strongly altered, Vareš (sample T99/3);

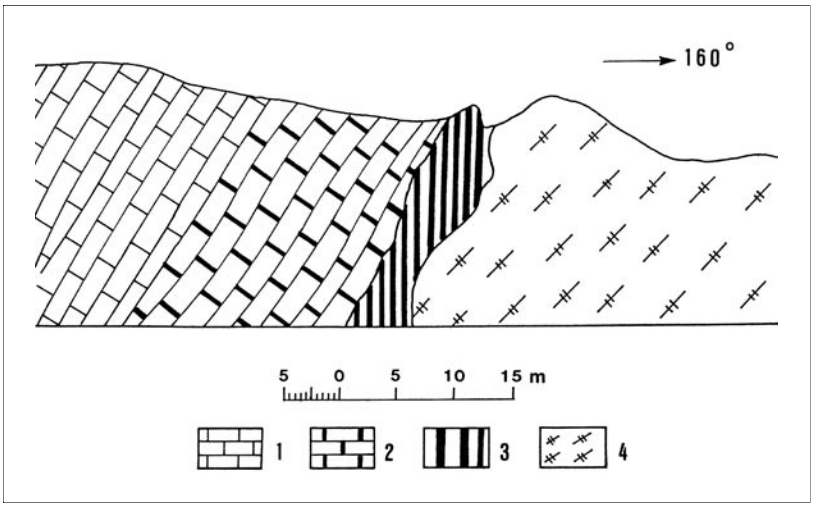

Fig. 3 Profile through the contact of gabbro–diorite and platy crinoidal limestone with a magnetite ore body (after ČELEBIĆ, 1967). Legend: 1) platy crinoidal limestones; 2) contact-metamorphic limestones/marbles; 3) scarn; 4) gabbro diorite.

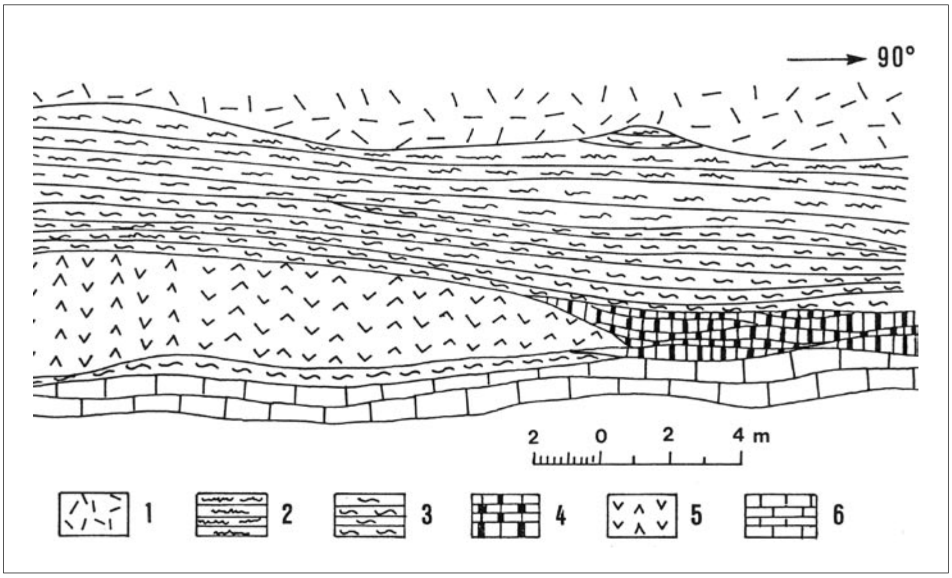

Fig. 4 Basalt concordant in the volcanogenic–sedimentary association, area of Konjic, Jablanica, Prozor (after ČELEBIĆ, 1967). Legend: 1) Upper Triassic limestones and dolomites; 2) cherts and basalts; 3) reddish shales and radiolarites; 4) haematite; 5) basalt; 6) Middle Triassic reddish limestones.

4 – cumulate gabbro-norite, strongly altered, Jablanica (sample T99/4);

5 – cumulate gabbro-norite with subplanar fabric, weakly altered, Jablanica (sample T99/5);

6 – cumulate gabbro-norite with subplanar fabric, weakly altered, Jablanica (sample T99/6);

7 – olivine-bearing gabbro-norite, weakly altered, Novi Travnik (sample T99/7);

8 – andesite or dacite, strongly altered, Trnova, Sanski Most (sample T00/5);

9 – sodium rhyolite, medium alteration, Fojnica (sample T00/6);

10 – fine-grained quartz diorite, strongly altered, Ćusine, Jajce (sample T2/00/1);

11 – tholeiitic basalt, medium alteration, Babino Selo, Vrbas river valley (sample T2/00/3);

12 – tholeiitic basalt, strongly altered, Vrbas river valley (sample T2/00/4);

13 – tholeiitic basalt, medium alteration, Tjentište (sample T3/00/2);

14 – olivine-bearing tholeiitic basalt, strongly altered, Kalinovik (sample T3/00/3);

15 – tholeiitic basalt, strongly altered, Dobro Polje (sample T3/00/4).

The mineral assemblages and petrographic details are listed in Table 1.

The modification of the mineral content in the weakly altered samples is expressed by devitrification of glass (in T99/1, T2/00/3), by replacement of olivine to various extents by nontronite (T99/7) or carbonate (T3/00/4), by replacement of pyroxene by clinoamphibole (T99/7) or by a mixture of chlorite, sphene, carbonate, quartz/chalcedony or very fine-grained undeterminable

Table 1 Mineral assemblages and petrographic details of the rocks.

Number of sample	Type of rock; Location	Texture and deformation	Composition	Estimation of alteration
T99/1	pyroxene andesite; Doljanka	porphyric	**phenocrysts:** plagioclase with pyroxene and glass inclusions; cloudy alteration to zoisite, chlorite, carbonate; pyroxene (two types): fresh augite and pseudomorphs (with chlorite, carbonate, sphene, chalcedony); Ti-bearing magnetite; **groundmass:** originally glass, with magnetite grains; recrystallized to a mixture of plagioclase, chlorite, leucoxene, carbonate	weak; mainly introduction of CO_2 and H_2O
T99/2	keratophyre; Trešanica, Bradina	microporphyric	**phenocrysts:** plagioclase (albite): corroded and deformed, with clouds of sericite and chlorite; amphibole (and pyroxene?), replaced by chlorite and carbonate; opâque phases, replaced by leucoxene; quartz (very rare); **groundmass:** plagioclase laths in fluid arrangement, sericite, leucoxene and carbonate–quartz veins	strong; alteration of plagioclase, mafic grains; probable introduction of Si, K, Mg, Fe, CO_2; strongly schistosed, with tendency to augen texture; chlorite–sericite
T99/3	(tholeiitic?) basalt; Vareš	microporphyric, vesicular	**phenocrysts:** mafic phases, totally replaced by pumpellyite±epidote; **groundmass:** plagioclase laths (cores filled with pumpellyite), diopsidic augite, chlorite; vesicules filled with pumpellyite, prehnite, quartz	strong; probable introduction of Ca and loss of Si
T99/4 T99/5 T99/6	cumulate gabbro-norite; Jablanica	subhedral granular, partly with subplanar plagioclase fabric	plagioclase with clinopyroxene and magnetite inclusions; round hypersthene (~10 vol. %, partly replaced by diopside); diopside with inclusions of biotite, amphibole and opâque phases; ilmenite; quartz (rare; in interstices); **replacements:** plagioclase replaced by sericite, epidote, prehnite, chlorite, pumpellyite; pyroxene replaced by green amphibole (cores), actinolite and barroisite (rims), biotite, sphene, carbonate, chlorite; ilmenite replaced by biotite (biotite replaced by chlorite, sphene)	slightly (T99/5,6) to strongly (T99/4) altered
T99/7	olivine-bearing gabbronorite; Novi Travnik	subophitic	plagioclase; orthopyroxene; clinopyroxene; olivine (partly as corroded inclusions in pyroxene), replaced by nontronite; titanomagnetite–orthopyroxene symplectites; biotite oikocrysts with inclusions of plagioclase, or biotite rims enclosing corroded titanomagnetite; green fibrous amphibole and clay minerals in interstices between plagioclase;	very slight (replacement of olivine, pyroxene, titano-magnetite)
T00/5	andesite; Trnova, Sanski Most	microporphyric, intergranular	**phenocrysts:** plagioclase with albite-rich rims, filled with sericite and epidote; pseudomorphs of chlorite ± sphene after mafic phases (biotite; amphibole; pyroxene?) opâque grains (few); **groundmass:** plagioclase (albite-rich), mafic grains, primary quartz, apatite; alteration phases: sericite, sphene, secondary quartz; aggregates and network of epidote (very common), chlorite, carbonate	strong; replacement of all primary phases, formation of epidote
T00/6	sodium rhyolite, Fojnica	pilotaxitic	**phenocrysts:** albite (few grains; stained by fluid inclusions and opâque dust); **groundmass:** albite laths and interstitial quartz (anhedral); numerous microveins filled with sericite and green clusters of radiating tourmaline (zoned); network of anhedral carbonate and individual carbonate grains	medium; modified by introduction of Ca, CO_2, K, Ba
T2/00/1	quartz diorite, fine-grained; Ćusine, Jajce	subhedral granular, graphic	plagioclase (completely replaced by sericite aggregates and epidote patches); interstices: graphic intergrowth of plagioclase and quartz; some skeletal opâque grains with leukoxene rims; some clinoamphibole grains (replaced by chlorite)	very strong; abundant sericite and epidote formation
T2/00/3	tholeiitic basalt; Babino Selo, Vrbas valley	microporphyric, hyalopilitic	**phenocrysts:** plagioclase (albite-rich; filled with sericite, chlorite, epidote); mafic phases (pyroxene, probably some amphibole), completely replaced by chlorite, opâque dust, sphene, very fine-grained phyllosilicates; opâque phases; **groundmass:** formerly glass, with plagioclase laths; glass replaced by a fine-grained mixture of chlorite, sphene, phyllosilicates, opâque dust	medium; introduction at least of K, H_2O
T2/00/4	andesite; Vrbas valley	microporphyric, hyalopilitic, vesicular	**phenocrysts:** plagioclase, largely replaced by carbonate+chlorite; mafic phases, completely replaced by chlorite±quartz; **groundmass:** formerly glass, altered to a fine-grained mixture of chlorite, sericite, opâque dust, sphene; vesicles filled with quartz	very strong; introduction of Si, Ca, CO_2, H_2O
T3/00/2	tholeiitic basalt (spilite); Tjentište	fine-grained subophitic	plagioclase (stained by sericite and zoisite?) and diopsidic augite (Ti-bearing) with interstitial chlorite and patchy sphene; numerous patches filled with chlorite and a radiating sheet silicate; Cr-bearing spinel (290 ppm Cr in analysis!)	medium; introduction of CO_2 and H_2O
T3/00/3	olivine-bearing tholeiitic basalt; Kalinovik	subophitic vesicular	**phenocrysts:** olivine (euhedral pseudomorphs, filled with phyllosilicates, carbonate) with primary inclusions of Cr-bearing spinel); plagioclase: rounded grains, stained by phyllosilicates and epidote; **groundmass:** plagioclase (strongly stained) and clinopyroxene with interstitial phyllosilicates, chalcedony, opâques; vesicles filled with very fine-grained phyllosilicates (Fe-rich saponite/griffithite?); some radiated carbonate aggregates	strong; introduction of CO_2 and H_2O
T3/00/4	tholeiitic basalt (diabase), similar to T 3/00/3; Dobro Polje	subophitic vesicular	some carbonate pseudomorphs after olivine? (spinel inclusions!); rather fresh; plagioclase laths strongly stained by sericite and chlorite; accessory Cr-bearing spinel in the groundmass	strong; as in T3/00/3

Location Sample	1 T99/1	2 T99/2	3 T99/3	4 T99/4	5 T99/5	6 T99/6	7 T99/7	8 T00/5	9 T00/6	10 T2/00/1	11 T2/00/3	12 T2/00/4	13 T3/00/2	14 T3/00/3	15 T3/00/4
SiO_2	52.07	63.33	46.54	53.70	51.92	51.49	49.42	60.64	70.35	56.53	51.00	53.35	51.09	47.63	51.34
TiO_2	1.00	0.57	0.83	0.94	0.89	0.96	0.57	0.48	0.13	1.02	1.16	0.85	1.13	0.80	1.09
Al_2O_3	16.74	15.35	16.62	17.14	17.92	15.91	16.68	17.77	15.64	17.79	19.48	15.79	16.72	13.91	17.28
Fe_2O_3	8.53	6.19	7.77	8.00	9.03	10.83	9.36	5.00	0.50	7.88	8.79	6.11	7.71	6.23	7.74
MnO	0.16	0.09	0.11	0.14	0.19	0.22	0.17	0.12	0.01	0.07	0.15	0.14	0.09	0.12	0.11
MgO	2.78	3.29	7.09	3.64	5.38	6.38	8.47	1.90	0.97	1.77	4.82	2.06	6.83	3.33	6.64
CaO	7.66	1.00	12.15	6.52	10.01	10.36	11.23	4.46	1.52	7.09	2.91	8.98	6.61	13.24	5.22
Na_2O	5.27	6.15	3.24	4.20	2.92	2.65	2.41	4.57	7.41	2.75	5.21	3.26	4.78	5.37	4.97
K_2O	0.19	0.72	0.20	1.65	0.99	0.69	0.86	1.79	0.63	1.94	2.36	1.75	0.98	0.48	1.33
P_2O_5	0.22	0.12	0.14	0.20	0.12	0.07	0.06	0.20	0.06	0.19	0.16	0.15	0.19	0.15	0.17
LOI	4.99	2.89	4.94	3.38	0.22	0.19	0.39	2.57	2.51	2.50	3.59	6.97	3.45	8.22	3.65
Total	**99.62**	**99.70**	**99.63**	**99.51**	**99.60**	**99.75**	**99.63**	**99.49**	**99.74**	**99.52**	**99.63**	**99.41**	**99.58**	**99.48**	**99.54**
Cs	1.21	0.91	0.28	2.17	2.27	1.01	2.61	3.49	0.50	1.83	2.21	2.83	0.33	0.32	2.64
Rb	4.58	13.9	2.12	62.8	35.8	22.3	36.0	40.6	5.32	40.6	46.8	32.2	13.2	10.8	27.0
Ba	133	196	60	316	216	171	167	131	52	398	208	197	211	59	303
Th	7.17	5.75	1.87	6.64	3.43	1.78	3.10	8.38	0.80	6.50	8.30	4.20	2.50	2.70	3.80
U	2.20	1.46	0.52	1.50	0.97	0.49	0.73	1.80	0.24	1.89	0.66	1.20	0.75	0.80	0.86
Ta	0.79	0.59	0.63	0.73	0.40	0.28	0.32	0.61	0.094	0.54	0.61	0.36	0.61	0.57	0.78
Nb	10.5	7.63	8.40	8.49	5.29	3.62	3.52	7.54	1.13	7.40	8.60	5.40	10.7	9.90	12.6
Pb	11.6	2.06	1.52	4.82	7.53	3.85	6.62	9.73	1.09	7.90	5.20	6.90	2.30	2.90	4.80
Sr	242	63	63	184	328	236	246	370	114	261	90	119	280	198	338
Zr	160	137	66	126	70	52	57	139	41	65	58	46	59	50	60
Hf	4.38	3.83	1.92	2.84	1.97	1.26	1.53	3.69	1.24	4.30	4.10	3.20	2.50	2.20	2.80
Y	33.0	15.8	18.4	28.2	20.6	19.9	16.0	16.1	2.14	22.2	24.2	17.0	28.6	22.1	26.7
Cr	18	141	238	41	71	55	256	21	38	31	12	51	311	280	366
Ni	udl	18	69	10	10	udl	86	6	9	8	10	14	46	68	38
V	216	119	235	194	259	216	195	122	12	178	143	137	306	235	289
Sc	23	16	30	23	33	46	42	9	2	27	25	21	50	43	50
Zn	104	66	39	110	96	87	66	106	8	29	99	240	52	76	63
La	22.4	15.2	8.69	18.2	11.6	7.38	9.26	23.2	4.11	20.7	28.7	15.1	13.0	12.6	16.4
Ce	47.2	31.8	18.9	40.5	26.0	16.9	19.6	44.7	8.29	34.5	48.9	26.4	29.4	28.5	33.9
Pr	5.67	3.56	2.59	5.29	3.44	2.38	2.70	5.50	0.96	5.19	6.14	3.35	3.44	2.93	3.85
Nd	23.4	13.2	11.2	22.0	14.6	10.8	11.4	20.5	3.67	22.8	26.1	14.8	14.4	12.9	16.4
Sm	5.42	2.67	2.82	5.09	3.59	2.93	2.77	3.86	0.69	4.82	5.24	3.37	4.02	2.94	3.80
Eu	1.35	0.65	0.95	1.34	1.16	1.04	0.84	0.97	0.18	1.24	1.59	0.99	1.25	1.01	1.16
Gd	5.82	2.68	3.27	5.35	3.87	3.41	3.03	3.43	0.59	5.00	5.61	3.60	4.08	3.31	4.25
Tb	0.92	0.44	0.54	0.82	0.60	0.57	0.48	0.49	0.079	0.81	0.93	0.60	0.66	0.59	0.73
Dy	5.69	2.73	3.37	5.04	3.73	3.62	2.94	2.81	0.40	5.13	5.63	3.85	4.54	3.41	4.30
Ho	1.18	0.58	0.71	1.01	0.77	0.74	0.59	0.55	0.07	1.04	1.18	0.80	0.92	0.72	0.91
Er	3.50	1.78	2.03	2.94	2.23	2.22	1.76	1.66	0.18	3.02	3.57	2.43	2.63	2.18	2.65
Tm	0.51	0.27	0.30	0.44	0.32	0.33	0.25	0.25	0.026	0.46	0.52	0.35	0.38	0.31	0.37
Yb	3.38	1.81	1.95	2.83	2.13	2.14	1.63	1.68	0.170	2.91	3.14	2.27	2.45	2.29	2.43
Lu	0.56	0.29	0.31	0.46	0.34	0.35	0.26	0.28	0.027	0.48	0.56	0.39	0.39	0.37	0.39

Table 2 Bulk rock chemical compositions. Oxides from SiO_2 to P_2O_5 (in wt. %) by XRF; total iron as Fe_2O_3. Trace elements and REE (in ppm) by ICP–MS; udl – under the detection limit.

phyllosilicates (T99/1, T2/00/3), and by replacement of plagioclase by sericite, zoisite, chlorite, carbonate, or epidote (T99/1, T3/00/2, T2/00/3). Strongly altered samples are characterised by the above, but more advanced modes of replacement. Clino- and orthopyroxene are mainly conserved (T99/1, T99/5, T99/6), but may be largely to completely replaced by secondary phases (T99/2, T99/3, T99/4, T99/7, T2/00/3, T2/00/4) in both slightly and strongly altered samples. Chromium-bearing spinels are rather common in the basalt samples, but are not altered. They occur either as inclusions in former olivine in the strongly altered sample T3/00/3 or as an accessory phase in olivine-free rocks (T3/00/2, T3/00/4). Accessory Ti-bearing magnetite is common in andesites (weakly to strongly altered) and is rimmed by sphene, which is also present as patches throughout the rocks. The gabbroic rocks (T 99/4, T 99/6) contain ilmenite with rims of biotite which is replaced by chlorite.

It can be concluded from microscopic observations that Cr, Ti, and V (incorporated in spinel) and, to some extent, the HREE (conserved pyroxene!) showed rather immobile behaviour during alteration. The contents of Na, K, Ni (formerly incorporated in olivine), and to some extent of Ca, Mg were evidently modified and are unable for consideration in the discrimination of the original tectonic setting of the investigated rocks.

5. CHEMICAL COMPOSITION OF BASALTIC AND GABBROIC ROCKS

The chemical composition of the 15 analysed samples is shown in Table 2. Eleven samples have the composition of basalts or gabbroic rocks (SiO_2<54%) and will be discussed later. For samples T99/4 to T99/6 (gabbroic rocks with cumulate fabric) the further use of basalt discrimination diagrams below is subject to the restricted

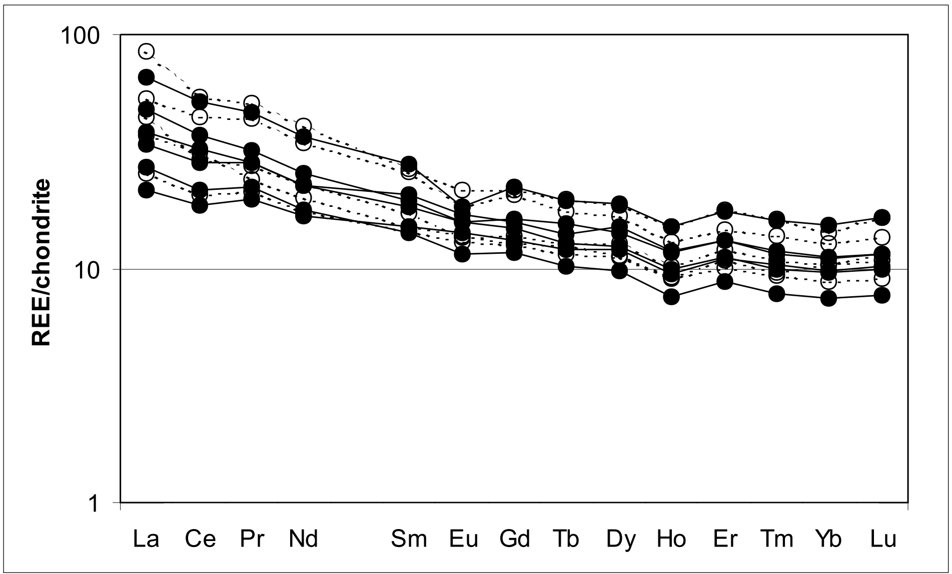

Fig. 5 Rare earth elements normalized on a chondrite basis (WAKITA et al., 1971) for basaltic and gabbroic samples. Two different signatures show two different stages of alteration: full line and full circles for weakly altered samples and stripped line and empty circles for strongly altered samples.

application of these diagrams to rocks of non-cumulate origin.

Figure 5 shows the REE content normalized on a chondrite basis (WAKITA et al., 1971) of eleven samples with basaltic or gabbroic composition. There is no major discrepancy between the patterns of basalts and gabbroic rocks. The patterns in general are typical for E-MORB with enrichment of LREE in comparison to HREE (La/Lu_{cn} between 3 and 5). Two different signatures were used for samples with observed weak alteration and for samples with strong alteration; no significant differences between these two stages of alteration are recognized. It is well known that strong alteration can influence LREE and transfer them into a soluble phase. We explain the same contents of LREE in strongly altered samples with transfer of LREE from the original primary minerals during their disintegration to secondary minerals.

A common and approved tool for the specification of tectonic settings of basaltic rocks is the Ti/100–Zr–3Y diagram introduced by PEARCE & CANN (1973). Most of the basalts and two gabbroic rocks plot into field B (Fig. 6), which is the ambiguous field between island arc basalts, ocean floor basalts, and calc-alkalic basalts. Hence this diagram is not very suitable for discrimination of the tectonic setting of rocks which fall into field B. The field should be further divided, but the fact that none of the samples is situated in the field of "within plate basalts" (D) is considered as a geochemical argument against rifting as the tectonic setting of the investigated rocks. The plotted samples include those

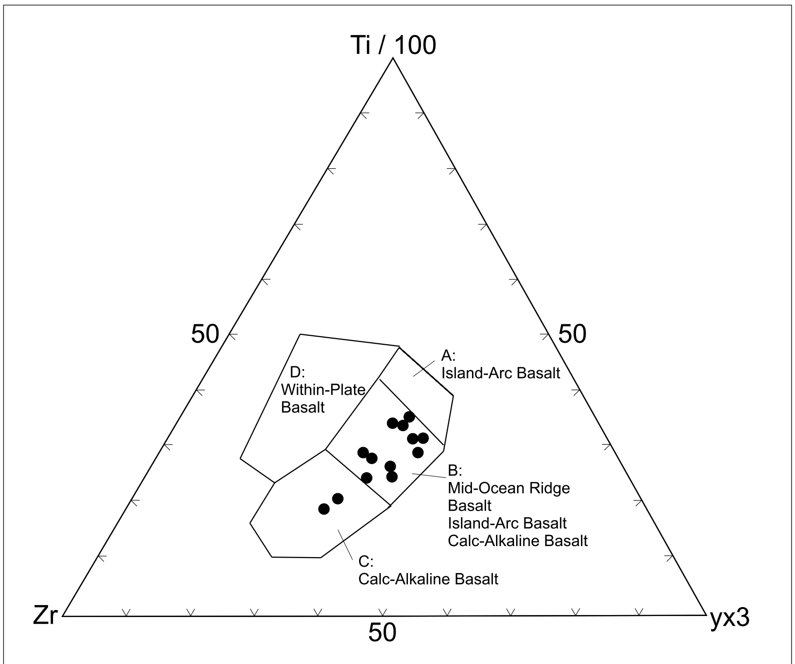

Fig. 6 Ti–Zr–Y diagram for differentiation between basalts from different tectonic settings (after PEARCE & CANN, 1973).

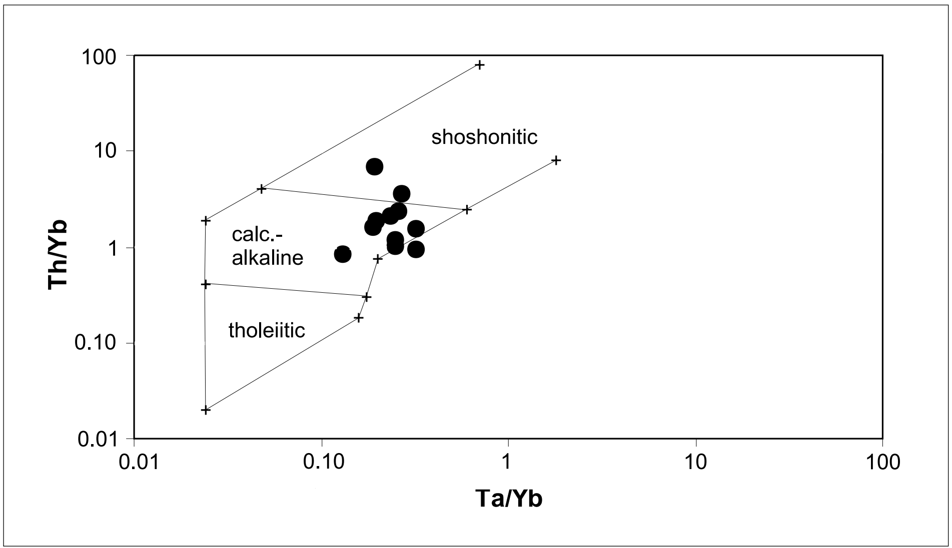

Fig. 7 Th/Yb vs. Ta/Yb diagram for discriminating between tholeiitic, calc-alkaline and shoshonitic basalts (after MÜLLER et al., 1992).

with weak as well as those with strong alteration, but they do not cluster separately. This indicates that Ti, Zr, and Y behaved in a largely immobile manner during alteration.

MÜLLER et al. (1992) proposed Th/Yb vs. Ta/Yb diagrams for discriminating between subduction-induced basaltic volcanism against basaltic rocks crystallised from mantle-derived melts in other tectonic settings. Th is considered to be derived from the sedimentary component of the subducted slab, although the exact mechanism responsible for the enrichment of Th with respect to Ta in subduction-induced volcanism is controversial. Yb is used as a denominator to neutralise the effects of partial melting and/or fractional crystallisation. Figure 7 shows the discrimination diagram after MÜLLER et al. (1992): most of the investigated rocks are within the field of orogenic magmatism (calc alkaline and shoshonitic rocks). Here also no clustering of the investigated samples with strong alteration is visible compared to those with weak alteration.

Another commonly used diagram for the discrimination of basalts from different tectonic settings is the Hf/3–Th–Ta plot proposed by WOOD (1980). Thorium is used as indicator for the influence of subducted sediments (as in MÜLLER et al., 1992) and Hf and Ta are considered as two immobile elements. This diagram should be especially suitable to identify volcanic arc basalts. The possible mobility of Th during alteration could move the position of samples in the direction of MORB-types, but if samples plot in the volcanic arc field, then there is no doubt about a volcanic arc setting. This is exactly the case for our samples plotted in Fig. 8.

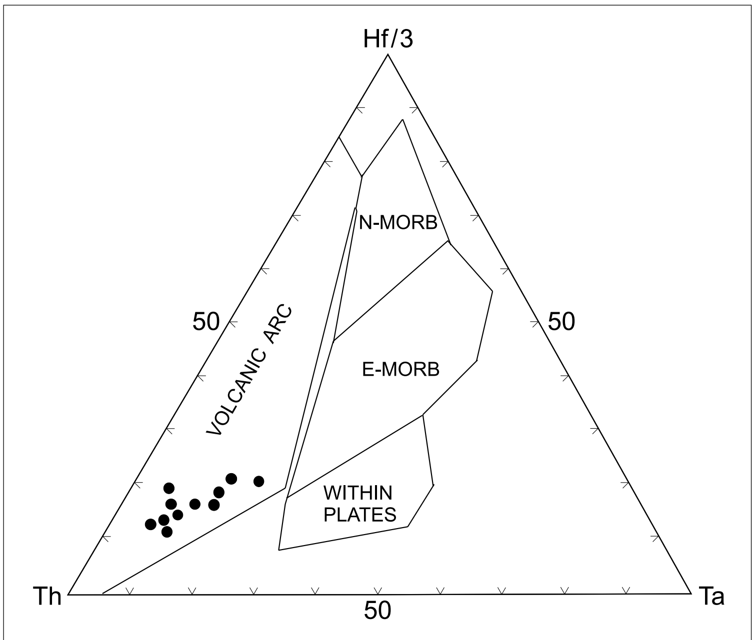

Fig. 8 Hf–Th–Ta diagram for discrimination between basalts from different tectonic settings (after WOOD, 1980).

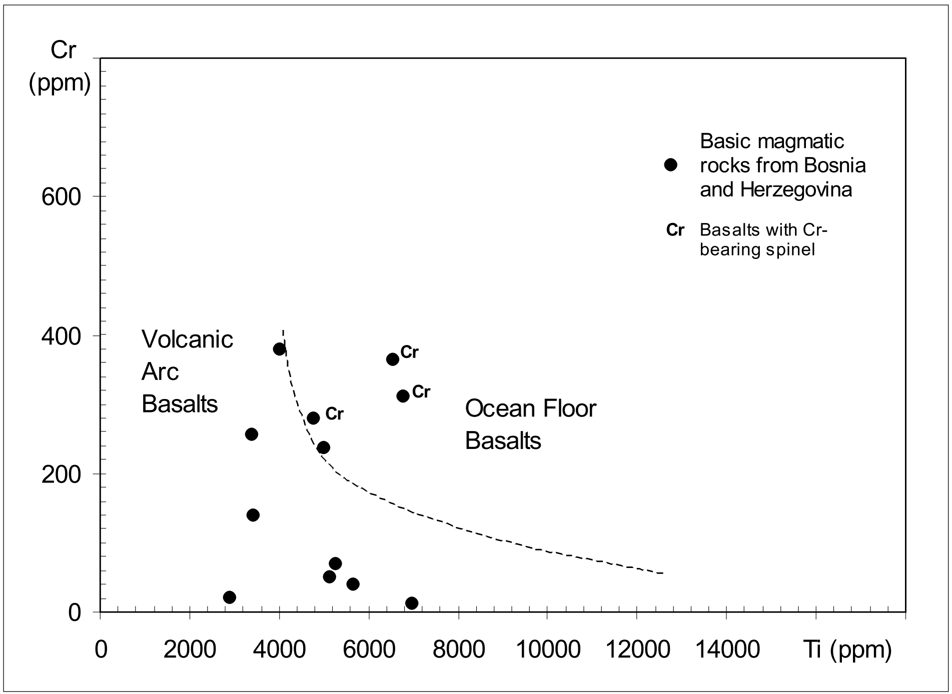

Fig. 9 Cr vs. Ti diagram after GARCIA (1978). The striped line divides the diagram into fields for ocean floor basalts and volcanic arc basalts.

It is further observed that the geotectonic specification of samples containing Cr-bearing spinel (tiny euhedra crystallized from basaltic melt), and consequently with elevated chromium contents (T3/00/2, T3/00/4) is equivocal (either mid-ocean ridge or arc origin in the discrimination diagrams). Figures 9 and 10 show Cr vs. Ti after GARCIA (1978) and Cr vs. Y after PEARCE et al. (1984), respectively. In both cases several samples including those with a spinel content plot outside the field of volcanic arc basalts. The samples are interspersed with innumerable patches of leucoxene which suggests introduction of Ti during alteration. This process could be responsible for the diverging position in the plots of Cr vs. Ti and Cr vs. Y. However,

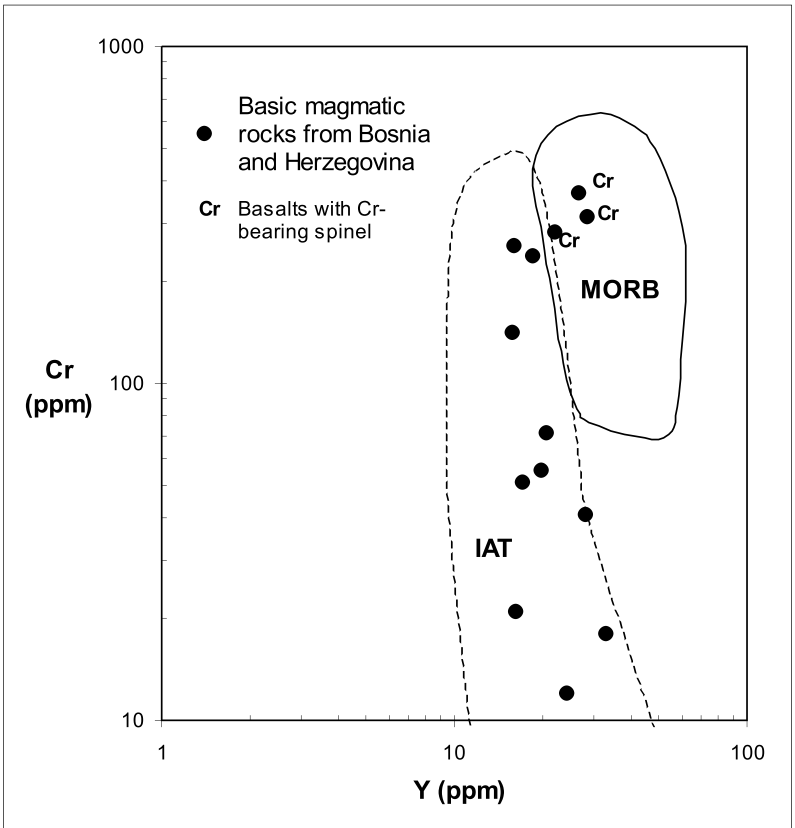

Fig. 10 Cr vs. Y diagram after PEARCE et al. (1984). The field for mid ocean ridge basalts (MORB) is framed with a solid line; the field for island arc tholeiites (IAT) is framed with a striped line.

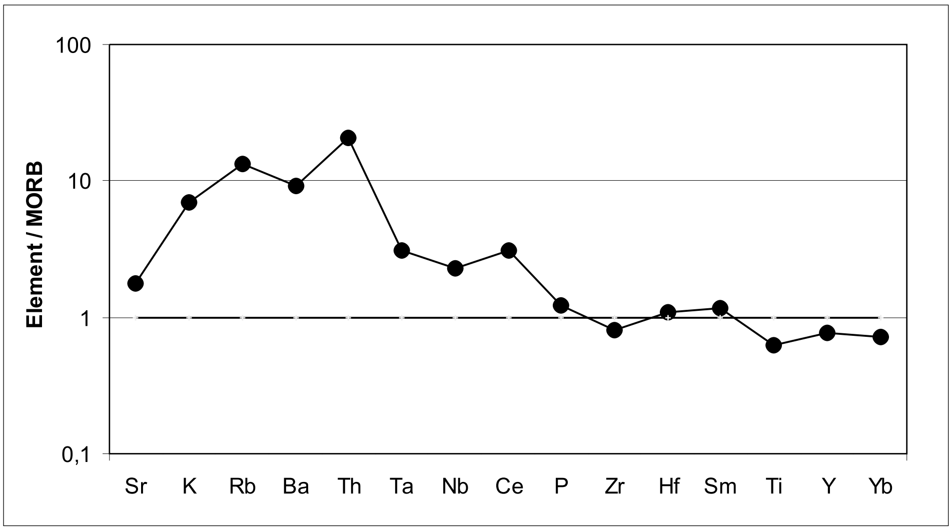

Fig. 11 Spider diagram for average of eleven magmatic rocks with SiO_2<54%, normalized to mid ocean ridge basalts (MORB) as suggested by PEARCE (1983).

it is noticed that Ti and Y are generally recognized as rather immobile during low-T alteration (e.g. JUTEAU & MAURY, 1997) and that Ti and Y are positively correlated in samples T3/00/2 to T3/00/4 (cf. Table 2). The leukoxene patches are mainly restricted to chlorite–phyllosilicate-rich interstitial positions which indicate formation via devitrification and thus the elevated contents of these elements are explained as a primary magmatic signature.

This is not in contradiction with the classification of the other investigated samples as volcanic arc rocks because a wide range of magmatic rocks, from ridge basalts via IAT to calc-alkaline rocks can be associated in zones of former convergent margins, e.g. in Semail, Oman (BEURRIER et al., 1989), Pindos, Greece (BECCALUVA et al., 1979) or Mirdita, Albania (GJATA, 1997[3]; HÖCK et al., 1998).

The spider diagram in Fig. 11 shows the average values for basic rocks, and the enrichment of LIL elements in comparison to normal MORB (SAUNDERS & TARNEY, 1979). This shows that all basic rocks from our investigated area, without exception (individual spider diagrams for every sample not shown), were already changed by additions from the subducted slab although some characteristics of MORB are still preserved. The characteristic enrichment of LIL elements together with the depletion of HFS elements are also known to be unique for calc-alkaline arc-related volcanic rocks.

6. CHEMICAL COMPOSITION OF ROCKS WITH HIGHER DEGREE OF DIFFERENTIATION

Figure 12 shows rare earth element patterns normalized on a chondrite basis for four samples which are of a higher degree of differentiation (up to rhyolite with >70% SiO_2). They also display a similar, but stronger enrichment of LREE compared to HREE as in the basic rocks. The most differentiated rock (the lowest one on Fig. 12) reveals an La/Lu_{cn} of 15.

Hitherto, subduction or rifting was suggested as the tectonic setting for the Triassic magmatic rocks of the Dinarides. Generally these settings are both characterised by a wide range of differentiation, but the applied discrimination diagrams are unfortunately limited to basaltic compositions. GORTON & SCHANDL (2000) enlarged their use to intermediate and felsic magmatic rocks with SiO_2 contents from 54–77 wt.% SiO_2. These enlarged diagrams were developed on the basis of a large collection of rock analyses with known tectonic settings. In Fig. 13 four samples with higher SiO_2 contents of our investigation are plotted. Their position is within the field of subduction-induced volcanism, and, furthermore, in the field of active continental margins.

7. CONCLUSIONS

Triassic magmatic rocks in the area of the Central Dinarides in the territory of Bosnia and Herzegovina are explained as products of subduction-triggered volcanism at an active continental margin (Andean type volcanism). The mobility of elements during alteration was tested by means of comparing the compositions of samples with either strong or weak alteration. The use of rather immobile trace elements shows the influence of subducted slab material, including sediments on the investigated magmatic rocks**.**

[3] GJATA, K. (1997): An overwiev of the geology and metallogeny of Albanian ophiolites.– Unpubl. manuscript, Albanian Geol. Survey, 16 p.

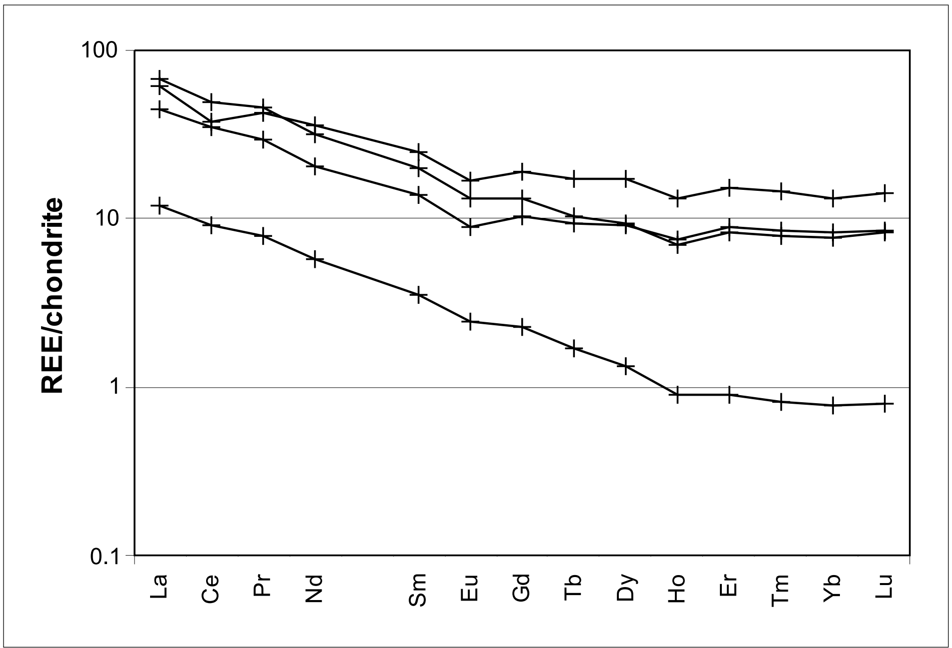

Fig. 12 Rare earth elements normalized on a chondrite basis (WAKITA et al., 1971) for four evolved rocks from the investigated area.

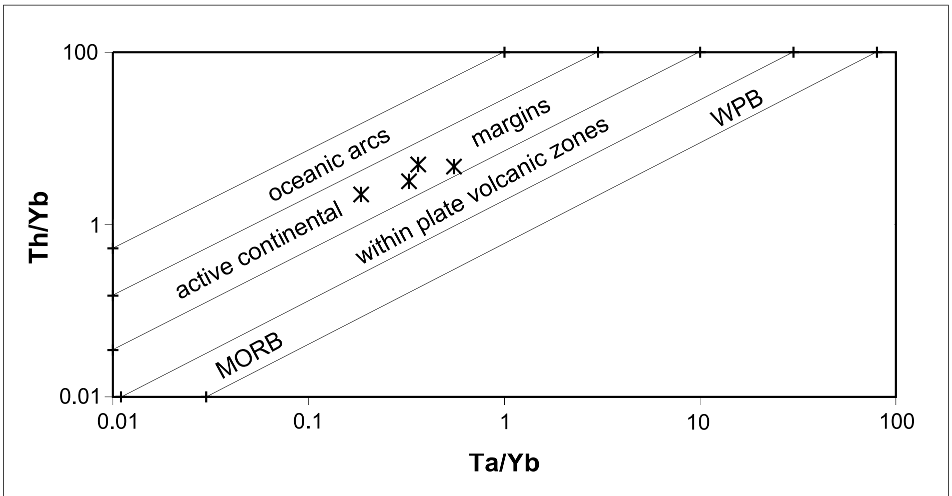

Fig. 13 Th/Yb vs. Ta/Yb diagram (after GORTON & SCHANDL, 2000) with four evolved rocks from the investigated area which plot in the field of an active continental margin.

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