Petrological and Geochemical Features of the Neogene Volcanites of the Osogovo Mountains, Eastern Macedonia

Petrološke in geokemične značilnosti neogenskih vulkanskih kamnin Osogovskih planin (vzhodna Makedonija)

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Abstract: The subject of the presented study was the petrological and geochemical characterization of the Neogene volcanic rocks from the Osogovo Mountains. In this paper we present new results of petrological and geochemical analyses of igneous rocks, mostly from Sasa, Toranica and Ruen. The mineralogical and geochemical characteristics of the studied rocks confirmed the results of some previous investigations that indicated that the exposed lithologies are mostly dacites, quartzlatites, trachyandesites, lamprophyres and rhyolites. An absolute age determination using a standard K-Ar method gives ages between 31.16 ± 1.40 and 14.0 ± 3.0 m.y., and also confirmed their proposed Oligocene-Miocene age. The parent material of these rocks is supposed to originate from the contact zone between the lower crust and upper mantle. A possible assimilation of crustal material during magma formation was also suggested. This supposition was further confirmed by the results of the strontium isotope ($^{87}Sr/^{86}Sr$) ratios, which are in the range from 0.70954 to 0.71126, as well as by other geochemical characteristics.

Izvleček: Članek obravnava petrološke in geokemične značilnosti neogenskih vulkanskih kamnin na območju Osogovskih planin v vzhodni Makedoniji. Podani so najnovejši rezultati geokemičnih analiz in izotopske sestave stroncija ter podatki o njihovi absolutni starosti, dobljeni na podlagi konvencionalne K-Ar metode. Na podlagi mineralne sestave in geokemičnih značilnosti uvrščamo raziskane kamnine med riolite, kremenove latite, trahiandezite in lamprofirske žilnine. Ti različki so bili ugotovljeni tudi v okviru prejšnjih, zvečine petroloških raziskav. Kamnine so oligocensko-miocenske starosti. Glede na podatke o absolutni starosti, dobljeni na podlagi K-Ar metode, lahko rečemo, da so nastale v razponu od pred 31.16 ± 1.40 do 14.0 ± 3.0 milijonov let. Izotopska sestava stroncija in nekatere geokemične značilnosti kažejo, da je magma, iz katere so kristalizirale, najverjetneje izvirala iz kontaktne cone med spodnjim delom zemeljske skorje in zgornjim plaščem. Pri tem dopuščamo tudi možnost njene delne kontaminacije z materialom zemeljske skorje.

Key words: Osogovo mountains, volcanic rocks, absolute age, magma origin, Neogene volcanism

Ključne besede: Osogovske planine, vulkanske kamnine, absolutna starost, izvor magme, neogenski vulkanizem

Scientific paper

INTRODUCTION

Volcanic and volcano-intrusive rocks of the Osogovo volcanic and ore-bearing district are a part of a greater metallogenic unit known as the Besna Kobila-Osogovo-Tasos metallogenic zone. The zone has a northwest direction and a total length of 100 km, and is extended on both sides of the Macedonia-Bulgaria border (BOGOEVSKI, 1965; SERAFIMOVSKI, 1990; SERAFIMOVSKI, 1993; ALEXANDROV, 1992; JANKOVIĆ ET AL., 1995). Volcanic rocks in the zone have similar morphological, petrological and geochemical features, and all of them are of Tertiary age. In Macedonia they were found in the northeastern part on the border with Bulgaria (Fig. 1). It should be mentioned that volcanic rocks of similar composition were also found in Bulgaria.

The volcanic rocks in the investigated area occur as elongated dykes with a northwestern direction, a thickness of 50 m and an azimuth of 260°. From the Osogovo to the Besna Kobila Mountains volcanic rocks are represented by pyroclastites, volcanic domas, dykes, necks and veins. In the Osogovo-Besna Kobila mountains they cut the Paleozoic and Riphean-Cambrian metamorphic and igneous rocks and/or cover the older sedimentary rocks of the Upper Eocene age. In the vicinity of the Sasa and Toranica Pb-Zn ore deposits they are represented mostly by dacitic tuffs, dacites, quartzlatites, rhyolites, trachyandesites, andesite-latites and occasionally by lamprophyre veins.

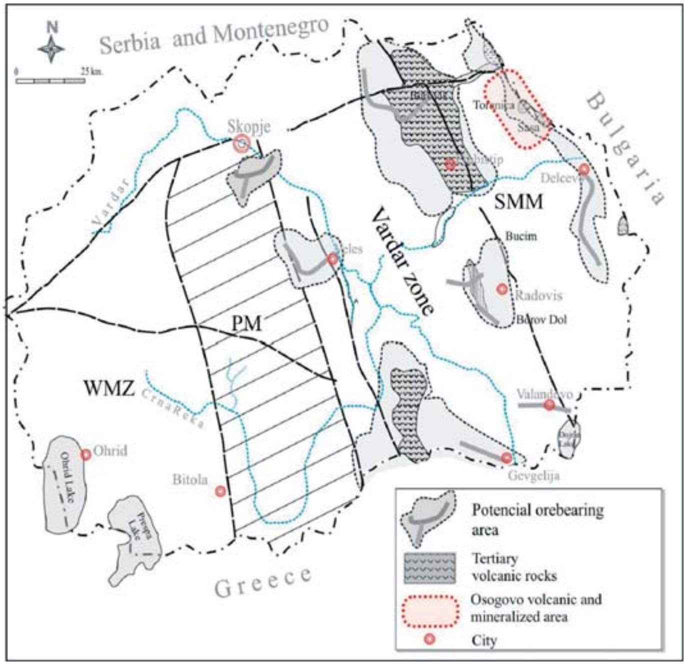

Figure 1. Distribution of the Tertiary magmatism in Macedonia.
Slika 1. Geografska razprostranjenost terciarnega magmatizma v Republiki Makedoniji.

Geological setting

A detailed description of the major lithologies exposed in the investigated area is summarized by Bogoevski (1965), Serafimovski (1990), Serafimovski (1993), Alexandrov (1992), Janković et al. (1995). Large areas of the Osogovo Mountains are covered by various rocks of different origin. Metamorphic rocks such as two mica-type gneisses and quartz graphite schists are the most abundant. These rocks belong to the crystalline basement of the Serbo-Macedonian Massif (SMM). Quartz graphite schists are of special importance, because they are one of the most important host rocks

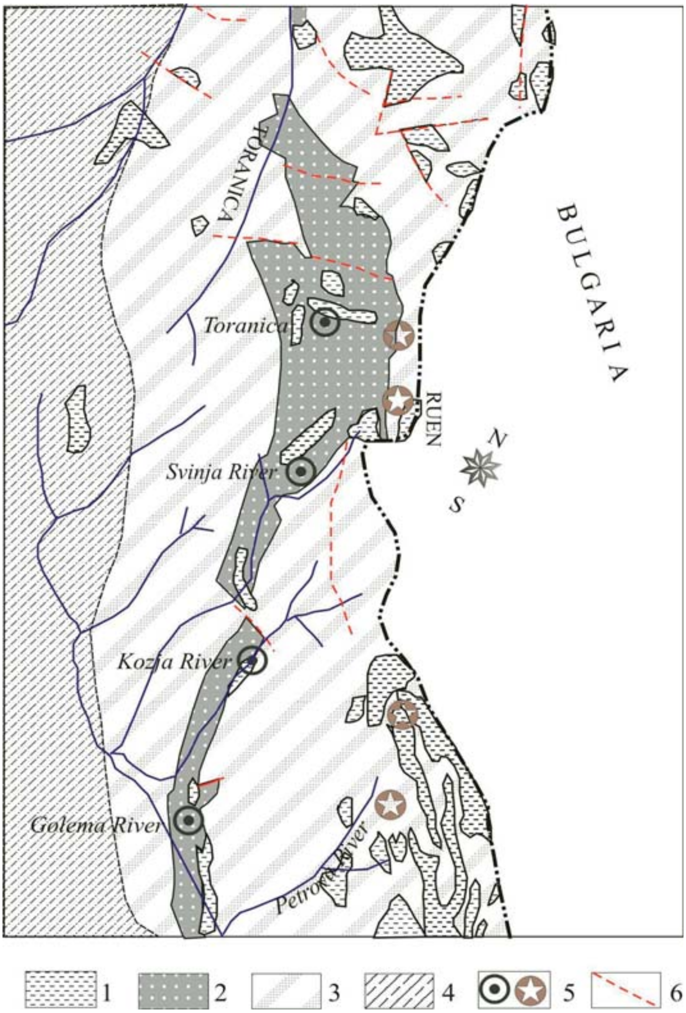

Figure 2. Geologic setting of the Sasa-Toranica ore district. 1) Quartzlatites, 2) Quartz graphite schists, 3) Sericite-chlorite schists, 4) Gneiss, 5) Lead-zinc deposits and occurrences, 6) Faults.
Slika 2. Geološka zgradba rudonosnega območja Sasa-Toranica. 1) kremenovi latiti, 2) kremenovo-grafitni skrilavci, 3) sericitno-kloritni skrilavci, 4) gnajsi, 5) svinčevo-cinkovo orudenje in mineralizacija, 6) prelomi.

for the Pb-Zn mineralization. They are usually interbedded with cipolin marbles, which are also very favorable for metasomatic Pb-Zn mineralization. The geological composition of the area is further comprised of quartzlatite, trachyandesite, dacite, trachydacite dykes and necks, which cut older lithological formations. Small lamprophyre dykes and veinlets were also observed (Fig. 2).

The most characteristic tectonic features of the investigated area are the plicative and disjunctive structures. Plicative structures are represented by different scale-size folds observed in quartz graphite schists. The disjunctive - fault structures are the most abundant in the Sasa and Toranica ore deposits. The productive Pb-Zn mineralizations have been found in different ore deposits and mineralizations. The most important deposits are Sasa, Toranica and Ruen. The detailed geological investigations revealed that the ore mineralization is closely related to the Neogene volcanism.

MATERIALS AND METHODS

For the purpose of this study various igneous, metamorphic and sedimentary rock and ore samples were collected in the field and in the Pb-Zn ore deposits Sasa and Toranica according to the sampling programme designed at the Faculty of Mining and Geology in Štip.

All samples were evaluated by petrographic methods to assess their mineralogical characteristics, ore genesis and hydrothermal alterations. For further geochemical and geochronological analyses unweathered and hydrothermally unaltered or only slightly altered samples were chosen. They were then ground in a mechanical agate grinder to a fine powder for further analyses. Major, minor and trace element analyses were performed in a certified commercial Canadian laboratory (Acme Analytical Laboratories, Ltd.) by ICP-MS. Rock reference samples JR-2 (rhyolite) and JA-2 (andesite) were used to validate the analytical procedure. Major and minor elements were also determined by XRF at the Laboratories of the Geological Department of the University of Padova, Italy. The determination of the $^{87}Sr/^{86}Sr$ ratios by TIMS on ten selected volcanic bulk rock samples was made in the Geology Department, Royal Holloway University of London, U.K. Conventional K-Ar dating was performed on seven volcanic bulk rock samples at the Geological Institute in Budapest, Hungary. The accuracy and precision of the analyses were acceptable. The details of the geochemical and isotopic analyses as well as of age determination analyses can be found in BOEV ET AL. (1997) AND TASEV (2003).

RESULTS AND DISCUSSION

Petrography

The results of the microscopic study revealed that the dacites in the Luke-Kiselica area, which extend from the Karamanica Mountain to the southeast of the Osogovo mountains (SERAFIMOVSKI AND ALEXANDROV, 1995) are characterized by plagioclase phenocrystals with approximately 37 % An content followed by a small amount of orthoclase, quartz, biotite and amphiboles. Their matrix is holocrystalline to hypocrystalline with glassy remains. Accessory minerals, such as apatite, sphene and zircon, were found only in traces, while sericite, chlorite, kaolinite, carbonates and ore minerals are of secondary origin.

Quartzlatites were found near the springs of the river Lucka and Kuprina Padina as dykes, and at Samar and Karamanica as dykes and/ or volcanic flows (Samar and Crcorija) which cover the underlying volcano-sedimentary rocks. They are characterized by a coarse grained porphyric structure due to the presence of sanidine and plagioclase phenocrystals with approximately 35-40 % An content. Amphiboles and augite were also found as phenocrystals. The accessory minerals are sphene and zircon. These rocks were also mineralized.

Hyaloandesites appear as necks and lava flows over the Upper Pliocene sediments at Gradeška mountain. These rocks are of porphyry-vitrophyric structure with plagioclase phenocrystals containing about 37 % An component, followed by more or less well developed biotite, amphibole and augite crystals, and accessory apatite and zircon grains.

At the Sasa-Toranica ore district prevail the volcanic rocks, such as dacite and quartzlatite of hypoabyssal and subvolcanic characteristics. In the whole district these volcanites are hydrothermally altered. Dacites exhibit a holocrystaline structure with about 30 % of the andesine phenocrystals containing 5-16% of An component. Next abundant are the femic minerals (13-20 %) followed by quartz (2-3 %) and a small amount of orthoclase, mainly replaced by epidote, chlorite and carbonates. Hydrothermal alterations of the andesites were of various character; illitization, sericitization and propylitization are the most abundant. Apatite, zircon, sphene and magnetite are accessory minerals, while pyrite, chalkopyrite, sphalerite and galena are ore minerals related to mineralization of hydrothermal origin.

The most abundant rocks in the investigated area are represented by quartzlatites. They occur as elongated dykes a few kilometers long. These rocks are characterized by large phenocrystals, mostly sanidine, andesine and femic minerals such as biotite, amphiboles and rarely augite. The sanidine crystals are fresh and large; they are up to 6 cm long. Quartzlatites were also considerably hydrothermally altered. Transition rocks, from quartzlatites to rhyolites, were also found in few locations at the Osogovo Mountains. They are slightly more acidic and are exposed near the Sekirica Tower close to the Macedonian-Bulgarian border. The rocks were intensively propylitized.

The volcanic rocks from the Kozja and Svinja River (Sasa mining district) are mainly represented by dacites and quartzlatites. They are highly propylitized and hydrothermally altered. These rocks also contain ore minerals such as pyrite, galena, sphalerite and others.

Trachyandesites of the Sasa-Toranica and broader area form smaller bodies at subvolcanic-volcanic levels. They are characterized by a porphyry structure (fine-grained porphyry) and a crystallized microlitic or microtrachytic matrix. The phenocrystals are up to 3 mm long, and are represented by andesine, sanidine, biotite, augite and hornblende euhedral grains. Apatite, sphene and zircon occur as accessory minerals. In comparison to the quartzlatites, trachy-andesites are depleted in SiO_2 content. Similar rocks are also exposed in Pečovska Mala in the Osogovo Mountains in Bulgaria.

Lamprophyres occur as small dykes near Sredno Brdo and Toranica. They are dark gray to brown with a fine-grained porphyry structure and a glassy matrix. The phenocrystals are pyroxenes, amphiboles and biotite. Accessory minerals are represented by apatite, sphene and zircon.

Geochemistry

Major, minor and selected trace elemental compositions of the most important volcanic rocks of the Sasa-Toranica ore district are presented in Table 1, while Table 2 shows the results of the REE analyses. In Figure 3 the Total Alkali Silica diagram (LE MAITRE ET AL., 1989) with the position of the analyzed samples is shown. The Figure 4 represents the IRVING AND BARAGAR (1971) classification for volcanic rocks.

From Figures 3 and 4 it is clear that the investigated volcanites mostly plot in the fields that define dacites, trachydacites and rhyolites. Only sample 3, with the highest $Na_2O + K_2O$ content, plots in the border between the trachydacite and trachyandesite fields. Furthermore, a classification according to IRVING AND BARAGAR (1971) revealed that the volcanites from the Sasa-Toranica ore district are of calcalkaline rock suites. The whole rock C1 chondrite

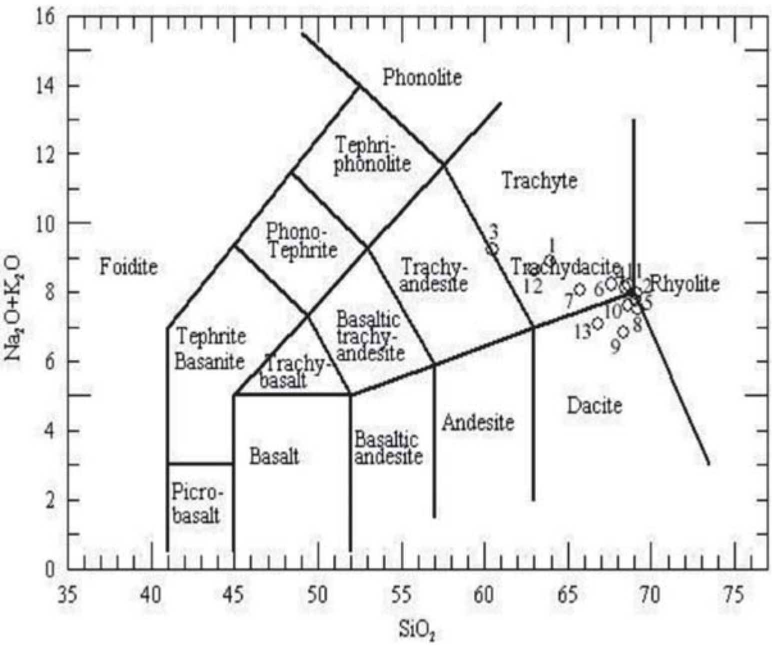

Figure 3. Chemical classification and nomenclature of the volcanic rocks in the Sasa-Toranica ore region, using diagram total alkalis vs. silica (LE MAITRE ET AL., 1989).
Slika 3. Klasifikacija vulkanskih kamnin rudonosnega območja Sasa-Toranica na podlagi vsebnosti alkalij in kremenice (TAS) (LE MAITRE ET AL., 1989).

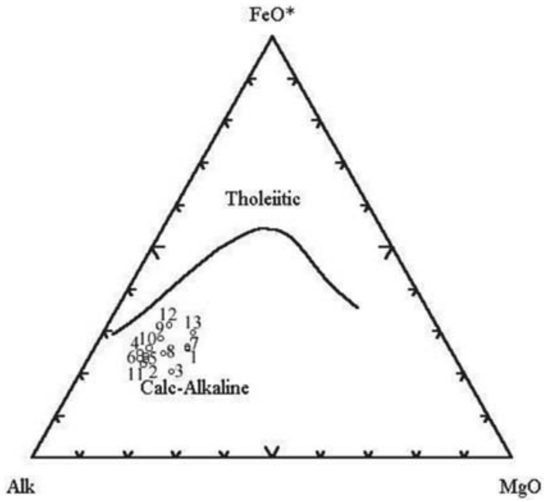

Figure 4. Classification of volcanic rocks from the Sasa-Toranica ore region (Alk=Na_2O + K_2O; FeO* = FeO + 0.8998 x Fe_2O_3 (IRVING AND BARAGAR, 1971).
Slika 4. Klasifikacija vulkanskih kamnin rudonosnega območja Sasa-Toranica po IRVINGU IN BARAGARJU (1971); (Alk=Na_2O + K_2O; FeO* = FeO + 0.8998 x Fe_2O_3).

normalized REE patterns (Fig. 5) show a strong LREE enrichment above the average continental crust and moderate negative europium anomalies with Eu/Eu* values between 0.728 and 0.829 (Table 2). Such a strong LREE enrichment could be related to crystal fractionation and/or assimilation of the LREE-enriched continental material or a combination of the two mechanisms (DRAUT ET AL., 2002).

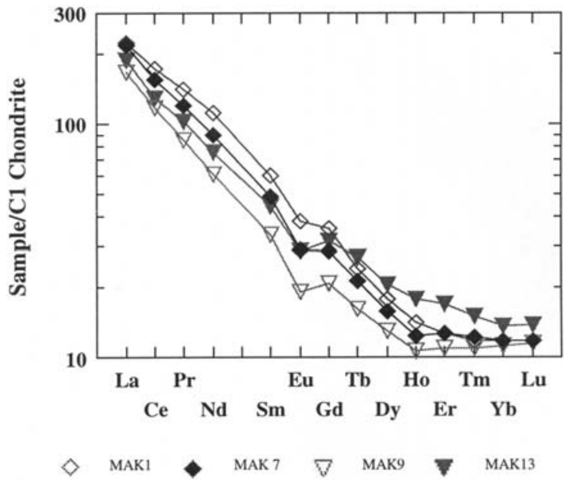

Figure 5. Rare-earth element patterns normalized to C1 chondrite for the volcanic rocks from the Sasa-Toranica ore region.
Slika 5. Vzorec redkih zemelj za vulkanske kamnine rudonosnega območja Sasa-Toranica normaliziran na C1 hondrit.

Table 1. Chemical composition of the volcanic rocks in the Sasa-Toranica ore region (major oxides in %), trace elements in ppm).
Tabela 1. Kemična sestava vulkanskih kamnin iz rudonosnega območja Sasa-Toranica (glavni oksidi v %, sledne prvine v ppm).

Elem.	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	**M12**	**M13**
SiO_2	63.93	69.10	60.48	68.46	69.09	67.62	65.73	69.19	68.35	68.59	68.65	63.00	66.83
TiO_2	0.65	0.43	0.54	0.44	0.44	0.46	0.63	0.40	0.41	0.42	0.40	0.52	0.56
Al_2O_3	14.35	14.92	16.43	15.47	15.00	15.53	14.94	14.72	15.15	15.29	15.29	16.24	15.52
Fe_2O_3	1.29	0.67	0.81	0.57	0.82	0.92	0.91	0.67	0.73	0.53	0.58	2.31	0.61
FeO	3.05	2.37	2.37	2.58	2.20	2.19	3.07	2.49	2.62	2.69	2.44	2.81	3.53
FeOt	4.43	3.11	3.22	3.26	3.07	3.17	4.04	3.22	3.50	3.31	3.09	5.17	4.33
MnO	0.11	0.08	0.10	0.08	0.10	0.07	0.09	0.31	0.34	0.30	0.24	0.10	0.40
MgO	3.15	1.38	2.86	1.24	1.40	1.42	2.86	1.87	1.46	1.38	1.32	2.00	2.58
CaO	3.91	2.78	6.85	2.69	2.89	3.27	3.14	2.51	3.70	2.85	2.55	4.04	2.47
Na_2O	2.56	3.38	3.67	2.66	3.40	3.24	2.88	1.58	1.46	1.95	2.85	3.28	2.43
K_2O	6.32	4.58	5.57	5.47	4.37	4.98	5.19	5.93	5.37	5.66	5.35	5.36	4.66
P_2O_5	0.60	0.24	0.28	0.23	0.24	0.24	0.49	0.27	0.25	0.24	0.24	0.28	0.21
LOI	3.96	3.43	3.05	4.03	4.06	3.87	3.69	2.77	5.31	4.33	3.56	4.96	4.93
Cr	50	27	27	38	24	14	69	71	50	30	27	17	73
Ni	30	32	34	49	18	16	46	52	45	29	37	12	61
Ba	2339	1236	1586	1199	1151	1336	1587	2290	1873	1900	2550	1297	2722
Rb	247	211	137	270	214	224	213	218	236	242	191	165	196
Sr	964	499	1216	415	464	555	580	408	268	347	460	664	314
La	59	59	52	57	71	66	39	56	48	47	59	95	53
Ce	106	71	110	98	63	78	95	62	84	66	62	139	58
Nd	29	16	31	9	26	24	29	16	7	0	0	38	5
Zr	297	186	135	195	199	195	221	251	189	200	181	163	173
Y	22	21	24	19	19	19	22	23	19	22	22	24	32
Nb	15	11	10	12	12	10	13	12	11	12	10	10	11
Th	44	31	34	30	34	30	34	49	33	39	40	49	37
U	9	7	5	9	7	8	7	8	8	9	7	6	7

Legend: 1. M-1 Trachydacite; 2. M-2 Trachyte-rhyolite-dacite; 3. M-3 Trachyandesite-trachydacite; 4. M-4 Trachydacite; 5. M-5 Dacite; 6. M-6 Trachydacite; 7. M-7 Trachydacite; 8. M-8 Dacite; 9. M-9 Dacite; 10. M-10 Dacite; 11. M-11 Trachydacite; 12. M-12 Trachydacite; 13. M-13 Dacite.
Legenda: 1. M-1 trahidacit; 2. M-2 trahit-riolit-dacit; 3. M-3 trahiandezit-trahidacit; 4. M-4 trahidacit; 5. M-5 dacit; 6. M-6 trahidacit; 7. M-7 6 trahidacit; 8. M-8 dacit; 9. M-9 dacit; 10. M-10 dacit; 11. M-11 6 trahidacit; 12. M-12 6 trahidacit; 13. M-13 dacit.

Table 2. Rare-earth elements content (in ppm) in the volcanic rocks from the Sasa-Toranica ore region.
Tabela 2. Vsebnost REE (v ppm) v vulkanskih kamninah iz rudonosnega območja Sasa-Toranica.

Elem.	MAK1 I	MAK7 I	MAK9 II	MAK13 II
La	53.10	52.00	39.60	44.90
Ce	106.00	95.40	72.10	79.30
Pr	13.30	11.40	8.08	9.72
Nd	52.50	42.10	28.30	35.20
Sm	9.20	7.50	5.10	6.80
Eu	2.22	1.68	1.11	1.65
Gd	7.30	5.90	4.30	6.50
Tb	0.90	0.80	0.60	1.00
Dy	4.50	4.00	3.30	5.20
Ho	0.80	0.70	0.60	1.00
Er	2.10	2.10	1.80	2.80
Tm	0.30	0.31	0.28	0.38
Yb	2.00	2.00	1.90	2.30
Lu	0.30	0.30	0.29	0.35
Eu*	0.83	0.77	0.73	0.76

Legend: MAK-1I Trachydacite; MAK-7I Trachydacite; MAK-9II Dacite; MAK-13II Dacite
Legenda: 1. MAK-1I trahidacit; MAK-7I trahidacit; MAK-9II dacit; MAK-13II dacit

The Eu anomaly is mainly controlled by the presence of feldspars. Eu^{2+} is compatible in plagioclase and K-feldspar, relative to the Eu^{3+} that is incompatible. Thus the removal of feldspar from a felsic melt by crystal fractionation or partial melting of a rock containing K-feldspars gave rise to a negative Eu anomaly in the melt. A crystal fractionation and/or partial melting of the continental material could thus explain a negative europium anomaly in the investigated samples (Draut et al., 2002).

Table 3. $^{87}Sr/^{86}Sr$ ratios in the volcanic rocks from the Osogovo mountain.
Tabela 3. Izotopsko razmerje $^{87}Sr/^{86}Sr$ v vulkanskih kamninah Osogovskih planin

No.	Locality	Rock type	$^{87}Sr/^{86}Sr$
1.	Golema R.950, Sasa	Quartzlatite	0.71051
2.	Kozja R. IV_o, Sasa	Quartzlatite	0.70994
3.	Svinja R. IV_o, Sasa	Quartzlatite	0.71126
4.	Toranica – 2	Quartzlatite	0.71016
5.	Toranica, TO-1	/	0.70979
6.	Sasa	Andesite-latite	0.71064
7.	Sasa	Quartzlatite	0.71024
8.	Sasa, SA-2	/	0.70954
9.	Toranica, MK-1	Trahydacite	0.71055
10.	Sasa, MK-9	Dacite	0.71096

(1-8) Boev et al. (1997), (9-10) Tasev (2003).

The $^{87}Sr/^{86}Sr$ initial ratios of the analysed rocks are reported in Table 3. Their isotopic results range from 0.70954 to 0.71125. These values are mostly in the range of the igneous rocks of the crustal origin, and are somewhat higher than the values commonly found in the andesites (0.703 – 0.708) and the plutons aligned along the continental margins (CARMICHAEL ET AL., 1974). Such values also suggest that the magma that has produced Neogene igneous complexes at the Osogovo mountains is a product of the primary magmatic melt that originated from the border zone between the upper mantle and the continental crust where processes of mixing and the contamination of primary magma occurred. This is also supported by strontium isotope data for the Upper Tertiary calc-alkaline complexes of the Serbo-Macedonian metallogenic province and Kožuf Mountain ($^{87}Sr/^{86}Sr$ is in the range from 0.7088 to 0.7090) as well as by those for volcanic rocks from the Rogozna, where the initial range of $^{87}Sr/^{86}Sr$ is between 0.7074 and 0.7085 (SERAFIMOVSKI, 1990).

The above mentioned magmatic activity was related to the processes that took place after the closure of the Tethys Ocean and subduction of the oceanic plate under the SMM (Serbo-Macedonian masif - Cretaceous), due to the collision of the African plate with the Euroasian plate. The collision of these two continental segments produced the calc-alkaline magmatism during the Middle and Upper Jurassic. The collision also resulted in thickening of the continental crust and in isostatic uplifting. Due to discontinued compression, temporal, partial melting of the basal parts of the continental parts took place. The pulsations of the tectono-magmatic activities were repeated many times during the Oligocene, Miocene and Pliocene (KARAMATA, 1982; SERAFIMOVSKI AND TASEV, 2002). From the metallogenic point of view, of special interest is the zone of deep fractures along the west margin of the SMM, which represents the active continental margin. The fractures served as feeding channels for the uplifting of calk-alkaline magmas and hydrothermal ore bearing solutions (JANKOVIĆ ET AL., 1997).

Nevertheless, some other authors (BOEV AND YANEV, 2001) relate these magmatic and hydrothermal activities to Late Tertiary Aegean subduction, referred to active continental margin of the Andean type. They supposed that the Macedonian igneous rocks were formed by mildly alkaline magmas

Table 4. Absolute age determination of the volcanic rocks in the Sasa-Toranica ore region by the K/Ar method (TASEV, 2003).
Tabela 4. Absolutna starost vulkanskih kamnin iz rudonosnega območja Sasa-Toranica, določena na podlagi K/Ar metode (TASEV, 2003).

No.	Locality	Rock type	K-Ar age (m.y.)
1.	Mal Ruen	Quartzlatite	28.38±1.09
2.	Toranica-I	Quartzlatite	28.36±1.09
3.	Sasa (Kozja R.)	Quartzlatite	30.72±1.19
4.	Sasa (Kozja R.)	Andesite	29.25±1.13
5.	Sasa (Crvena R.)	Granodiorite	31.16±1.40
6.	Sasa	Andesite-latite	14.0±3.0
7.	Sasa	Quartzlatite	24.0±3.0

originating from the upper part of the supra-subduction area. The subduction process in the Miocene and Pliocene moved to the south and southwest, probably due to the extension in the north Aegean region (Gautier et al., 1999) causing migration of the volcanic activity in Macedonia in the same direction, from the Kratovo-Zletovo to the Kožuf area.

Tertiary igneous rocks from the Osogovo mountains are characterized by an unusual distribution of the Pb, Ba, Sr, Rb, Li, Cs and Be contents. They exhibit relative to the Clark background values elevated concentrations of Pb, Ba, Sr and Be and similar contents of Li, Rb and Cs. During the magmatic processes the increase in the concentrations of Li, Pb, Cs, Be, Rb and Ba was observed from fine-grained porphyry quartzlatites to coarse-grained porphyry quartzlatites (Serafimovski, 1993a; Serafimovski et al., 2003). The observed distribution of trace elements most probably indicates that the igneous rocks were formed of magma from the same magmatic chamber, which in different time intervals produced different rock types.

The age of the volcanic rocks of the Sasa-Toranica ore district according to the standard K/Ar method is in the range from 31.16 ± 1.13 to 14.0 ±3.0 to m. y. (Table 4). This range is of the Oligocene-Miocene age, and was also confirmed by other methods.

Conclusions

The presented study of the volcanic rocks from the Sasa-Toranica ore district revealed very different granitoid lithologies, such as rhyolites, dacites, trachydacites and trachyandesites of the Oligocene-Miocene age. According to the standard K/Ar method the age of those rocks range from 31.16 ± 1.40 to 14.0 ± 3.0 m.y. The volcanic rocks display a relatively large range in Sr isotopic ratios. This could be interpreted as a result of fractional crystallization processes occurring at the contact zone between the lower continental crust and the upper mantle, and associated with a possible assimilation of crustal material.

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