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Geochemistry of migmatite-granite connection: a case study from the Central Rhodope, Bulgaria

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Э. Раева, З. Чернева – Геохимия связи между мигматзацией и гранитообразованием на примере с территории Центральных Родоп, Болгария. Экстензионный этап в Альпийской эволюции Родопского массива сопровождался экстензивным плавлением коры и интрузивным гранитным магматизмом. Внедренные в разное время граниты и граниты разной структурной обусловленности могут выявить связь между составами продуктов анатектической мигматизаци и гранитными магмами, а также – соотношения соответствующих процессов во времени. Нами изучались посткинематический Смилянский плутон и небольшие синкинематические граниты, размещенные среди мигматизированных гнейсах Маданской единицы. Район исследования расположен на юго-западной периферии метаморфического ядерного комплекса, слагающего Центральнородопский купол (CRD). Доминирующие геохимические особенности гранитов Маданской единицы показывают замечательное сходство с образованными in situ анатектическими расплавами диатектического ядра CRD, т.е. с Ардинской единицей. К этим особенностям относятся: кислый пералюминиевый состав, ниские содержания HFSE и REE, высокие содержания LILE и значения отношений LILE/HREE, а также – незначительная (до положительной) Eu аномалия. Некоторые отклонения в геохимии синкинематических гранитов являются подтверждением идеи о том, что различия в продуктах частичного плавления обусловлены различиями в составах исходных пород. Среди этих отклонений отметим: метаалюминиевый состав, повышенные содержания HFSE и REE и значения отношений LREE/HREE, а также – вариации в отношении Eu/Eu*. Данные о возрасте (Смилянский плутон – 43 Ма и анатектиты ядра CRD – 38–37 Ma) исключают прямую связь между интрузивными гранитами Маданской единицы и мигматитами Ардинской единицы. Мы рассматриваем связь гранитов и мигматитов как единый процесс продолжительного третичного плавления коры, которое происходило во время эволюции CRD. Плавление охватывало разные коровые источники и при этом происходило образование обособленныйх порций гранитных расплавов. Геохимия основных элементов и элементов-следов выявляет потенциальные линии родства между группами пространственно связанных гранитных пород на основании того-же самого механизма, по которому осуществилось образование расплавов.

Abstract. Extensive crustal melting and intrusive granite magmatism accompanied the extensional stage of the Rhodope massif Alpine evolution. Granites of different structural position and time of crystallization could reveal compositional and temporal relations between anatectic migmatization and granite magma generation. We have studied the post-kinematic Smilyan pluton and smaller syn-kinematic granite bodies hosted by the Madan unit metatexitic gneisses in the southwestern periphery of a metamorphic core complex known as Central Rhodopian Dome (CRD). The dominant geochemical features of the Madan unit granites display remarkable similarities with in situ formed anatectic melts from the CRD diatexitic core (Arda unit): felsic peraluminous compositions, low HFSE and REE, high LILE contents and LREE/HREE ratios, and negligible to positive Eu anomaly. Some deviations of the syn-kinematic granites geochemistry (metaluminous compositions, REE and HFSE enrichment, LREE/HREE ratios and Eu/Eu* variation) support an idea of separate partial melt batches extracted from different precursor compositions. Age data available (Smilyan pluton 43 Ma, and CRD core anatectic melts 37–38 Ma) preclude direct feedback relations between Madan unit intrusive granites and Arda unit migmatites. We infer that the migmatite-granite connection should be considered a common process of protracted Tertiary crustal melting that operated during CRD evolution and affected different crustal sources to produce discrete portions of granite melts. Major and trace elements geochemistry reveals potential lines of descent amongst groups of spatially related granitic rocks due to the same mechanism of melt generation.

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Key words: geochemistry, leucogranites, Smilyan granite, crustal melting, migmatites, metamorphic core complex.

Introduction

The processes of crustal melting and granite magma generation in continental collision settings play an important role in crustal recycling and differentiation. Migmatite-granite connection refers usually to mechanisms of melt transfer during orogeny (Brown, 1994, 2001, Brown, Solar, 1998, 1999; Vanderhaeghe, 1999). Granite geochemistry reflects source composition and magma fractionation. Geochemistry of migmatites and granites coupled together permit further expansion of the examination whether migmatites are sources or feeder zones for granites (Brown, 2001; Solar, Brown, 2001). The age and structural position of the crystallized anatectic melts (migmatites and granite bodies) are crucial for migmatite-granite linkage interpretation. The aim of the study is to compare granites of different structural position and time of crystallization in the Central Rhodope (allochtonous syn- to post-kinematic granites, and autochthonous anatectic granites) to examine compositional and temporal connections between anatectic migmatization and granite magma generation.

Geological setting

The compression-extensional Alpine evolution of the Rhodope massif (Ivanov, 1989, 2000; Ricou et al., 1998) is accompanied by a clockwise metamorphic

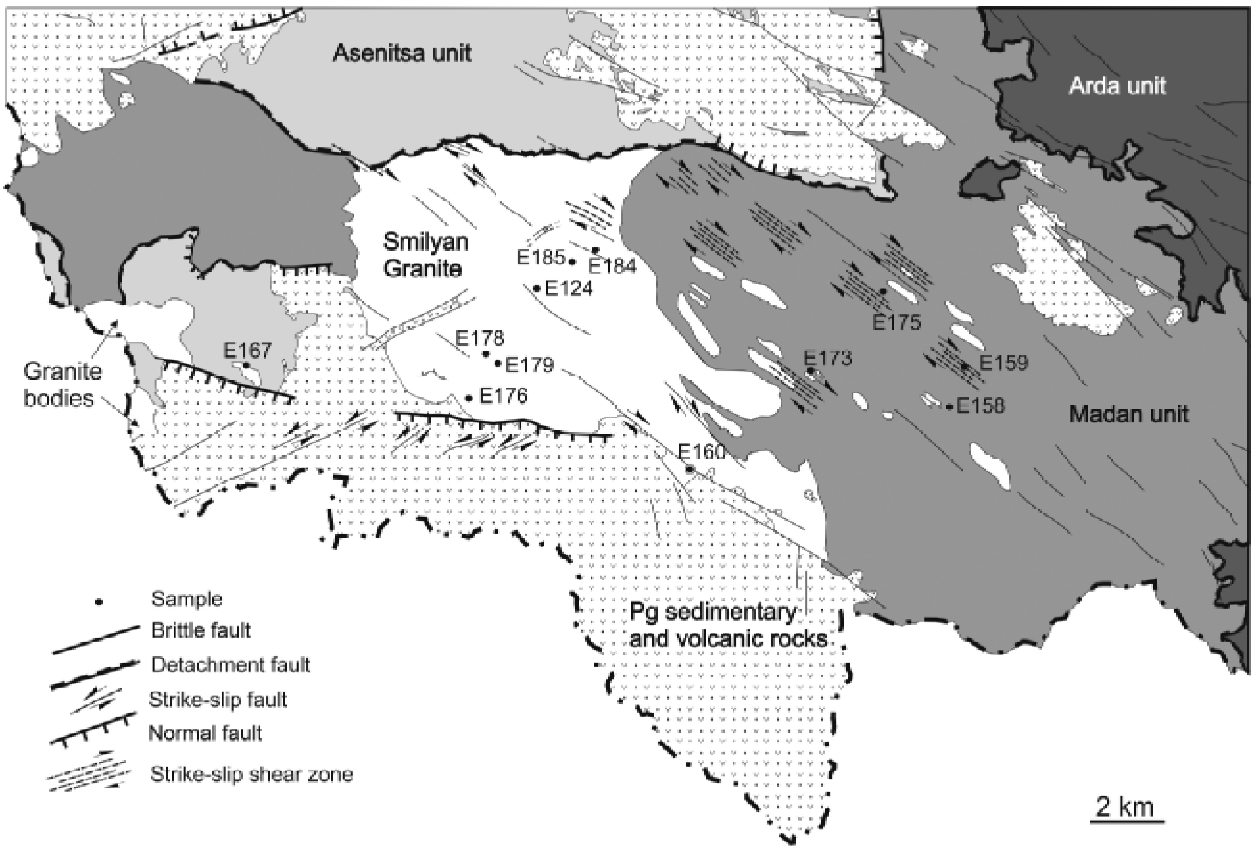

Fig. 1. Geological sketch map of the area studied (after Sarov et al., 2007)

P–T path (Kostov et al., 1986). The decompression stage favoured extensive crustal melting, intrusive granite magmatism and migmatite exhumation from lower crust levels corresponding to metamorphic core complex models (Ivanov, 2000). The Central Rhodopian Dome (CRD) is composed of a diatexitic core (Arda unit), overlaid by an intermediate metatexite trust sheet (Madan and Startzevo units) and a non-migmatitic trust sheet on the top (Assenitza and Borovitza units), all bounded by ductile-brittle shear zones.

Extensive late Alpine fluid-present melting in the CRD core (760–680°C/1–0.6 GPa, Cherneva, Georgieva, 2005, 2007 and reference therein) produced 37–38 Ma old leucosomes and felsic anatectic granites of crustal signatures (zircon εHf_t – 6.6; Ovtcharova, 2002, 2003a, b, 2004; Peytcheva, 2000, 2004). Syn- to post-kinematic 43–53 Ma old granites of mixed crustal-mantle isotope signatures (Ovtcharova, 2003) intruded the intermediate and upper trust sheet pre-dating the anatectic melts crystallization in the dome core.

The area of study covers part of the southwestern side of the CRD (Fig. 1). The subjects of the study are granites of the Madan unit that is dominated by migmatitic biotite and amphibole-biotite gneisses (Belmustakova, 1995; Sarov et al., 2007). Our field observations suggest prevailing granite melt injection concordant to the gneiss foliation rather than extensive in situ migmatization. Syn- to post-kinematic granite and aplite-pegmatite bodies and veins of different scale and NW-SE elongation intruded the gneisses, controlled by ductile strike-slip shear zone (Naydenov at al., 2005). The biggest post-kinematic body (Smilyan granite) postdated the final strike-slip deformation (Sarov et al., 2007). The Smilyan granite is 43 Ma old (zircon εHf_t from +0.1 to +2; Ovtcharova et al., 2003), hence the syn-kinematic granite bodies should be considered older.

Geochemistry

Selected whole rock samples (Fig. 1) represent typical compositional features of the Smilyan pluton and smaller syn-kinematic granite bodies and veins. The geochemical information is obtained from instrumental XRF and ICP MS techniques (Table 1). Data available on Smilyan granite (Belmustakova, 1995) and on anatectic melts from the CRD core (Cherneva, Georgieva, 2005) are used to make comparison.

The Smilyan granite body and the majority of syn-kinematic ones are dominated by leucogranite mineral assemblage composed of quartz, plagioclase, K-feldspar ± biotite and muscovite (Belmustakova, 1995; Raeva et all., 2006). The accessory minerals are apatite, zircon, allanite and magnetite. Larger proportions of mafic minerals and accessories are found in some of the syn-kinematic bodies. The rock-forming and accessory mineral assemblages of the Madan unit leucogranites correspond to those of the CRD core anatectic granites except for monazite that is common in the latter (Cherneva et al., 2003).

The Madan unit granite suit ranges from granodiorite to leucogranite, nevertheless the felsic compositions dominate both Smilyan pluton and syn-kinematic granite bodies and veins (Tabl. 1). Leucogranite compositions display close to eutectic normative ratios in the system Qtz-Or-Ab-An-H_2O (Fig. 2a) and have low contents of mafic oxides (Fe_2O_3*+MgO+TiO_2 < 2% wt, Fig. 2b). The most of them are peraluminous (A/CNK up to 1.26) and plot in the field of the CRD core anatectic melts (Fig. 2c). Among the syn-kinematic granite bodies however there are some metaluminous compositions (A/CNK = 0.78–0.97) with mafic components enrichment. The major elements distribution patterns of all the granites do not show clear magma fractionation trends.

Compatible trace elements contents (Cr, Ni, Co, V, Sc and Cu) in the rocks studied are depleted when

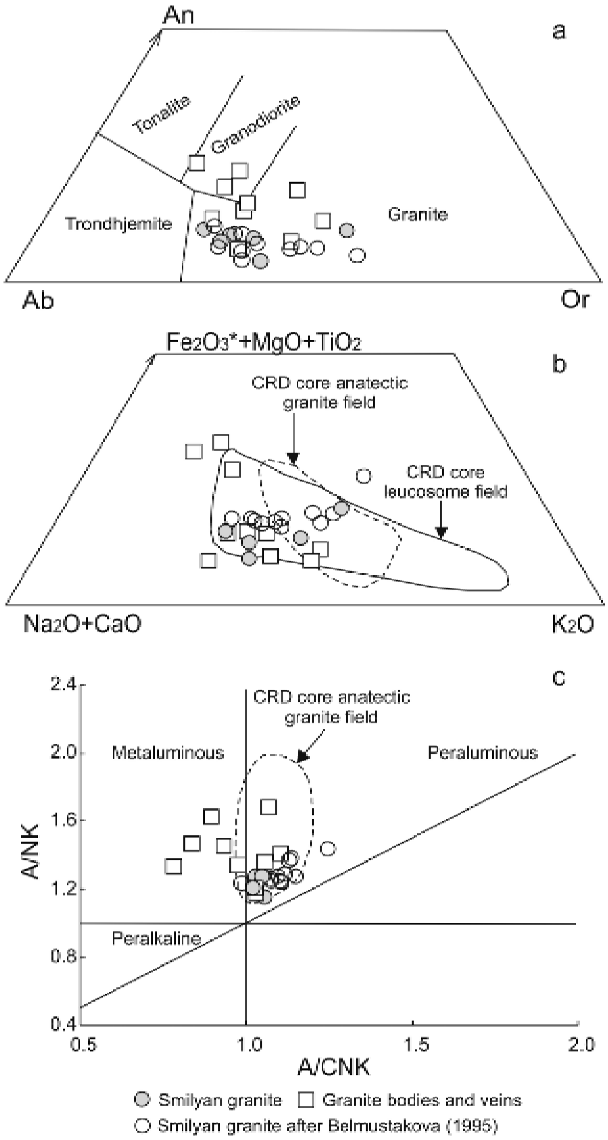

Fig. 2. Major elements geochemistry: a) normative An-Ab-Or composition after Barker (1983); b) major oxides distribution of granites studied compared with the CRD core leucosomes and anatectic granites; c) A/CNK vs. A/NK after Maniar and Piccoli (1989)

Table 1

Selected analyses of major oxides (wt %) and trace elements (ppm) of Smilyan granite and related bodies

Sample	Smilyan granite						Small granite bodies					Granite and aplite-pegmatite veins				
	E124	E176	E178	E179	E185	E160	E167	E173	E176A	E159B	E184	E158C	E178A	E175A	E148	E149C
SiO_2	73.27	73.49	73.41	72.26	71.13	72.17	67.89	68.15	73.41	71.10	59.99	70.49	74.63	72.73	71.89	71.12
TiO_2	0.13	0.14	0.12	0.17	0.15	0.08	0.12	0.45	0.16	0.15	0.64	0.33	0.09	0.08	0.39	0.42
Al_2O_3	17.10	14.59	14.48	14.99	15.38	12.61	15.99	15.92	14.66	14.25	17.12	14.48	13.76	13.34	14.64	14.27
$Fe_2O_3^t$	1.58	0.70	1.20	1.31	1.40	2.46	0.85	2.68	1.25	0.87	5.01	2.74	0.89	0.74	1.06	0.89
MnO	0.00	0.02	0.04	0.03	0.04	0.04	0.03	0.06	0.02	0.05	0.17	0.06	0.02	0.02	0.03	0.03
MgO	0.10	0.15	0.11	0.26	0.09	0.81	0.41	0.94	0.25	0.20	1.09	1.68	0.12	0.14	0.44	0.55
CaO	0.98	1.33	1.17	1.53	0.65	3.86	1.77	3.01	1.74	4.16	4.87	4.03	0.92	1.09	2.27	3.04
Na_2O	2.00	4.51	4.85	5.00	4.76	3.86	3.25	3.73	4.48	4.08	4.76	4.03	4.46	3.58	4.13	3.12
K_2O	4.01	3.76	3.77	3.31	5.11	3.87	5.50	3.07	3.13	3.67	3.53	2.11	4.02	4.76	3.80	4.30
P_2O_5	n.d.	0.04	0.04	0.05	0.04	n.d.	0.04	0.17	0.05	0.19	0.29	0.22	0.03	0.03	0.24	0.18
LOI	0.56	0.44	0.59	0.72	0.56	0.16	3.65	1.07	0.44	0.85	1.66	0.67	0.48	0.78	0.84	1.58
total	99.64	99.17	99.78	99.63	99.31	99.92	99.5	99.25	99.59	99.57	99.13	100.84	99.42	97.29	99.73	99.5
Ba	2478	1840	1577	2166	2785	1093	3832	1533	1843	1426	2170	723	1895	2472	960	2641
Rb	117	117	94.4	80.9	127.4	124	96.3	83.8	96.3	93.2	94.6	75.2	106.2	102.8	136.8	88.2
Sr	1254	800	947	994	1116	422	603	1751	890	637	2175	289	586	460	564.6	673
Cs	2.6	2	0.7	0.6	0.8	1.6	1	3.2	2	1.7	1	1.9	0.7	1.3	2.7	3.6
Ga	17.9	19.9	19.9	19.6	18.1	17.8	21.7	22.6	17.9	20.4	23	18	19.8	15.3	21.1	16.7
Ta	0.3	0.2	0.4	0.3	0.7	0.4	0.4	0.5	0.3	0.3	1.5	0.6	0.2	0.2	0.7	0.1
Nb	4.6	4.2	6.2	5.8	15.6	4.1	11.2	7.3	4.7	4.6	22.8	8.8	4.6	2.9	7.7	2.6
Hf	2.9	3	3.1	4.1	5.8	2.3	2	4.8	3.2	4.2	7.3	8	2.8	1.7	3.5	4
Zr	106	97.2	105	138.6	233	55.5	60.1	158	103	115	316	272	71	43.5	112	152
Y	6.2	4.8	16.7	9.7	10.1	8.8	13.7	10.5	5.6	7.1	60.6	16	4.9	6.1	11.6	6.3
Th	12	11.4	14.2	14.8	45.1	8.9	15	13.4	8.2	22.2	28.3	19.5	10.5	10.3	19.2	31.3
U	9.2	2.1	3.4	2.9	4.6	1.5	5.8	2.3	1.5	3.2	5.3	2.8	4	1.1	5.9	1
Co	0.25	0.25	0.25	0.25	0.25	0.25	0.25	5	0.25	0.6	5.1	2	0.25	0.5	0.6	1.2
V	7	11	12	12	17	2.5	12	50	12	2.5	97	17	10	12	11	11
Pb	n.d.	69	62	50	77	n.d.	n.d.	n.d.	56	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sn	2	2	3	3	3	2	2	2	2	2	4	4	2	2	2	2
W	0.2	0.3	0.2	0.1	0.3	0.4	0.6	0.2	0.4	0.2	0.4	0.9	0.2	0.4	0.3	0.7
La	19.6	9.9	30	38.9	38	15.8	55.1	33.4	9.6	40.4	87.7	47.6	15.7	17.8	41.2	86
Ce	35.4	17.9	53.2	70	91.1	28.6	106.9	66.8	17.1	70.4	193.9	89.5	25.8	35.3	74.5	149.6
Pr	3.5	2.14	6.38	7.82	7.03	3.02	11.65	7.78	1.88	6.92	23.5	9.68	3.71	3.87	7.35	13.81
Nd	12.3	8.1	24.1	26.8	23.4	12	43.4	29.9	6.9	22.2	94.8	34.3	14	13.7	25.5	43.7
Sm	2	1.74	3.86	3.7	3.37	2.3	5.72	4.38	0.98	4.2	16.01	6.8	2.31	2.31	4.4	5.6
Eu	0.65	0.62	0.93	0.82	0.73	0.59	1.27	1.14	0.43	0.94	3.95	1.02	0.54	0.69	0.77	1.27
Gd	1.38	1.09	3.01	2.42	2.21	1.63	3.67	2.86	0.75	2.36	13.32	4.63	1.47	1.68	3.18	2.3
Tb	0.17	0.17	0.48	0.36	0.36	0.25	0.55	0.41	0.12	0.34	2.12	0.7	0.21	0.26	0.45	0.32
Dy	0.91	0.74	2.06	1.57	1.83	1.58	2.36	1.86	0.7	1.54	9.64	3.49	0.89	1.11	2.22	1.3
Ho	0.16	0.12	0.36	0.24	0.29	0.27	0.41	0.32	0.16	0.25	1.75	0.55	0.16	0.2	0.36	0.21
Er	0.55	0.38	1.01	0.68	0.91	0.85	1.05	0.9	0.51	0.62	4.77	1.39	0.44	0.52	0.95	0.51
Tm	0.09	0.06	0.15	0.09	0.14	0.13	0.17	0.12	0.08	0.09	0.7	0.19	0.07	0.08	0.14	0.08
Yb	0.69	0.42	0.91	0.72	1.1	0.87	0.98	0.83	0.66	0.52	4.6	1.3	0.56	0.5	0.82	0.55
Lu	0.12	0.07	0.12	0.11	0.15	0.13	0.14	0.14	0.11	0.1	0.67	0.16	0.08	0.09	0.13	0.09

Major elements determined by wet silicate analysis, Chemical Laboratory at Sofia University "St. Kliment Ohridski"; major elements and Pb determined by XRF, Institute of Mineralogy and Petrology, University of Graz; trace elements and REE determined by ICP-MS, ACME Analytical Laboratories Ltd., Canada; n.d. = not determined. The whole rock samples (1–2.5 kg) were crushed and coned to 150 g, which were pulverized in an agate mill.

compared with bulk continental crust values (Rudnik, Gao, 2003). Crude positive correlations with Fe do not prove yet general magma differentiation in the Madan unit granite suite.

Incompatible LIL elements are higher than average continental crust values with remarkable enrichment of Ba and Sr up to 3800 and 2200 ppm respectively. The Smilyan granite Rb/Sr ratios display a negative correlation with Ba contents overlapping the CRD core anatectic granite field (Fig. 3). The Rb/Sr and Rb/Ba ratios of the smaller granite bodies do not show systematic changes and most of them correspond with the unfractionated anatectic melts of the CRD core (Cherneva, Georgieva, 2005). These features indicate a dominant role of feldspar melting in granite magma origin and limited LILE fractionation during magma evolution (Fig. 3).

REE patterns give reasons for analogy with the anatectic melts as well. The uniform Smilyan granite REE-patterns coincide with the CRD core anatectic granite field (Fig. 4a), showing high LREE/HREE ratio and negligible Eu-anomaly close to 1 (Eu/Eu*=0.82–1.38). Significant variation in total REE contents, LREE/HREE ratios, and Eu-anomaly values (Eu/Eu* = 0.56–1.53) is typical for the synkinematic granites (Fig. 4b). The Eu-anomaly values display negative correlation with the total REE contents emphasizing the role of the accessory minerals (allanite mainly). The REE variation could be referred to host rocks contamination or differences in the magma source compositions and P–T conditions of melt generation.

HFSE contents in the most widespread leucogranites are close to or lower than the average continental crust values. Yet again some of the syn-kinematic granite bodies are distinguished with HFSE enrichment and higher Zr/Hf and Nb/Ta ratio values. In spite of above mentioned differences, all the Madan unit granites have low contents of HFSE and insufficient contents of Rb to plot in the field of the syn-collision granites (Fig. 5a, b). Instead they plot in volcanic-arc and late or post-collision granites field (Fig. 5c) like the CRD core anatectic granites (Cherneva, Georgieva, 2005).

Discussion

Summarized geochemical features of the Madan unit syn- and post-kinematic granites indicate a dominant role of granite magma generation due to low temperature crustal melting involving quartz and feldspars mainly with limited participation of mafic and accessory minerals of the substratum. Similarly to the CRD core anatectic melts these have felsic peraluminous compositions, high LILE/HFSE and

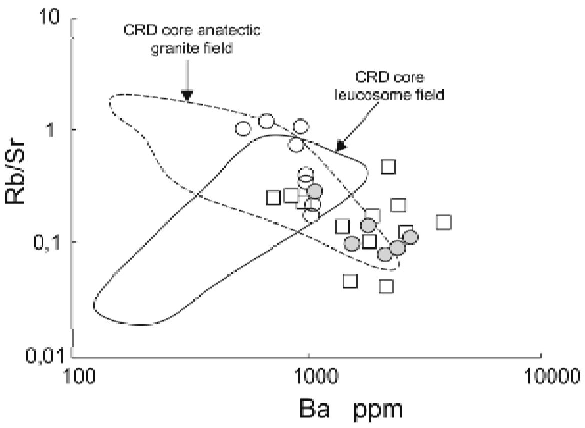

Fig. 3. LILE distribution of granites studied compared with leucosomes and anatectic granites from the CRD core. Symbols as on Fig. 2

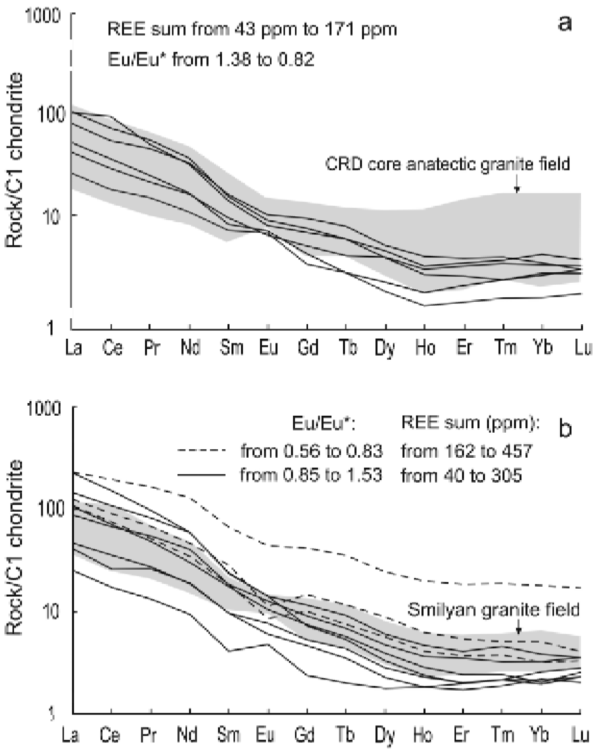

Fig. 4. Chondrite-normalized REE patterns: a) Smilyan granite; b) small granite and aplite-pegmatite bodies and veins

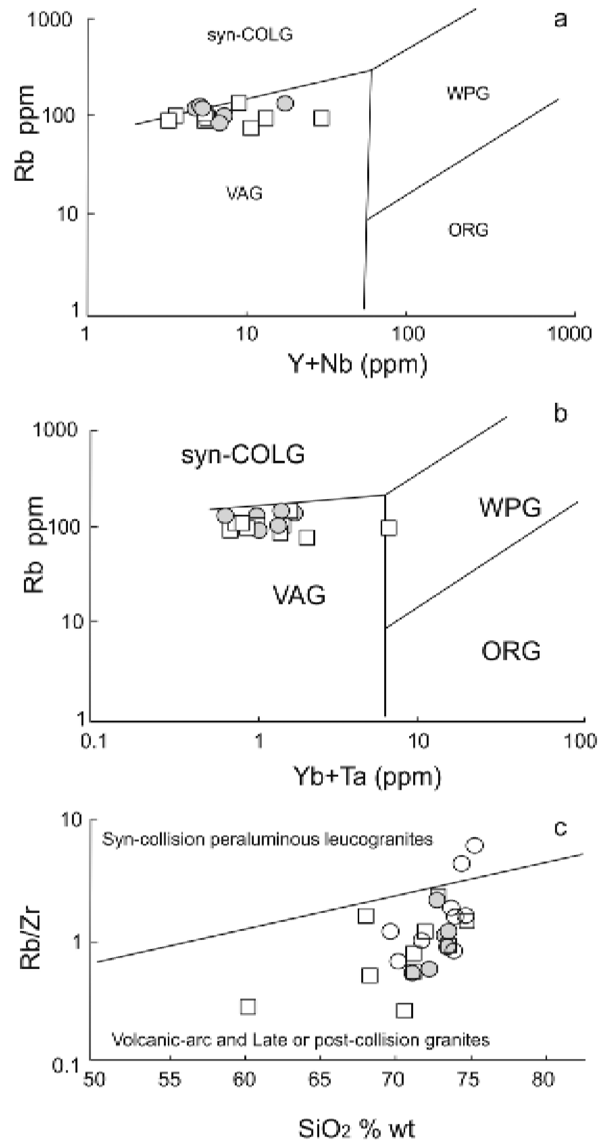

Fig. 5. Trace elements discrimination diagrams: a) and b) after Pearce et al. (1984); c) after Harris et al. (1986). Symbols as on Fig. 2

LREE/HREE ratios and negligible Eu-anomaly. The latter considered together with the lack of fractionation trends in major and HFS elements suggest a short distance of granite magma migration after melting like the autochtonous anatectic granites in the CRD core.

The geochronological data however do not support direct feedback relations between CRD core anatectic melts and Madan unit granite bodies because of different time of crystallization (37–38 Ma for the CRD core and 43 Ma for the Madan unit Smilyan granite). The isotope εHf_t signatures of dated zircons (–6.6 for the CRD core melts and +0.1 to +2 for the Smilyan granite) suggest source compositional differences. The syn-kinematic granites in the Madan unit are supposed to be even older than the Smilyan one, and contemporaneous with the strike-slip deformation that controlled their emplacement. Some of the syn-kinematic granites deviate from the above summarized geochemical characteristics. They have metaluminous compositions, REE and HFSE enrichment and variable trace elements fractionation patterns. Combined, these features support an idea of separate partial melt batches from different precursor compositions and probably variable proportions of residual phase inheritance or contamination.

We infer that migmatite-granite connection is manifested by a common process of protracted Tertiary crustal melting that operated during CRD evolution to produce discrete portions of granite melts. The transfer and emplacement of the latter started before the final crystallization of the CRD core migmatites (37–38 Ma). The time span of granite emplacement into the intermediate and upper CRD trust sheets (43–53 Ma, Ovtcharova et al, 2003a, and b) corroborates this interpretation. Major and trace elements geochemistry reveals potential lines of descent amongst groups of spatially related granitic rocks due to the same mechanism of melt generation.

Conclusions

The majority of Madan unit granites (the post-kinematic Smilyan pluton and smaller syn-kinematic leucogranite bodies) are geochemicaly similar to autochthonous anatectic granites from the core of the Central Rhodopian Dome (Arda unit). The nature of migmatite-granite connection is dominated by identical mechanisms of low-temperature fluid-present granite melt generation. The process of Tertiary crustal melting operated during Central Rhodopian Dome evolution and produced discrete melt portions, which geochemistry maintain record of precursor compositions and melt generation mechanism.

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Е. Раева, З. Чернева – Геохимия на връзката мигматити-гранити: един случай от Централните Родопи, България. Екстензионният етап от алпийската еволюция на Родопския масив е съпроводен с корово топене и интрузивен гранитен магматизъм. Геохимията на гранити с различно структурно положение и време на кристализация може да даде информация за веществените и темпорални отношения между процесите на анатектична мигматизация и генериране на гранитни магми. Изследвани са посткинематичният Смилянски плутон и малки синкинематични гранитни тела, внедрени в метатекситовите гнайси на Маданската тектонска единица от югозападната периферия на метаморфен ядрен комплекс (Централнородопска подутина). Най-типичните геохимични характеристики на изследваните гранити от Маданската единица показват сходство с анатектичните топилки от диатекситовото ядро (Ардинска единица) на метаморфния ядрен комплекс: левкократен, пералуминиев състав; ниско съдържание на HFSE и REE; високи съдържания на LIL елементи; високи LREE/HREE отношения; незначителна до положителна Eu-аномалия. Някои отклонения от тези характеристики, установени в синкинематичните гранитни тела (металуминиев състав, обогатяване с REE и HFSE, вариация на LREE/HREE и Eu/Eu*) подкрепят идеята за изолирани порции топилка, образувани от различни субстрати. Съществуващите данни за възрастта (37–38 Ма за анатектичните топилки от ядрото на комплекса и 43 Ма за Смилянския гранит) изключват пряко подхранване на интрузивния гранитен магматизъм в Маданската единица от топилки, генерирани в Ардинската единица. Връзката между мигматизация и гранитообразуване се разглежда като проява на общ процес на терциерно корово топене, действал по време на развитието на Централнородопската подутина, засегнал различни корови субстрати с образуване на изолирани порции гранитни топилки. Геохимичните характеристики разкриват възможно родство между пространствено свързани гранити, основано на еднакъв механизъм на генериране на гранитната магма.