PETROGRAPHIC AND GEOCHEMICAL STUDY OF MAFIC DYKES IN APUSENI, POIANA RUSCĂ, AND BANAT (ROMANIA); ARE ALL ASSOCIATED TO THE UPPER CRETACEOUS BANATITIC MAGMATISM IN ROMANIA?

MIHAI TATU[1], ELENA-LUISA IATAN-CODREAN[1], VIOREL MIREA[1], IOAN SEGHEDI[1*]

[1] "Sabba S. Ştefănescu" Institute of Geodynamics, Romanian Academy, 020032 Bucharest, Romania,
E-mail:luisa.iatan@geodin.ro ORCID ID: 0000-0001-6895-0887; E-mail: vmirea@geodin.ro
ORCID ID: 0000-0002-4671-7889; E-mail: seghedi@geodin.ro, ORCID ID: 0000-0001-7381-7802.
[*] Corresponding author

Abstract. Apuseni-Banat-Timok-Srednogorie Belt (ABTS) is a complex calc-alkaline magmatic system that formed during the Late Cretaceous period. This belt runs across southeastern Europe, with a north-south orientation in Romania and Serbia and an east-west orientation in Bulgaria, reaching the Black Sea. A large volume of these dominantly calc-alkaline rock association crops out in Romania and is represented by volcanic, subvolcanic and plutonic intrusions and in a late stage by mafic dykes.
This research is focused on the mafic dykes of assumed Upper Cretaceous/Paleogene age occurring sporadically and intruding Banatitic subvolcanic/plutonic bodies, metamorphic or sedimentary rocks in the Banat and Apuseni areas. They have been termed before as lamprophyres, however, never properly documented. This is the first dedicated geochemical study on the mafic dykes associated with Banatitic magmatism. The study reveals the presence of two types: calc-alkaline, plotting in basaltic and basaltic andesite fields and alkaline rocks showing two different compositions: alkali basalt and basanite. With the exception of the alkali basaltic dykes that suggest being older (Lower Mesozoic), all the other are following the Banatitic magmatic activity in the studied areas. The calc-alkaline mafic dykes were generated after ~0.5-1 Myr and the basanite dykes during Paleogene times. The calc-alkaline mafic dykes resulted probably by melting of residual metasomatized subcontinental lithospheric mantle (SCLM) with minor contributions with melts of asthenospheric geochemical affinities. The alkaline mafic dykes require an asthenospheric source and generation through an extension condition.

Keywords: Upper Cretaceous/Paleogene, mafic dykes, calc-alkaline, alkaline, Banatites, Apuseni-Banat.

Résumé: La ceinture Apuseni–Banat–Timok–Srednogorie (ABTS) est un système magmatique calco-alcalin complexe formé durant le Crétacé supérieur. Cette ceinture traverse le sud-est de l'Europe, avec une orientation nord-sud en Roumanie et en Serbie, et est-ouest en Bulgarie, jusqu'à la mer Noire. Un grand volume de ces roches principalement calco-alcalines affleure en Roumanie et se compose d'intrusions volcaniques, subvolcaniques et plutoniques, auxquelles s'ajoutent, à un stade tardif, des dykes mafiques.
Cette recherche porte sur les dykes mafiques d'âge supposé Crétacé supérieur / Paléogène, apparaissant de manière sporadique et recoupant les corps subvolcaniques/plutoniques banatitiques, ainsi que les roches métamorphiques ou sédimentaires des régions du Banat et des Apuseni. Ces dykes ont auparavant été désignés comme lamprophyres, sans avoir toutefois été correctement documentés. Il s'agit de la première étude géochimique dédiée aux dykes mafiques associés au magmatisme banatitique. L'étude met en évidence la présence de deux types : calco-alcalin, se plaçant dans les champs des basaltes et basaltes andésitiques, et alcalin, présentant deux compositions distinctes : basalte alcalin et basanite. À l'exception des dykes basaltiques alcalins, qui semblent plus anciens (Mésozoïque inférieur), tous les autres sont postérieurs à l'activité magmatique banatitique dans les zones étudiées. Les dykes mafiques calco-alcalins se seraient formés environ 0,5 à 1 million d'années après celle-ci, tandis que les dykes de basanite datent du

Paléogène. Les dykes calco-alcalins mafiques résultent probablement de la fusion partielle d'un manteau lithosphérique subcontinental métasomatisé (SCLM), avec de faibles contributions de magmas d'affinité asthénosphérique. Les dykes mafiques alcalins, quant à eux, nécessitent une source asthénosphérique et une genèse dans un contexte extensif.

Mots-clés: Crétacé supérieur/Paléogène, dykes mafiques, calco-alcalin, alcalin, Banatites, Apuseni–Banat.

1. INTRODUCTION

The Apuseni-Banat-Timok-Srednogorie belt (ABTS) extends over a vast distance of approximately 1,500 kilometers with a width of 30 to 70 km, traversing territories of Romania, Serbia, and Bulgaria and is represented by complex calc-alkaline magmatic rocks that emerged during the Late Cretaceous period (Fig. 1). This expansive ABTS belt stretches across southeastern-central Europe, characterized by a predominant north-south orientation as it traverses the territory of Romania, extending into Serbia, and an east-west-oriented configuration as it courses through the terrain of Bulgaria, reaching the shores of the Black Sea (Berza *et al.*, 1998; Popov *et al.*, 2002; Gallhofer, 2015).

The recognition of these igneous rocks dates back to the 19th century, with the pioneering work of Bernhard von Cotta in 1864. He is credited as the first geologist to systematically describe a suite of cogenetic magmatic rocks that were observed in the form of volcanic rocks, shallow intrusions or subvolcanic and plutonic bodies.

As evident from von Cotta's original documentation, the term "Banatites" distinctly highlights their "locus tipicus" – the Banat region, which encompasses portions of southwestern Romania and northeast Serbia. Since their initial characterization, the Banatites have garnered significant attention, with intensified focus directed towards their petrology, age determination, structural-tectonic implications, and their associations with various ore deposits: skarn (Fe, Cu, Zn-Pb), porphyry-copper (Cu±Mo±Au), and epithermal (Cu–Au–Ag) (Cioflica and Vlad, 1973; Ciobanu *et al.*, 2002; Ilinca *et al.*, 2011; Berza *et al.*, 1998; Vlad, 2020).

ABTS belt (Fig. 1) is subdivided into five distinct parts: (1) the Apuseni, (2) the Banat, (3) the Timok, (4) the Panagyurishte, and (5) the Eastern Srednogorie. Each of these segments is characterized by specific magmatic and metallogenic features (e.g., Gallhofer, 2015).

The current orientation results from an 80° clockwise rotation of the Tisza – Dacia Megaunit during the Cenozoic (Panaiotu, 1998), shifting the Apuseni–Banat segment from an initial east-west configuration to a north-south one (e.g., Vander Auwera *et al.*, 2015).

Gallhofer (2015) integrated U-Pb zircon ages and geochemical whole rock data for Banat and Apuseni (Romania) with previously published data to reconstruct the magmatic evolution and refine its tectonic development. The trace elements and isotopic signatures of these magmas suggest a subduction-enriched mantle source across all segments, with varying degrees of contamination from continental crust. The magmatic activity is attributed to the Campanian subdivision of Upper Cretaceous between 81–75 Ma.

The primary objective of this research, as initially envisaged by the first author attempted to gain an additional petrographic and geochemical understanding of the Upper Cretaceous volcanic and subvolcanic/plutonic rocks in Banat and Apuseni areas, other than already sampled and published recently by the previous authors (e.g., Gallhofer, 2015; Vander Auwera *et al.*, 2015). The additional petrographic and geochemical data, as a result of this new collection, even from locations that were not yet sampled, are not different from the already published ones, and besides, the new data are missing isotope compositions.

Though during the field study, another target of our colleague (M.T.) was to collect samples from mafic dykes, both in Banat and Apuseni areas. With this occasion resulted a reasonable collection of mafic dyke samples, considered by himself and previous authors as lamprophyres (e.g., Ştefan *et al.*, 1992; Gallhofer, 2015). Such rocks have never been particularly well documented from a petrographic or geochemical point of view. In the following article, we aim to address this issue by presenting an original study. We hope that our work will make a significant contribution to understanding of mafic dikes at the end of Upper Cretaceous Banatitic magmatism.

2. REGIONAL GEOLOGICAL SETTING

The Apuseni Mountains, Poiana Ruscă and Banat districts (in Romania) are the northernmost segments of the Apuseni-Banat-Timok-Srednogorie Belt (ABTS) (Fig. 1; e.g., Ciobanu *et al.*, 2002).

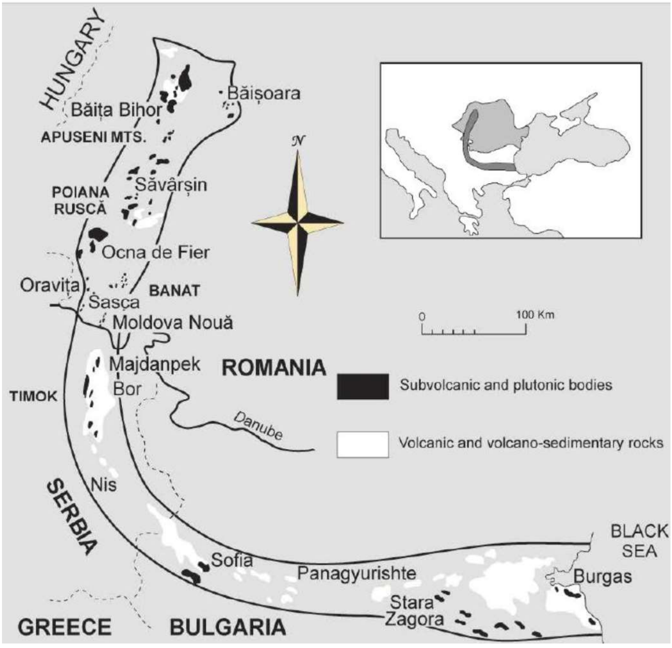

Figure 1. The Apuseni-Banat-Timok-Srednogorie Belt (ABTS) across Romania, Eastern Serbia, and Bulgaria (shown in dark gray in the inset and in bold outline on the map). After Ilinca *et al.* (2011), simplified after Cioflica and Vlad (1973).

The Apuseni Mountains are an internal mountain range between the Carpathians and the Dinarides. They belong to the tectonic Megablock of Tisia (or Tisza), and include the Jurassic ophiolitic zone of Mureș that is assimilated to the East Vardar zone. The northern slopes are characterized by a sequence of metamorphic basement tectonic nappes that underwent deformation during the Variscan orogeny, subsequently overlain by Permian-Cretaceous sediments (Pană *et al.*, 2002; Balintoni *et al.*, 2009). The southern Middle Jurassic ophiolitic sequence is traversed and overlain by Upper Jurassic calc-alkaline igneous rocks and Upper Jurassic-Lower Cretaceous sedimentary deposits trapped in north-facing tectonic nappes (Bortolotti *et al.*, 2004; Nicolae and Saccani, 2003; Gallhofer *et al.*, 2015; Seghedi, 2024).

In the Apuseni Mountains, the most northern occurrence of banatitic rocks in Romania (Fig. 2), the Banatites occur both as volcanics associated to Gosau-type basins, as mafic dyke swarms or major plutonic intrusions (e.g., Ilinca *et al.*, 2011).

Ştefan (1980), Ştefan *et al.* (1982, 1992), and Istrate (1978) have carried out detailed mapping of the Late Cretaceous magmatic rock outcropping in the Apuseni Mountains. Several types of volcanic rocks, ranging from andesites to dacites and rhyolites were identified by these researchers. The intrusive rocks mainly consist of granodiorite, but quartz diorites, quartz monzodiorites, and granites are also widespread (e.g., Ştefan *et al.*, 1992).

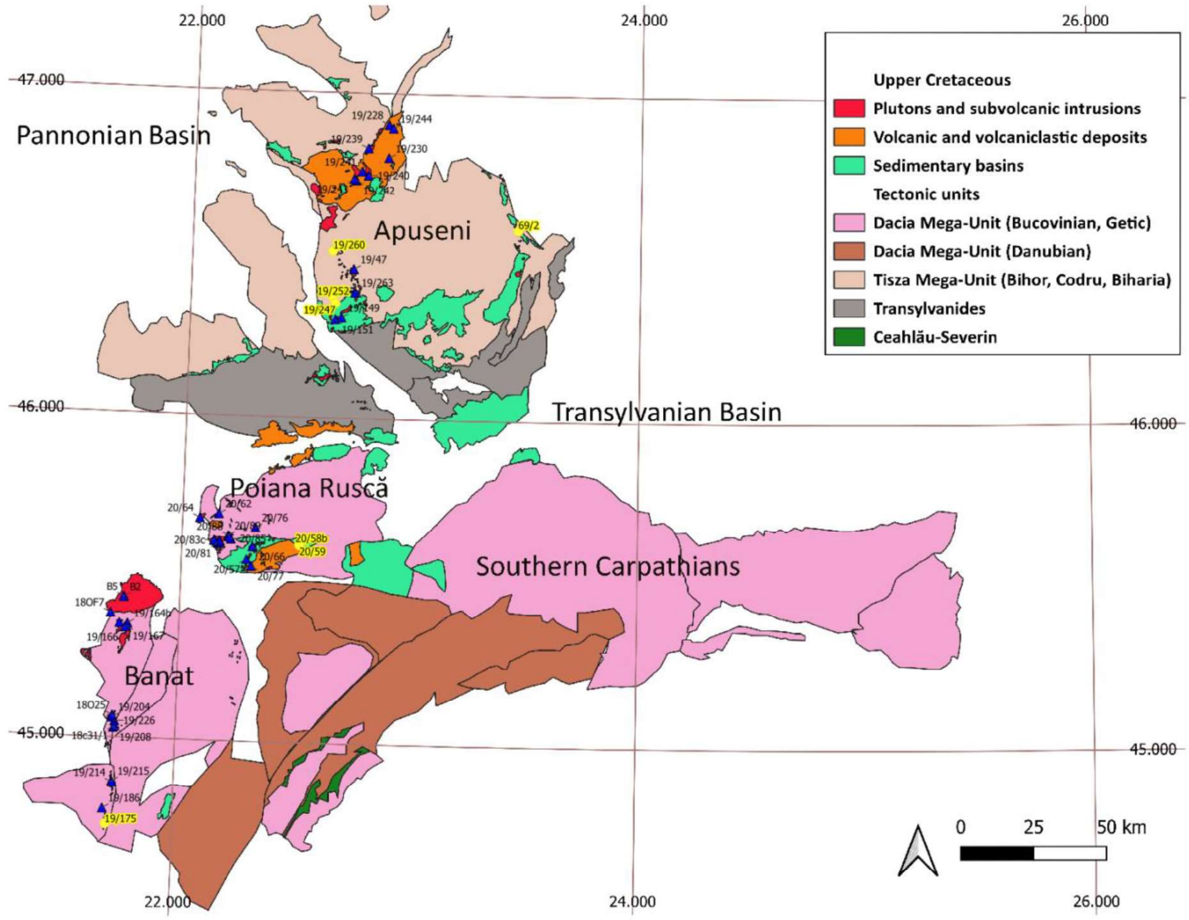

Figure 2. Distribution of banatitic rocks in Apuseni Mts, Poiana Ruscă and Banat area (modified after Geological map 1.200.000 of Geological Institute of Romania). Sample name and sample locations collected in this study are shown in yellow circles for mafic dykes and with blue triangles for all other calc-alkaline rocks.

The Banat and Poiana Rusca areas belong to the tectonic Megablock of Dacia. Here, Late Cretaceous magmatic rocks are present within both the upper (Supragetic and Getic) and lower (Danubian) tectonic units of the basement nappes (Fig. 2). The intrusive rocks are predominantly consisting of diorite and granodiorite, along with various volcanic rocks, andesites, dacites, and rhyolites associated with Gosau basins (Cioflica *et al.*, 1994; Russo-Săndulescu *et al.*, 1978, 1986a, 1986b; Gheorghiţescu, 1975; Constantinescu, 1977; Gheorghiţă, 1975; Vornicu and Seghedi, 2025). Basanite Paleogene dykes have been located in Supragetic Nappes in Poiana Ruscă Mts. (Kräutner *et al.*, 1986; Downes *et al.*, 1995; Tscheg *et al.*, 2010).

3. SAMPLES SELECTION AND ANALYTICAL METHODS

In order to offer a geochemical record that is characteristic of the region, our colleague (MT) collected over 100 samples of Late Cretaceous igneous rocks from various sites in the Apuseni and Banat Mountains. The locations of the analysed collected samples are shown in Figure 2 and GPS coordinates and name of location in Supplementary Table A[1].

All samples were sectioned and examined under an optical microscope (Olympus BX41 TF microscope – Olympus Corporation, Tokyo, Japan) to assess their degree of alteration, selecting petrographically less altered specimens for further study. A total of 54 representative samples were selected and analyzed for geochemical analysis (Supplementary Table A).

In this study we selected 14 samples, the most primitive ones, representing 9 mafic dykes and 5 calc-alkaline gabbros/microgabbros. In our diagrams we also used the basic rocks from Gallhofer *et al.*, (2015) (one mafic dyke considered as lamprophyre and 3 gabbros) and Vander Auwera *et al.* (2015) (2 gabbros) for comparison reasons (Supplementary Table B). According to our observations, most of the mafic dykes studied samples suffered various slight to extensive post-emplacement alteration that caused various mineralogical changes, manifested by growth of secondary phases and, in some cases, by obliteration of the original magmatic paragenesis (see Petrography).

Whole-rock major and trace element compositions were analyzed by ALS Geochemistry (*http://www.alsglobal.com/geochemistry*) following standard laboratory protocols. Powdered samples were submitted to lithium borate fusion followed by acid dissolution and then analyzed using inductively coupled plasma-atomic emission spectrometry (ICP-AES) for major elements (ALS code ME-ICP06) and inductively coupled plasma-mass spectrometry (ICP-MS) for trace elements including rare-earth elements (ALS codes ME-MS42, ME-MS61, ME-MS81). Weight loss on ignition (LOI) was determined gravimetrically after heating the rock powders to ~1000°C using a thermogravimetric analyzer (TGA) (ALS code OA-GRA05).

4. RESULTS

4.1. CLASSIFICATION AND PETROGRAPHY

4.1.1. Classification

Whole-rock major and trace element results were used to characterize the rocks in various classification diagrams. However, before displaying classic nomenclature diagram we checked if from the petrographic and geochemical point of view our mafic dyke rocks can be classified as lamprophyres, as it was suggested up to now (Ştefan *et al.*,1992; Gallhofer *et al.*, 2015).

According to Woolley *et al.*, (1996), lamprophyres are mesocratic to melanocratic igneous rocks, usually as dykes, with a panidiomorphic texture and abundant mafic phenocrysts of phlogopite/biotite, amphibole, clinopyroxene, olivine and occasionally melilite. Feldspars and feldspathoids may occur as groundmass minerals, but not as phenocrysts. These rocks have relatively higher concentration of P_2O_5, S, CO_2, K_2O, Na_2O, H_2O and Ba than igneous rocks with the same SiO_2 content. Lamprophyres also include carbonate minerals, apatite and zeolites. Plagioclase-bearing lamprophyres: spessartites (hornblede and plagioclase) kersantite (biotite and plagioclase) and camptonites (sodic amphibole, clinopyroxene and plagioclase) have plagioclase always in a fine-grained groundmass.

In the following, our dyke rock petrography and geochemistry do not correspond to a lamprophyre nomenclature, since the rocks have always plagioclase phenocrysts and lack an abundant

[1] Editor's note: For Supplementary data please consult the web version of the paper on the journal site: *https://acad.ro/RevueRoumaineGeologie.htm*

presence of hydrated minerals (amphibole, biotite) and, as well, show lower concentration of P_2O_5, K_2O, Na_2O and LILE elements. This is the reason we will consider in the following our rocks as mafic dykes.

Whole-rock major data plotted in TAS diagram (Fig. 3a) reveal that with the exception of the low SiO_2 rocks (basanites) all the other rocks cover the basaltic, basaltic andesitic or basaltic trachy-andesite fields, regardless of whether they are calc-alkaline basalts/gabbros or alkali basalt. Plotting data in Zr/TiO_2 vs. Nb/Y diagram (Fig. 3b) reveals a clear separation between calc-alkaline rocks and alkaline ones. However, there is not evident any distinction between banatitic calc-alkaline basalts/gabbros and calc-alkaline mafic dykes using these classification diagrams, other than the mafic dykes show a lower total Na_2O+K_2O %.

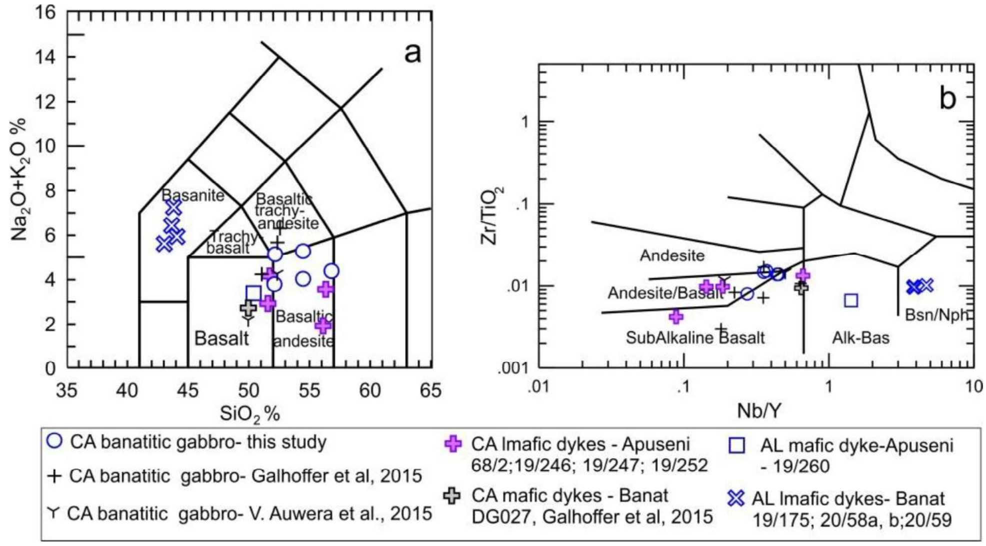

Figure 3. a. Total alkali vs. silica (wt%) (TAS) (Le Maitre, 1989), and b. Zr/TiO_2 vs. Nb/Y diagram (Winchester and Floyd., 1977); CA-calc-alkaline; AL-alkaline.

4.1.2. Petrography

The calc-alkaline basaltic and basaltic andesite mafic dykes (samples 69/2, 19/246, 19/247. 19/252 from Apuseni Mts.) show a porphyritic texture and heavy alteration with phenocrysts of albitized plagioclase, with amphiboles and pyroxene replaced by chlorite and carbonates in a devitrified groundmass, sometimes with secondary carbonates (Fig. 5a1-PL, a2_PP).

The alkali basalt mafic dyke is a unique occurrence (sample 19/260 from Apuseni Mountains; Figs. 3 and 4) showing individual crystals of iddingsite olivine, clinopyroxene and mafic minerals filling the spaces (interstices) between lath-shaped crystals of plagioclase in an intergranular texture; (Fig 5 b1-PL; b2-PP).

The basanitic mafic dykes were found in the Upper Cretaceous Rusca Montană basin (samples 20/58a, 20/58b, 20/59) and in Banat at Moldova Nouă (sample 19/175) where crossing they cross Lower Cretaceous limestones. The rocks show a similar large porphyritic texture. The phenocrysts are plagioclase and rare olivine or clinopyroxene set in a very fine-grained largely developed groundmass. The groundmass minerals in basanites consist mainly of olivine, clinopyroxene, plagioclase and nepheline (Fig. 5c1-PL, c2-PP).

Figure 4. Alkali basaltic mafic dyke (sample 19/260) crossing Jurassic limestone (Vârtop, N46 30,742; E22 37,465), Apuseni Mts.

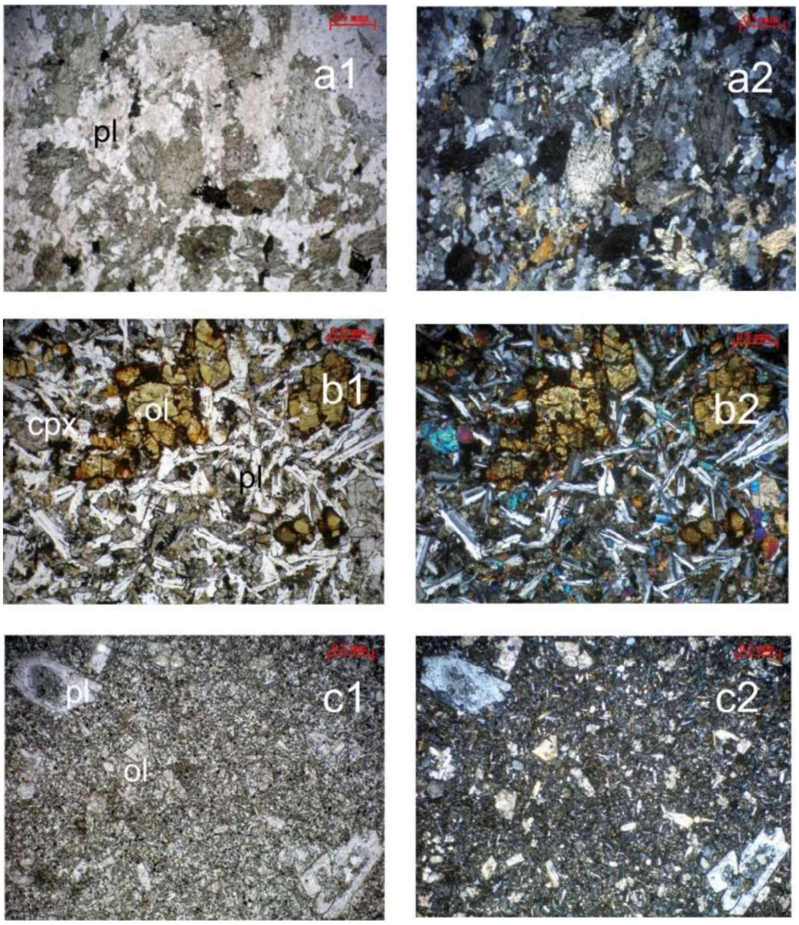

Figure 5. (a1-PL; a2-PP)- Calc-alkaline basaltic mafic dyke (sample 69/2) showing a porphyritic texture including altered plagioclase, pyroxenes and amphiboles in a devitrified groundmass; (b1-PL; b2-PP)- Alkali-basaltic mafic dyke (sample 19/260) showing an intergranular texture with individual grains of iddingsitized olivine, clinopyroxene and mafic minerals filling the spaces (interstices) between lath-shaped crystals of plagioclase; (c1-PL; c2-PP)- Basanitic mafic dyke (sample 20/58a) showing a porphyritic texture with rare plagioclase phenocrysts in a fine grain groundmass that includes olivine, clinopyroxene, feldspars and opaque minerals.

5. WHOLE-ROCK MAJOR, TRACE AND RARE-EARTH ELEMENT GEOCHEMISTRY

Whole-rock major and trace element concentrations of the analyzed samples are summarized in Supplementary Table B.

Taking into account that mafic dykes may represent small volumes of magma intruded in a complex tectonic setting, either secondary alteration or low-pressure crustal contamination might have played a role in their final geochemical and isotopic signatures. Such alterations should cause leaching of mobile elements (e.g., K, Rb and Ba) and an increase of LOI values. Additions of varying amounts of CaO also testify to the presence of secondary calcite. The examined mafic dykes show a wide range of LOI values, the highest being related to the mentioned secondary calcite or groundmass alteration (see petrography section) (Fig. 6). Such alterations seem to have an influence on the LILE contents, as suggested by K_2O and Rb content for samples with extremely variable LOI. This is the reason that geochemical considerations will be based only on ratios of HFSE immobile or less mobile elements.

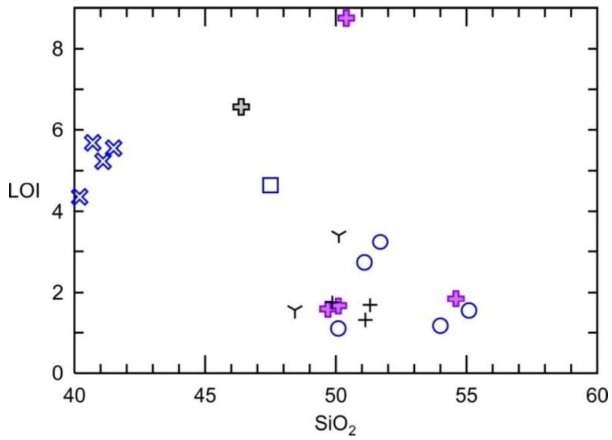

Figure 6. LOI vs. SiO_2 for the studied rocks. Symbols as in Fig. 3.

All discussed rocks have in general low MgO content with some exceptions. The mafic dykes show variable MgO content (4-9%), the highest belonging to the sample DG027 (12.39%) from Gallhofer *et al.*, (2015) (Fig. 7).

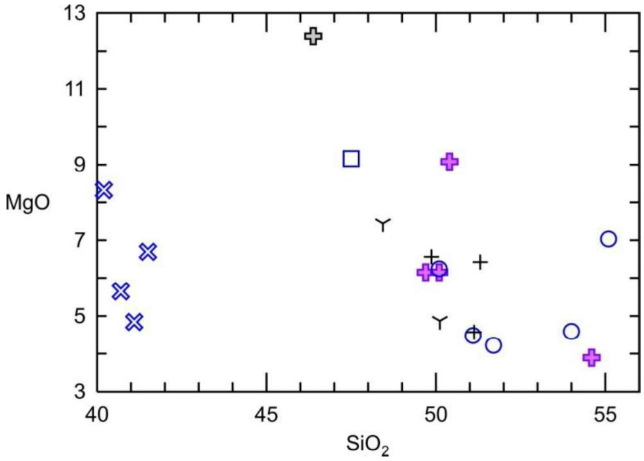

Figure 7. SiO_2 vs. MgO for the studied rocks. Symbols as in Fig. 3.

Compatible elements Ni and Cr for calc-alkaline mafic dykes show largely variable compositional ranges from 15 to 194 ppm and from 10 to 600 ppm, respectively; the same is for alkaline mafic dykes, in a range of 64 to 280 and from 70 to 420, respectively.

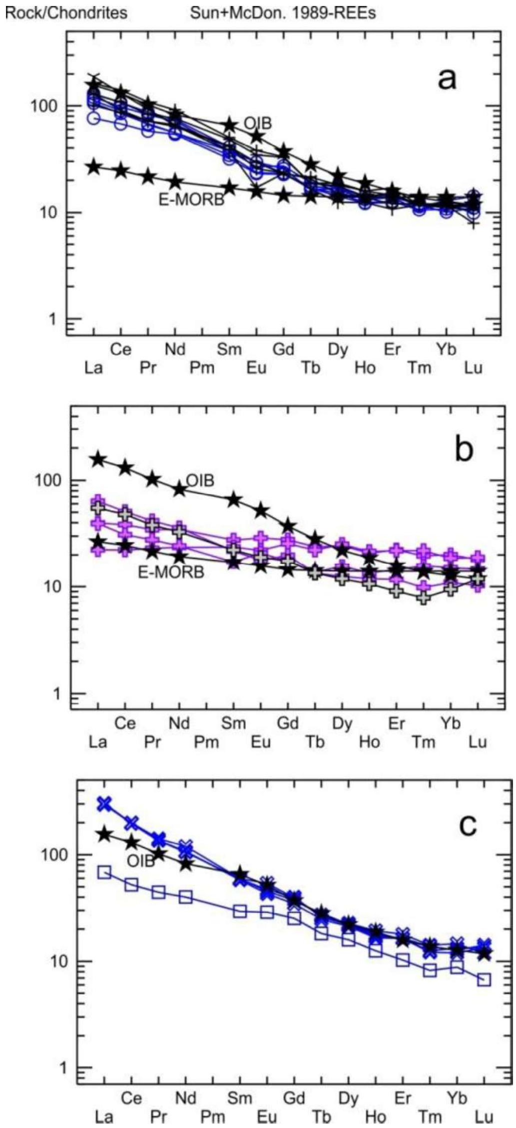

Figure 8. Chondrite CI-normalized REE patterns for the studied rocks.
(normalization values, OIB and E-MORB after Sun and McDonough, 1989). Symbols as in Fig. 3.

Chondrite-normalized REE patterns are making distinction between basic banatitic calc-alkaline rocks (BCA-Fig. 8a), calc-alkaline mafic dyke (CAMD-(Fig. 8b) and alkaline mafic dykes (Fig. 8c). The BCA show less variable contents, small Eu anomaly and a positive LREE (Fig. 8a). Calc-alkaline mafic dykes are more similar with E-MORB and show more variable content; however without any Eu anomaly and almost flat REE patterns (Fig. 8b); Calc-alkaline mafic dyke from Banat (Gallhofer *et al.*, 2015) is in the range of Apuseni mafic dykes, however is showing a small LREE augment, as well a small HREE depletion (Fig. 8b). The alkaline mafic dykes show very similar trends with OIB pattern

(Fig. 8c). The basanite mafic dykes (BAMD) show similar total REE as compared with OIB. Alkali basaltic mafic dykes (ABMD) show similar pattern as average OIB, with less total REE (Fig. 8c).

Primitive mantle-normalized incompatible element patterns (Fig. 9a, b, c) show some common features specific for each group. It is to be remarked a more evident Nb and Ta negative anomaly for BCA, less evident for CAMD due to the lower and variable LILE. In both cases there is an evident positive Pb anomaly. The basanite mafic dykes display a similar pattern as OIB with higher LILE and LREE. Alkali basaltic mafic dyke (ABMD) also displays a similar pattern, but below the average OIB trend, with a small positive Pb anomaly.

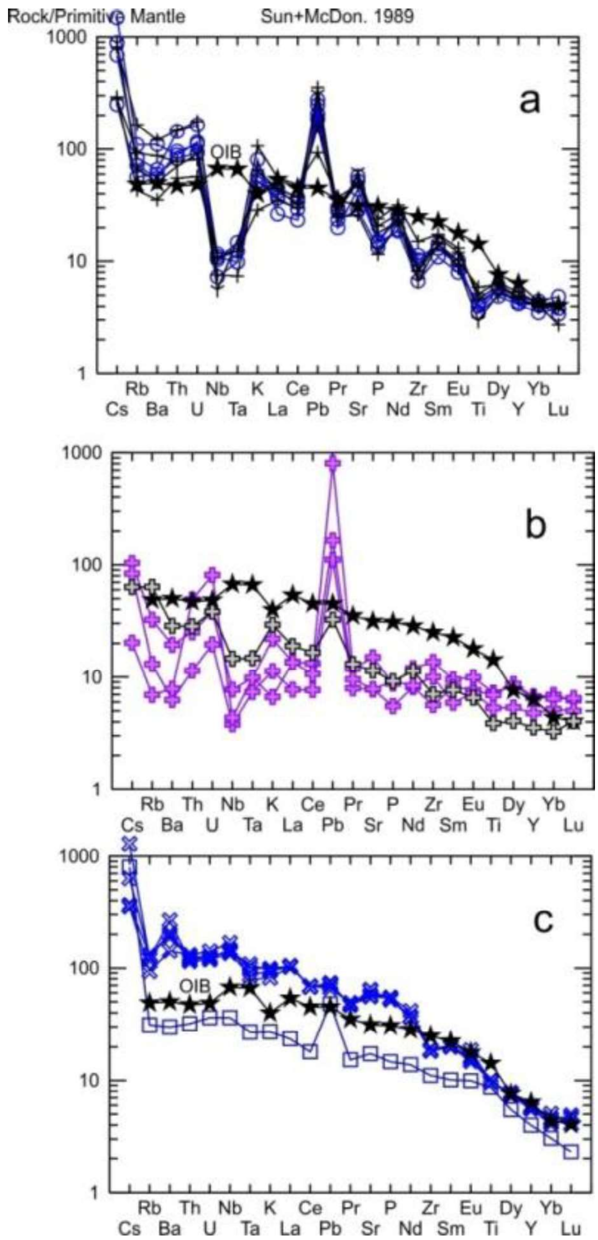

Figure 9 a, b, c. Primitive mantle normalized trace elements patterns for the studied rocks. (normalization values after Sun and McDonough, 1989). Symbols as in Fig. 3.

6. DISCUSSION

6.1. FRACTIONAL CRYSTALLIZATION AND CRUSTAL CONTAMINATION

Even the studied rocks can be considered as primitive, it is imperative to discuss if they have been affected by fractional crystallization and crustal contamination (in the absence of isotopic data). The exception is given by the sample DG027 in Gallhofer (2015). The Sr and Nd isotope data of this sample (0.704689; 0.512736) is not suggestive for the assimilation processes, and it was probably less affected by the fractionation processes. Ti and P depletion and enrichment of Th and LREEs can help to appreciate assimilation processes (Th is also considered a good proxy for the implication of subduction processes in the mantle; see Fig.11). Our mafic dykes have small P and Ti troughs on primitive mantle-normalized multi-element diagrams (Fig. 6) and considerably lower than the most primitive known banatitic calc-alkaline rocks (BCA). The confirmation is also given by the isotopic data of BCA rocks done by Gallhofer (2015) that suggest higher values for the Sr and lower for Nd isotopes than sample DG027 (e.g., DG 21, DG 24, see Supplementary table B), and suggesting insignificant assimilation processes. Th and La, as well, are lower for the CAMD and ABMD rocks, suggesting insignificant assimilation processes (Fig. 10a, b). Higher Th of BAMD may suggest assimilation, but as well fractionation processes, taking into account their low MgO values for assumed primitive rocks. ABMD and BAMD are in the line with MORB-E-MORB-OIB trend (Fig. 10 b).

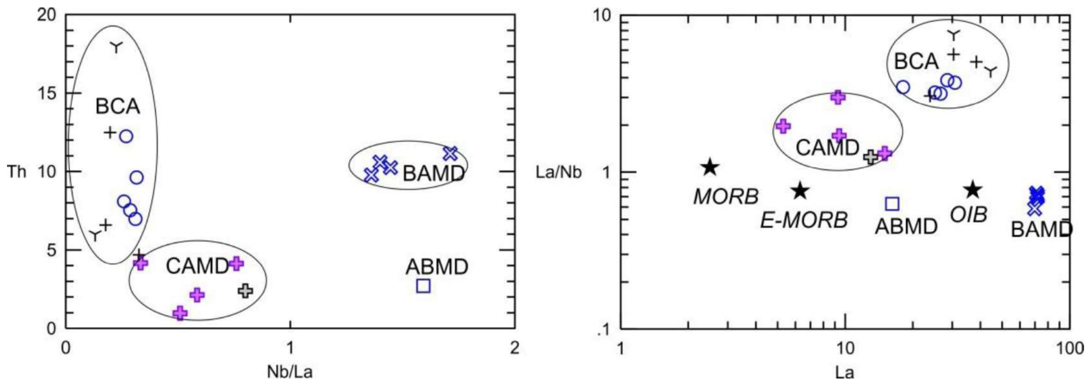

Figure 10. Nb/La vs Th and La Vs La/Nb for the studied rocks. Abbreviations: BAL-Basic calc-alkaline rocks; CAMD- calc-alkaline mafic dykes; ABMD- alkali basaltic mafic dykes; BAMD- basanite mafic dykes. Average MORB (Mid Oceanic Ridge Basalts), E-MORB- Enriched Mid Oceanic Ridge Basalts and OIB (Oceanic Island Basalts) composition is from Sun and McDonough, 1989. Symbols as in Fig. 3.

6.2. MANTLE SOURCE REGION AND SOURCE COMPONENTS

Depletion in LILE content in the calc-alkaline mafic dykes (CAMD) suggests a depleted mantle source that may signify a late episode of mantle partial melting after the generation of the calc-alkaline Banatites (BCA). This observation is further envisaged by the conspicuous negative HFSE anomalies, considered as a characteristic of subduction-related magmatism. HFSE/LREE is a proxy to identify the mantle source region and lower Nb/La (<1) of the CAMD is consistent with its provenance in the lithospheric mantle. On the other part the BAMD and ABMD suggest an OIB-like asthenospheric mantle origin by showing Nb/La > 1 (Fig. 10).

The evidence of subduction implication for CAMD and for BCA is revealed on the low Ce/Pb, and elevated Th/Yb vs Nb/Yb ratios (Fig. 11a), however along different trends and starting from different Th/Yb ratio, lower for CAMD. In the same time ABMD and BAMD plot along the mantle array proposing an asthenosphere mantle source. The La/Yb vs Nb/ La diagram (Fig. 11b; e.g., Abdel-

Rahman, 2002), useful for distinguishing mantle sources confirms the asthenosphere origin of the alkaline mafic dykes, however with higher La/Yb for the BAMD, suggesting a lower degree of melting. In the same time most of the CAMD rocks are plotting in a mixed mantle group, different from the banatitic BCA rocks that advise derivation from a metasomatized lithospheric mantle.

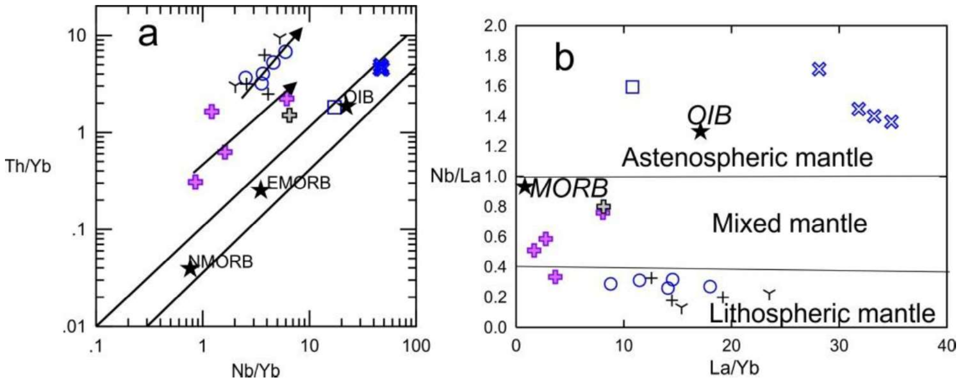

Figure 11. a. Nb/Yb vs. Th/Yb trace element ratio diagram (after Pearce, 2008) showing mantle array defined by MORBs and OIB; b. La/Yb vs Nb/ La trace element ratios for the studied rocks. Symbols as in Fig. 3.

6.3. REGIONAL IMPLICATIONS

The petrographic and geochemical data reveal similarities between Apuseni and Banat calc-alkaline mafic dykes. There are differences in the case of alkaline mafic dykes that can be explained by the different geotectonic basement of the two mentioned regions, as the Apuseni area belongs to Tisza (Tisia) Megaunit and Banat and Poiana Rusca to Dacia Megaunit, but also by different age of emplacement.

There is a single age determination for the mafic dykes and belongs to DG027 sample from Banat (Gallhofer, 2015). The measured zircon age of the dyke is 76.49 Ma and crosses a gabbro intrusion whose zircon age was determined at 77 Ma, suggesting at least 0.5 Ma between the two events.

In Apuseni area as a part of Tisza (Tisia) Megaunit the calc-alkaline mafic dyke that cross Upper Cretaceous sediments (sample 69/2) is very close to a dated diorite crossing, as well Upper Cretaceous Gosau type sediments (sample DG101) by Gallhofer (2015) whose zircon age is 77.4 Ma; this may propose a similar age difference interval as in Banat where the cutting mafic dyke show to be with ~0.5 Myr younger age than the host intrusion, but still Upper Cretaceous (Campanian) in age. The samples 19/246, 19/247 and 19/252 that are crossing Lower Cambrian metamorphic deposits of Biharia series (Balintoni, 1994) do not have any close-by banatitic rock age determination. Their relative age is difficult to be appreciated, however since these rocks show similar petrographic and geochemical characteristics with sample 69/2, for the moment, we indirectly consider them as post Banatite generated in Upper Cretaceous.

The basaltic alkaline mafic dyke (sample 19/260) is an unique occurrence in the Apuseni area that has not yet been revealed (Fig. 4). It is not possible to know without a doubt its relative age, so most probably it was generated much earlier than the Banatites, most probably during lower Mesozoic and obviously as post Jurassic since it cut Jurassic limestones. In Banat area, as part of Dacia Megaunit, we already discussed the calc-alkaline mafic dyke DG027 (Gallhofer *et al.*, 2015), as generated after large Banatite intrusion.

The basanites mafic dykes (BAMD) cutting Upper Cretaceous sediments and volcanoclastic deposits in Gosau type Ruscă Montana basin show similar petrographic and geochemical characteristics as numerous isolated basanites in Poiana Ruscă Mts. (Kräutner *et al.*, 1986; Downes *et* *al.*, 1995; Tschegg *et al.*, 2010), whose age is considered Paleogene according to K/Ar datings (Downes *et al.*, 1995). The rock/chondrite and primitive mantle diagrams of BAMD display a similar trend with basanites from Poiana Ruscă Mts. (Fig.13; Tschegg *et al.*, 2010) suggesting similar source and age of generation. It is envisaged an extension-related asthenospheric source. The generation and eruption of the melts was most probably facilitated by the post-collisional Paleogene extension processes in the Dacia Megaunit.

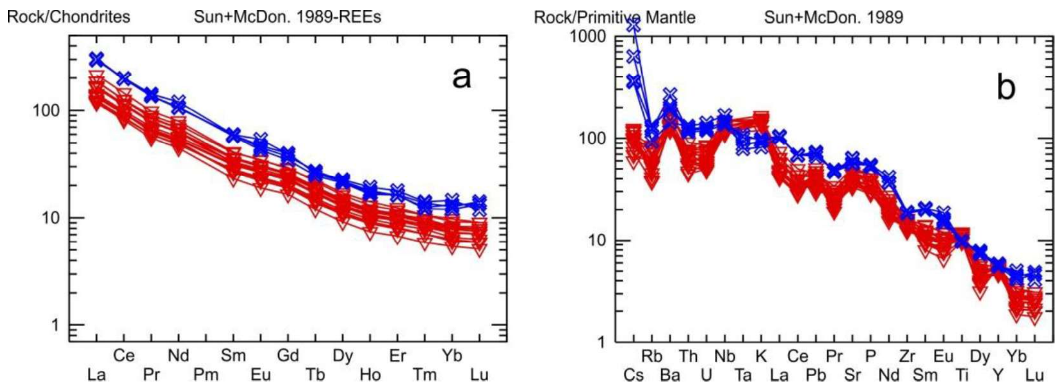

Figure 13. Rock/chondrite normalized trace elements patterns and Primitive mantle for basanite mafic dykes- in blue and Basanites from Poiana Rusca Mts. in red, acc. Tschegg *et al.*, 2010 (normalization values after Sun and McDonough, 1989). Symbols as in Fig. 3.

6.4. TECTONIC IMPLICATIONS

In the tectonic discrimination diagram La/10-Y/15-Nb/8 (Cabanis and Lecolle, 1989; Fig. 14) the majority of the calc-alkaline mafic dykes samples plot in the continental basalts field, different from the primitive Banatites that clearly plot in the calc-alkaline field. On the other part the alkaline mafic dykes plot in the alkaline field. This may confirm that the geodynamic setting of mafic volcanic rocks is post-collisional, intracontinental and extensional.

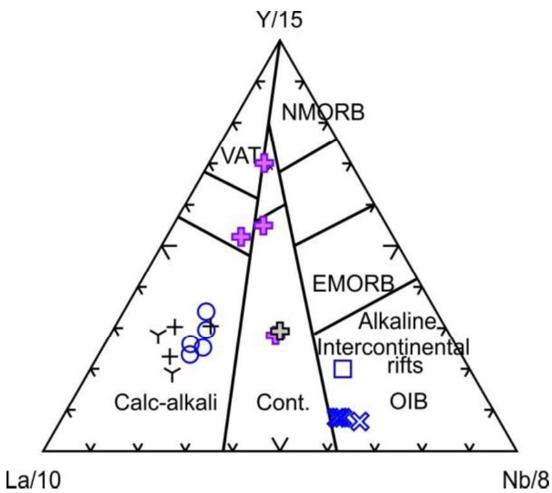

Figure 14. La/10-Y/15-Nb/8 diagram (Cabanis and Lecolle, 1989) for the studied rocks. Symbols as in Fig. 3.

7. CONCLUSIONS

The studied mafic dykes in the Apuseni and Banat areas are of two types: calc-alkaline and alkaline. The calc-alkaline mafic dykes have been generated during Upper Cretaceous (Campanian) either as cutting banatitic plutons in Banat or cutting Upper Cretaceous Gosau-type sediments, or other geological formations in Apuseni. Their petrography and geochemistry do not support the criteria to be named lamprophyres.

The source composition of the mafic dykes from Apuseni and Banat was controlled by at least three components, one depleted and two of them enriched. The depleted components originated from (i) residual subduction-related mantle metasomatism, and (ii) incipient melts from the asthenosphere during initiation of extension processes at the end of Banatite generation. Both enriched components suggest an asthenosphere origin generated in different conditions of source partial melting processes and extension tectonic development.

Geochemical data of the calc-alkaline mafic dykes signify that in a relatively short geologic time (~0.5-1 Myr), at ~76-70 Ma post–banatitic interval, small volume depleted mantle melts generated mafic dykes in the Apuseni and Banat regions with particular trace-element patterns showing depleted LILE and LREE. These magmas were probably generated by the melting of residual metasomatized subcontinental lithospheric mantle (SCLM) with minor contributions from a mantle source that produced melts with asthenospheric geochemical affinities.

Geochemical data of the alkaline mafic dykes suggest to be generated either in the Lower Mesozoic (alkali basaltic mafic dyke in Apuseni) or during Paleogene time (basanite mafic dykes - in Banat area) proposing an extension-related asthenospheric source.

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REFERENCES

Abdel-Rahman, A.M., 2002. *Mesozoic volcanism in the Middle East: geochemical, isotopic and petrogenetic evolution of extension-related alkali basalts from central Lebanon.* Geological Magazine, 139, 621–40.

Balintoni, I., 1994. *Structure of the Apuseni Mts. ALCAPA II. Field Trip Guidebook.* Rom. J. Tecton. Reg. Geol., 75 (Suppl. 2), 51–58.

Balintoni, I., Balica, C., Ducea, M.N., Chen, F.K., Hann, H.P. and Sabliovschi, V., 2009. *Late Cambrian–Early Ordovician Gondwanan terranes in the Romanian Carpathians: A zircon U–Pb provenance study.* Gondwana Research, 16(1), 119–133.

Berza, T., Constantinescu, E. and Vlad, S.-N., 1998. *Upper Cretaceous magmatic series and associated mineralisation in the Carpathian–Balkan Orogen.* Resource Geol., 48(4), 291–306.

Bortolotti, V., Marroni, M., Nicolae, I., Pandolfi, L., Principi, G. and Saccani, E., 2004. *An update of the Jurassic ophiolites and associated calc-alkaline rocks in the South Apuseni Mountains (western Romania).* Ofioliti, 29(1), 5–18.

Cabanis, B. and Lecolle, M., 1989. *Le diagramme La/10-Y/15-Nb/8: un outil pour la discrimination des series volcaniques et la mise en evidence des processus de mélange et/ou de contamination crustale.* C. R. Acad. Sci. Paris, Ser. II 309, 2023–2029.

Ciobanu, C.L., Cook, N.J. and Stein, H., 2002. *Regional setting and geochronology of the Late Cretaceous Banatitic Magmatic and Metallogenetic Belt.* Mineralium Deposita, 37, 541–567.

Cioflica, G., Pecskay, Z., Jude, R. and Lupulescu, M., 1994. *K–Ar ages of Alpine granitoids in the Hăuzeşti–Drinova area (Poiana Ruscăi Mountains, Romania).* Revue Roumaine de Géologie, Géophysique, Géographie, s. Géologie, 38, 3–8.

Cioflica, G. and Vlad, Ş.N., 1973. *The correlation of the Laramian metallogenic events belonging to the Carpathian–Balkan area.* Revue Roumaine de Géologie, Géophysique, Géographie, s. Géologie, 17, 217–214.

Constantinescu, E., 1977. *Mineralogy and petrology of Laramian magmatites between Nera Valley and Radimniuţa Valley*. Studii şi Cercetări de Geologie, Geofizică şi Geografie, s. Geologie, 22, 87–102 (in Romanian).

von Cotta, B., 1864. *Erzlagerstatten im Banat und in Serbien*. Braumuller, Wien, 108.

Downes, H., Vaselli, O., Seghedi, I., Ingram, G., Rex, D., Coradossi, N., Pécskay, Z. and Pinarelli, L., 1995. *Geochemistry of Late Cretaceous–early Tertiary magmatism in Poiana Ruscă (Romania)*. Acta Vulcanologica, 7, 209–217.

Gallhofer, D., 2015. *Magmatic geochemistry and geochronology in relation to the geodynamic and metallogenetic evolution of the Banat Region and Apuseni Mountains of Romania.* Diss. ETH no 22888, 145 pp.

Gallhofer, D., von Quadt, A., Peytcheva, I., Schmid, S.M. and Heinrich, C.A., 2015. *Tectonic, magmatic, and metallogenic evolution of the Late Cretaceous arc in the Carpathian–Balkan orogen.* Tectonics, 34(9), 1813–1836.

Gheorghiță, I., 1975. *Mineralogical and petrographical study of Moldova Nouă region (Suvorov–Valea Mare zone).* Studii Tehnice şi Economice, Inst. Geol. Geof., 11(1), 188 p. (in Romanian).

Gheorghițescu, D., 1975. *Mineralogical and geochemical study of thermal and metasomatic contact areas from Oravița (Coşovița).* Dări de Seamă ale Şedințelor – Institutul de Geologie şi Geofizică, 61(1), 59–103 (in Romanian).

Ilinca, G., Berza, T., Iancu, V. and Seghedi, A., 2011. *The Late Cretaceous magmatic and metallogenetic belt and the Alpine structures of the western South Carpathians*. 3rd International Symposium on the Geology of the Black Sea Region, Bucharest, 1–10 October 2011. Field Trip Guidebook. Geoecomar, 117 p. ISBN 1224–6808.

Istrate, G., 1978. *Petrologic study of the Vlădeasa Massif (western part).* Anuarul Institutului de Geologie şi Geofizică, LIII, 177–298.

Kräutner, H.G., Vîjdea, E. and Romanescu, O., 1986. *K–Ar dating of the banatitic magmatites from the Southern Poiana Ruscă Mts. (Rusca Montană sedimentary basin). Dări de Seamă ale Şedințelor – Institutul de Geologie şi Geofizică*, 70–71(1), 373–388.

Le Maitre, R.W., 1989. *A classification of igneous rocks and glossary of terms*. Blackwell, Oxford, 191 pp.

Nicolae, I. and Saccani, E., 2003. *Petrology and geochemistry of the Late Jurassic calc-alkaline series associated to Middle Jurassic ophiolites in the South Apuseni Mountains, Romania.* Schweiz. Min. Petr. Mitt., 83, 81–96.

Panaiotu, C., 1998. *Paleomagnetic constraints on the geodynamic history of Romania*. In: Sledzinski, J. and Ioane, D. (eds), *Monograph of Southern Carpathians*. Institute of Geodesy and Geodetic Astronomy, Warsaw University, 205–216.

Pană, D., Heaman, L.M., Creaser, R.A. and Erdmer, P., 2002. *Prealpine crust in the Apuseni Mountains, Romania: Insights from Sm–Nd and U–Pb data*. The Journal of Geology, 110(3), 341–354, 10.1086/339536.

Pearce, J.A., 2008, *Geochemical Ingerprinting of oceanic basalts with applications to ophiolite classiIcation and the search for Archean oceanic crust.* Lithos, v. 100, 14–48.10.1016/j.lithos.2007.06.016.

Popov, P., Berza, T., Grubić, A. and Ioane, D., 2002. *Late Cretaceous Apuseni–Banat–Timok–Srednogorie (ABTS) magmatic and metallogenic belt in the Carpathian–Balkan orogen.* Geol. Balc., 32(2–4), 145–164.

Russo–Săndulescu, D., Berza, T., Bratosin, I. and Ianc, R., 1978. *Petrological study of the Bocşa banatitic massif (Banat)*. Dări de Seamă ale Şedințelor – Institutul de Geologie şi Geofizică, 64, 105–172.

Russo–Săndulescu, D., Berza, T., Bratosin, I., Vlad, C. and Ianc, R., 1986a. *Petrological study of banatites in the Ocna de Fier–Dognecea zone.* Dări de Seamă ale Şedințelor – Institutul de Geologie şi Geofizică, 70–71(1), 123–142.

Russo–Săndulescu, D., Bratosin, I., Vlad, C. and Ianc, R., 1986b. *Petrochemical study of the Surduc banatitic magmatites (Banat).* Dări de Seamă ale Şedințelor – Institutul de Geologie şi Geofizică, 70–71(1), 97–121.

Seghedi, I., 2024. *Banatitic magmatism in the Eastern Europe with emphasis on Romanian territory; opinions on the published data.* Rev. Roum. Géophysique, 67, 11–20, Bucureşti, htpps://doi.org/10.59277/rrgeo.2024.67.2.

Sun, S.-S. and McDonough, W.F., 1989. *Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes.* Geol. Soc. London Spec. Publ., 42(1), 313–345.

Ştefan, A., 1980. *Petrographic study of the eastern part of the Vlădeasa eruptive massif.* Anuarul Institutului de Geologie şi Geofizică, LV, 207–325.

Ştefan, A., Roşu, E., Andăr, A., Robu, L., Robu, N., Bratosin, I., Grabari, G., Stoian, M., Vîjdea, E. and Colios, E., 1992. *Petrological and geochemical features of banatitic magmatites in Northern Apuseni Mountains*. Romanian Journal of Petrology, 75, 97–115.

Stefan, A., Lazar, C., Intorsureanu, I., Horvath, A., Gheorghita, I., Bratosin, I., Serbanescu, A. and Calinescu, E., 1982. *Petrological study of the banatitic eruptive rocks in the eastern part of the Gilau Mountains.* D.S. Inst. Geol. Geofiz., 69(1), 215–246.

Tschegg, C., Ntaflos, Th., Seghedi, I., Harangi, Sz., Kosler, J. and Coltorti, C., 2010. *Paleogene alkaline magmatism in the South Carpathians (Poiana Ruscă, Romania): Asthenospheric melts with geodynamic and lithospheric information.* Lithos, 120, 393–406.

Vander Auwera, J., Berza, T., Gesels, J. and Dupont, A., 2015. *The Late Cretaceous igneous rocks of Romania (Apuseni Mountains and Banat): The possible role of amphibole versus plagioclase deep fractionation in two different crustal terranes.* Int. J. Earth Sci. (Geol. Rundsch.), doi:10.1007/s00531–015-1210–2.

Vlad, S.N., 2020. *Banatite metallogeny in North Poiana Ruscă, revisited.* Geološki Anali Balkanskoga Poluostrva, 10 p, https://doi.org/10.2298/GABP19111300IV.

Vornicu, V.M. and Seghedi, I., 2025. *Petrography and geochemistry of the Upper Cretaceous volcaniclastic deposits of the Haţeg Basin (Southern Carpathians): Inferences on petrogenesis and magma origin.* Minerals, 15, 111, https://doi.org/10.3390/min15020111.

Winchester, J.A. and Floyd, D.A., 1977. *Geochemical discrimination of different magma series and their differentiation products using immobile elements.* Chemical Geology, 20, 325–343.

Woolley, A., Bergman, S.C., Edgar, A.D., Show Le Bas, M.G., Mitchel, R.H., Rock, N.M.S. and Scott Smith, B.H., 1996. *Classification of lamprophyres, lamproites, kimberlites, and the kalsilitic, melilitic, and leucitic rocks.* The Canadian Mineralogist, 34(2), 175–186.