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Geochemical response of magmas to Neogene–Quaternary continental collision in the Carpathian–Pannonian region: A review

Ioan Seghedi [a,*], Hilary Downes [b], Szabolcs Harangi [c], Paul R.D. Mason [d], Zoltán Pécskay [e]

[a] Institute of Geodynamics, 19-21, str. Jean-Luis Calderon, Bucharest 70201, Romania
[b] Birkbeck/UCL Research School of Earth Sciences, Birkbeck University of London, Malet St., London WC1E 7HX, UK
[c] Department of Petrology and Geochemistry, Eötvös Lorand University, H-1117, Budapest, Pázmány P. Sétány 1/c, Hungary
[d] Veining Meinesz Research School of Geodynamics, Utrecht University, Budapestlaan, 4, 3584 CD, Utrecht, The Netherlands
[e] Institute of Nuclear Research of the Hungarian Academy of Sciences, P.O. Box 51, Bém tér 18/c, H-4001 Debrecen, Hungary

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Abstract

The Carpathian–Pannonian Region contains Neogene to Quaternary magmatic rocks of highly diverse composition (calc-alkaline, shoshonitic and mafic alkalic) that were generated in response to complex microplate tectonics including subduction followed by roll-back, collision, subducted slab break-off, rotations and extension. Major element, trace element and isotopic geochemical data of representative parental lavas and mantle xenoliths suggests that subduction components were preserved in the mantle following the cessation of subduction, and were reactivated by asthenosphere uprise via subduction roll-back, slab detachment, slab-break-off or slab-tearing. Changes in the composition of the mantle through time are evident in the geochemistry, supporting established geodynamic models.

Magmatism occurred in a back-arc setting in the Western Carpathians and Pannonian Basin (Western Segment), producing felsic volcaniclastic rocks between 21 to 18 Ma ago, followed by younger felsic and intermediate calc-alkaline lavas (18–8 Ma) and finished with alkalic-mafic basaltic volcanism (10–0.1 Ma). Volcanic rocks become younger in this segment towards the north. Geochemical data for the felsic and calc-alkaline rocks suggest a decrease in the subduction component through time and a change in source from a crustal one, through a mixed crustal/mantle source to a mantle source. Block rotation, subducted roll-back and continental collision triggered partial melting by either delamination and/or asthenosphere upwelling that also generated the younger alkalic-mafic magmatism.

In the westernmost East Carpathians (Central Segment) calc-alkaline volcanism was simultaneously spread across ca. 100 km in several lineaments, parallel or perpendicular to the plane of continental collision, from 15 to 9 Ma. Geochemical studies indicate a heterogeneous mantle toward the back-arc with a larger degree of fluid-induced metasomatism, source enrichment and assimilation on moving north-eastward toward the presumed trench. Subduction-related roll-back may have triggered melting, although there may have been a role for back-arc extension and asthenosphere uprise related to slab break-off.

Calc-alkaline and adakite-like magmas were erupted in the Apuseni Mountains volcanic area (Interior Segment) from15–9 Ma, without any apparent relationship with the coeval roll-back processes in the front of the orogen. Magmatic activity ended with OIB-like alkali basaltic (2.5 Ma) and shoshonitic magmatism (1.6 Ma). Lithosphere breakup may have been an important process during extreme block rotations (~60°) between 14 and 12 Ma, leading to decompressional melting of the lithospheric and asthenospheric sources. Eruption of alkali basalts suggests decompressional melting of an OIB-source asthenosphere. Mixing of asthenospheric

* Corresponding author.
E-mail address: seghedi@geodin.ro (I. Seghedi).

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melts with melts from the metasomatized lithosphere along an east–west reactivated fault-system could be responsible for the generation of shoshonitic magmas during transtension and attenuation of the lithosphere.

Voluminous calc-alkaline magmatism occurred in the Cãlimani-Gurghiu-Harghita volcanic area (South-eastern Segment) between 10 and 3.5 Ma. Activity continued south-eastwards into the South Harghita area, in which activity started (ca. 3.0–0.03 Ma, with contemporaneous eruption of calc-alkaline (some with adakite-like characteristics), shoshonitic and alkali basaltic magmas from 2 to 0.3 Ma. Along arc magma generation was related to progressive break-off of the subducted slab and asthenosphere uprise. For South Harghita, decompressional melting of an OIB-like asthenospheric mantle (producing alkali basalt magmas) coupled with fluid-dominated melting close to the subducted slab (generating adakite-like magmas) and mixing between slab-derived melts and asthenospheric melts (generating shoshonites) is suggested. Break-off and tearing of the subducted slab at shallow levels required explaining this situation.

Keywords: Carpathian–Pannonian region; Geodynamic processes; Calc-alkaline magmas; Adakite-like magmas; Alkalic-basaltic magmas; Neogene–Quaternary

1. Introduction

This paper reviews the geochemical characteristics of Neogene–Quaternary magmatic rocks generated in both collisional and post-collisional settings in the Carpathian–Pannonian Region (CPR) of Eastern and Central Europe (Fig. 1). We discuss the various source-reservoirs responsible for the geochemical signature of the erupted magmas and attempt to connect them with the presumed geodynamic history via a temporal evolution study using well-established, internally consistent age determinations (e.g.. Pécskay et al., 1995a,b, 2000; Roşu et al., 1997; Pécskay, unpublished data). Our work is based on a large database of published whole rock and mineral geochemical and isotopic data, much of it produced in the same laboratories making comparisons highly reliable (Salters et al., 1988; Szabó et al., 1992; Embey-Isztin et al., 1993; Dobosi et al., 1995; Embey-Isztin and Dobosi, 1995; Downes et al., 1995a,b; Harangi et al., 1995, 2001, submitted for publication; Mason et al., 1996; Dobosi and Jenner, 1999; Harangi, 2001a,b; Roşu et al., 2001, 2005; Seghedi et al., 2001, 2004a).

We use the recently defined segmentation of the magmatic activity (Seghedi et al., 2004a) based on spatial distribution and timing: *Western Segment* (magmatism occurring in the central part of Alcapa block), *Central Segment* (magmatism occurring in front of the eastern part of Alcapa and western Tisia blocks), *Interior Segment* (magmatism occurring inside the Tisia block) and *South-Eastern Segment* (magmatism occurring at the eastern margin of the Tisia block) (Fig. 1). The study aims to determine variations in magma geochemistry in response to changes in tectonic setting, using the combination of isotopic and trace element data. Furthermore, we try to unravel the contributions of various mantle or crustal sources to the magmas, which have been sampled at the surface, in order to interpret the role of different tectonic processes in the region.

2. Geodynamic history

Tectonic reconstructions of the CPR have been given by numerous authors, e.g. Balla (1987), Ratschbacher et al. (1991), Csontos et al. (1992), Horvath (1993), Royden (1993), Csontos (1995), Nemčok et al. (1998), Fodor et al. (1999), Huismans et al. (2001), Sperner et al. (2002). The following is a short summary of their findings.

The Carpathians are an arcuate orogen in Central and Eastern Europe between the Eastern Alps and the Balkans. They were formed during Tertiary times, as a result of subduction of a land-locked basin and convergence of two continental fragments (here named Alcapa and Tisia) with the European foreland. (Note that the term “Tisia” is a simplified name; it was defined as “Tisza-Dacia” by Csontos et al., 1992, Csontos, 1995, and as “Tisia-Getia” by Seghedi et al., 1998). The age of deformation of the external Carpathian nappes (accretionary wedge), which involved thrust-loading of the foreland and coincided with the end of the collision event, is Karpatian (~17Ma) at the edges of the *Western Segment,* Badenian-Sarmatian (16.5–12 Ma) in the *Central Segment* and Sarmatian (13–11 Ma) in the *South-Eastern Segment* (e.g. Royden et al., 1982; Sãndulescu, 1988). An eastward progression of deformation along the thrust system is suggested (e.g. Royden et al., 1982; Csontos et al., 1992; Meulenkamp et al., 1996).

From the Eocene to Early Miocene (~33–24 Ma) an important NNE–SSW compression with ESE–WNW extension occurred. At this stage the blocks comprising the Intracarpathian area were already assembled. (Huismans et al., 2001; Sperner et al., 2002).

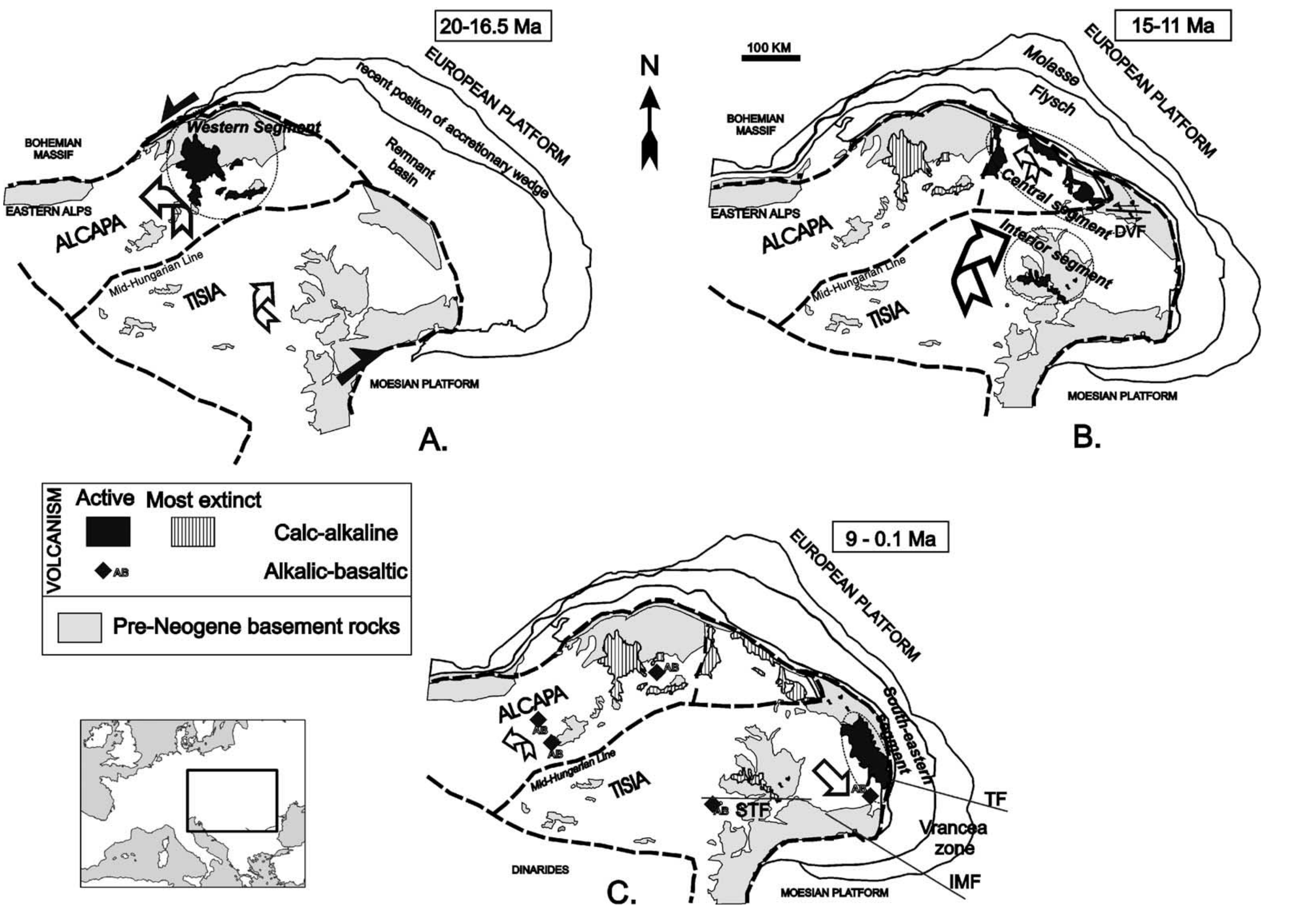

Fig. 1. Geotectonic sketches showing a tentative model of the geodynamic development and evolution of magmatic activity in the Carpathian–Pannonian region (e.g. Balla, 1987; Ratschbacher et al., 1991; Csontos et al., 1992, Royden, 1993; Horvath, 1993; Csontos, 1995; Nemčok et al., 1998; Fodor et al., 1999; Huismans et al., 2001; Sperner et al., 2002), as derived from kinematic, sedimentary and paleomagnetic data, at 20–16.5 Ma (A), 15.5–11 Ma (B) and 9–0.1 Ma (C) Locations of corresponding defined segments, based on time–space relationships: *Western segment*, *Central segment*, *Interior segment* and *South-Eastern segment* are shown. Abreviations: DVF = Dragoş Vodã fault; STF = South Transylvanian fault; TF = Trotuş fault; IMF = IntraMoesian fault; AB = alkalic basalts.

Early to Middle Miocene (24–16.5 Ma) tectonics were characterised by NE to E-ward translations and rotation of Alcapa and Tisia, collision of the former block with the European continent, and initiation of an extensional strike-slip regime along the borders of Alcapa (Horváth, 1993; Sperner et al., 2002). Opposite-sense rotations occurred between the two continental blocks at the end of this interval. The Alcapa block, situated north of the Mid-Hungarian lineament, underwent counter-clockwise rotation (Márton and Márton, 1996), whereas the Tisia block began to rotate clockwise (Pătraşcu et al., 1994; Panaiotu, 1998) (Fig. 1). The driving forces behind compression in the region have been variously explained as being due to: (i) extrusion of crustal blocks into free space due to continuous convergence in the Alps (Ratschbacher et al., 1991) or lateral extrusion and local block rotation of Alcapa, accompanied by counter-clockwise rotation of several fault-bounded blocks (Sperner et al., 2002) (ii) slab pull causing roll-back along the Carpathian subduction zone (Royden, 1993), (iii) northward-directed convergence of the Adriatic plate (Linzer et al., 1998; Fodor et al., 1999) and/or (iv) eastward-directed flux of asthenosphere or relative westward drift of the lithosphere (Doglioni et al., 1999). This compression generated large-scale contractions in the northern part of the Outer Carpathians (Royden, 1988; Horváth, 1993; Sãndulescu, 1988) and initiated back-arc extension in the Pannonian Basin (Royden, 1988). The latter part of this interval coincides with the syn-rift phase of the Pannonian Basin, when core-complex type extension took place followed by a wide-rift extensional event (primarily due to the slab pull force; e.g. Tari et al., 1999; Huismans et al., 2001).

During Middle Miocene times (16.5–11 Ma), marked by a change in direction of foredeep depocenter migration (Meulenkamp et al., 1996), collision of Tisia took place and retreating subduction processes ceased due to the introduction of the East European platform into the deformation system (Maţenco et al., 1997; Zweigel, 1997). Between 16.5 and 14 Ma, the central Pannonian Basin was affected by pure E–W extension, resulting in the generation of deep basins and crustal thinning (Horvath 1993; Tari et al., 1999). This period also coincided with very fast clockwise rotation of Tisia (around 70°), between 14.5 and 12 Ma (Panaiotu, 1999). Between 14 and 12 Ma only the north-eastern part of Alcapa, known as the Zemplin Block, was affected by continuous rigid counter-clockwise block rotations from 50° to 20° (Panaiotu, 1998; Márton et al., 2000) between 6–3 Ma counter-clockwise rotational conditions and extensional faulting have been noticed in the western part of Alcapa (Márton and Fodor, 2003).

Between 10 and 0.3 Ma the East Carpathian volcanic area between Cãlimani and South Harghita evolved and shows along-arc migration of volcanism (Pécskay et al., 1995a,b) with a gap at ~3.5 Ma. In the southern part of the East Carpathians, associated with unusual foredeep basins (Maţenco et al., 2003; Bertotti et al., 2003), the stress field changed in Pliocene (~5 Ma) times from a NNE–SSW strike-slip configuration to a N–S compression, compatible with large-scale tearing and possible slab break-off in the southern part of the East Carpathians (Mason et al., 1998; Maţenco and Bertotti, 2000; Bertotti et al., 2003). In the internal zone the SSE-ward movement of the Carpathian bend area was accompanied by minor extension (Gîrbacea, 1997; Gîrbacea and Frisch, 1998; Ciulavu, 1998). A flat-lying high velocity S-wave anomaly in the mantle at depths of 400–650 km beneath the CPR has been interpreted as subducted lithosphere that sank into the mantle as a result of slab detachment along strike of the Carpathian arc (Wortel and Spakman, 2000; Sperner et al., 2001; Bertotti et al., 2003). Travel-time tomography also confirms the presence of a narrow slab in the Vrancea zone, which appears to be continuous down to 350 km (Wortel and Spakman, 2000). This unusual type of subduction is likely controlled by the thermo-mechanical age of the underthrusted lithosphere and lateral variations between the lithosphere and surface processes (Cloething et al., 2004).

3. Geochemistry and magmatic history

3.1. Temporal variations of Sr and Nd isotope compositions

Magmatic products are very varied and have been defined based on TAS diagram as: (a) a calc-alkaline series from basalts to rhyolites; here large volume intracontinental-type rhyolitic ignimbrite suites (Bükk rhyolites, Dej tuff complex rhyolites) have been distinguished from the local small volume rhyolites, closely associated with the calc-alkaline andesitic volcanism (Central Slovakian Volcanic Field, Tokaj, rear-arc Ukrainian, Gutâi, Cãlimani); (b) a calc-alkaline adakite-like series, consisting mainly of amphibole ± biotite-bearing andesites and dacites, which has been defined as having $SiO_2 \geq 56$ wt.%; $Al_2O_3 \geq 15$ wt.%; Sr > 400 ppm; Sr/Y = 30–300, Mg# > 45, relatively low $^{86}Sr/^{87}Sr$, but which not always plot inside of the adakite field as defined by Defant and Drummond (1990); (c) a shoshonitic series, which are defined as having higher K_2O contents than the calc-alkaline magmas and plot in basaltic trachy-andesite and trachy-andesite fields and (d) mafic alkalic series of various rocks, which plot in alkali basaltic, basanitic, nephelinitic, basaltic, trachy-basaltic, basaltic trachy-andesitic and phono-tephritic fields. As the main goal of this paper is to identify the various sources contributing to magmatism as a function of geodynamic variations, we will use radiometric isotope ratios such as $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ since they are powerful indicators of changes in source contributions. Furthermore, magmatic processes such as partial melting and fractional crystallization are considered to have a negligible effect on these ratios. The isotopic characteristics of different geochemical reservoirs are more variable for subducted sediments and continental crust, being characterized by relatively high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$, compared to those of the mantle. Along with variations in the source as a function of time, we will discuss the implication of magmatic processes in the different segments, since they are significant in the discussion of geotectonic history.

Variations of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ initial ratios through time are presented in Fig. 2. Low $^{143}Nd/^{144}Nd$ and high $^{87}Sr/^{86}Sr$ ratios seen in the oldest Bükk rhyolites (*B*) (Western Segment) suggest a dominant crustal source (e.g. Póka et al., 1998; Harangi, 2001a; Seghedi et al., 2004a). The next two younger groups, the Cserhát-Mátra-Börzöny volcanic areas (*CMB*) and the more northerly Central Slovakian Volcanic Field (*CSV*), display large isotopic variations trending from lower to higher $^{143}Nd/^{144}Nd$ and from higher to lower $^{87}Sr/^{86}Sr$. This tendency suggests a complex mixing between crustal and subduction-derived melts. Large variations in $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ are shown by Central and Interior Segments volcanic entities (Fig. 2), which evolved during the same time-span. The other regions of the Central Segment (Tokaj–*T*, front-arc Ukrainian–*FU*, and Gutâi–*G*) show a similar, but narrower, trend as the Western Segment magmas, i.e. a continuous decrease in $^{87}Sr/^{86}Sr$ and an increase in $^{143}Nd/^{144}Nd$. An exception is shown by the rear-arc magmatism of the Ukrainian Carpathians (*RU*), which does not exhibit any variation of $^{143}Nd/^{144}Nd$ with time, but an increase in $^{87}Sr/^{86}Sr$. The oldest magmas in the Central Segment, represented by the Dej-tuf complex (Dt), are rather similar to Tokaj, front-arc Ukrainian and Gutâi magmas, but display a higher $^{143}Nd/^{144}Nd$. In contrast, the contemporaneous Interior Segment magmas (Apuseni Mts.–*Ap*) trend toward the lowest Sr and higher Nd ratios, which are closer to a mantle-type reservoir. Initially, magmas in the Cãlimani (*Cl*) volcanic area \(South-Eastern Segment) displayed a large Sr and Nd isotopic spectrum, closer to crustal reservoirs. Younger magmas trend toward a mantle-type reservoir and show a continuous increase in $^{87}Sr/^{86}Sr$ and decrease in $^{143}Nd/^{144}Nd$, due to AFC processes (Mason et al., 1996; Seghedi et al., 2004a). The younger Gurghiu (*G*) and North Harghita (*NH*) magmas also show increasing $^{87}Sr/^{86}Sr$ and decreasing $^{143}Nd/^{144}Nd$ ratios, again explained by AFC processes, although with a more restricted range compared to Cãlimani samples. Magmas from South Harghita (*SH*) show initially large $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ variations, then an AFC trend. The isotope signature of younger alkalic basalts has been considered chiefly to represent a mantle reservoir, either asthenospheric or lithospheric (e.g. Embey-Isztin et al., 1993; Embey-Isztin and Dobosi, 1995; Downes et al., 1995b; Harangi et al. 1995; Seghedi et al., in print).

3.2. Timing vs. source and differentiation processes

To better constrain the various processes that have contributed to the magma generation in each segment, SiO_2 values are plotted vs. age and $^{143}Nd/^{144}Nd$ isotope ratio (Fig. 3). These diagrams are useful in separating source processes (mantle or crustal melting and mixing between melts) from various differentiation processes (FC or AFC) and in determining the relative role of source contamination via the contribution from the subducting slab (e.g. Hawkesworth et al., 1977; Ellam and Hawkesworth, 1988; Davidson, 1987, 1996; Tatsumi and Eggins, 1995; Thirlwall et al., 1996). In the Western segment magmas from the initial eruption events (B) show a narrow range of SiO_2 values, which contrasts with the large SiO_2 variation of the younger CMB and CSV magmas (Fig. 3). This variation may be interpreted in various ways, but most probably in terms of three independent reservoirs: (1) a crustal one for the early felsic magmas, (2) a lower crustal/upper mantle source, for intermediate magmas of the CMB volcanic area, some of which are garnet-bearing (Harangi et al., 2001), and (3) an a mantle source (principally asthenospheric) for the alkali basalts, showing also the lowest Zr/Nb ratio (e.g. Embey-Isztin et al., 1993; Dobosi et al., 1995; Harangi, 2001b; Seghedi et al., 2004a, in print-b). The larger variation in the CSV magmas is explained by mixing between a lower crustal/upper mantle source and a mantle source (e.g. Harangi et al., 2001). Younger felsic magmas were probably derived via differentiation processes (Konečny et al., 1995), but their higher $^{143}Nd/^{144}Nd$ and lower Zr/Nb ratios (Harangi et al., submitted) suggest a mantle-type

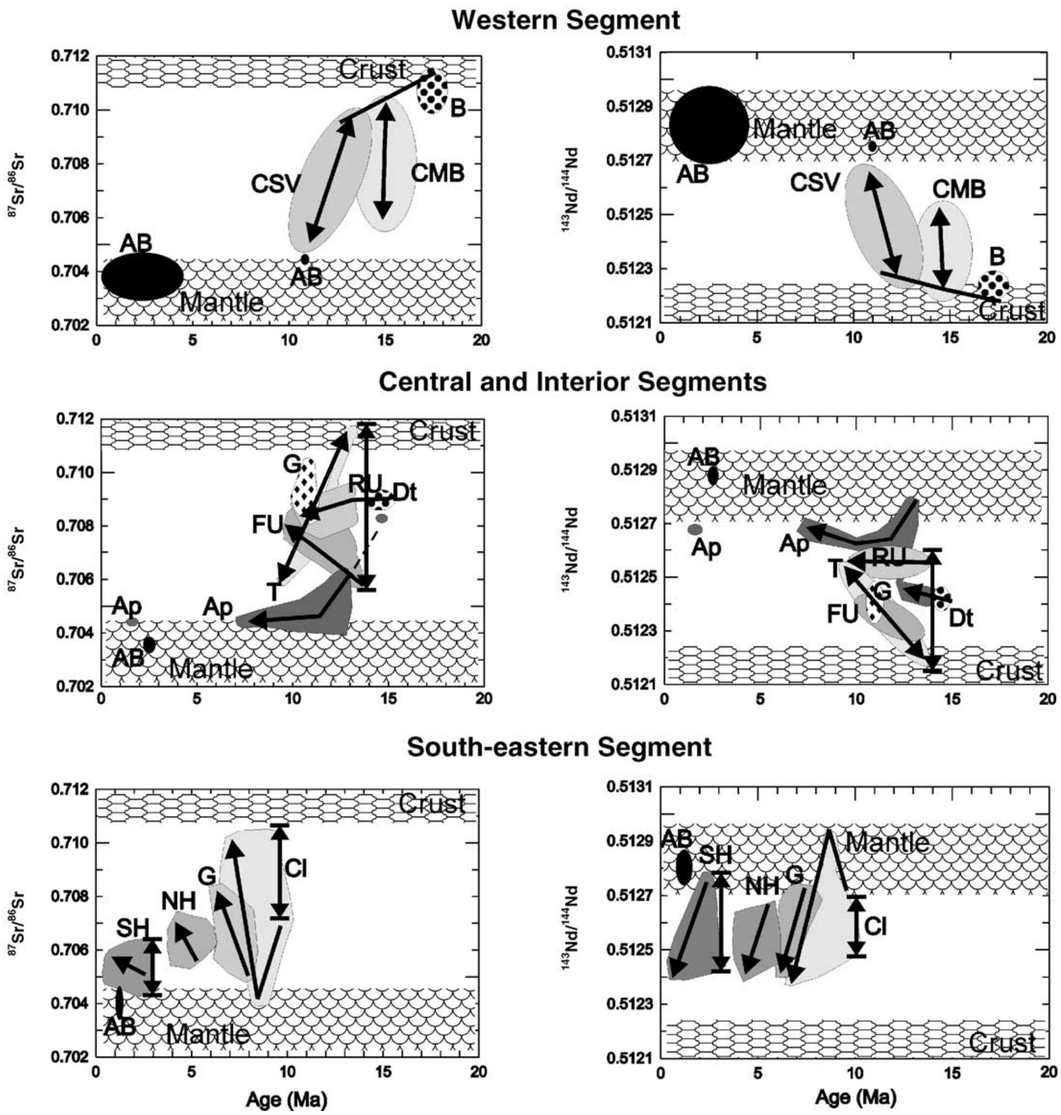

Fig. 2. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ vs. Age (Ma) for *Western*, *Central*, *Interior* and *South-Eastern segment,* showing the various source contributions to the Carpathian–Pannonian magmatism. Petrological data from Salters et al. (1988); Embey-Isztin et al. (1993); Dobosi et al. (1995); Downes et al. (1995a,b); Harangi et al. (1995, 2001, submitted); Mason et al. (1996); Seghedi et al. (2001, 2004a), Roşu et al. (2001, 2004) and age data from Pécskay et al. (1995a,b, 2000); Roşu et al. (1997); Pécskay (unpublished data). Abbreviations: for *Western segment* regions: B–Bükk Foreland rhyolites; CMB–volcanic rocks from Cserhat-Matra-Börzöny; CSV–volcanc rocks from Central Slovakian Volcanic Field; for *Central segment*: Dt–Dej tuff complex rhyolites; T–volcanic rocks from Tokaj; RU–rear-arc volcanic rocks of Ukrainian Carpathians, FU–front-arc volcanic rocks of Ukrainian Carpathians; G–volcanic rocks from Gutâi; for Interior segment—Ap–Apuseni area volcanic rocks; For *South-Eastern segment*: Cl–volcanic rocks from Cãlimani, G–volcanic rocks from Gurghiu; NH–Volcanic rocks from North Harghita, SH–volcanic rocks from South Harghita. AB–alkali basalts corresponding to each region.

(confined to an OIB-type) reservoir, but modified by subduction metasomatism.

With the exception of the initial felsic magmas (Dt), Central Segment magmas show several variable SiO_2 trends in the interval between 14 and 10 Ma. This suggests different parental magmas (lithospheric and/ or asthenospheric?) according to various $^{143}Nd/^{144}Nd$ trends, variably affected by subduction components (Seghedi et al., 2001; Kovacs, 2002). The trend shown by the youngest Tokaj basalt to lower SiO_2 and $^{143}Nd/^{144}Nd$, in combination with trace element variation, supports a mantle source (asthenospheric), without important sediment involvement (e.g. Downes et al., 1995a) as also shown by RU magmas and some terminal CSV magmas. The higher $^{143}Nd/^{144}Nd$ ratio for a narrower SiO_2 of Interior Segment magmas sug-

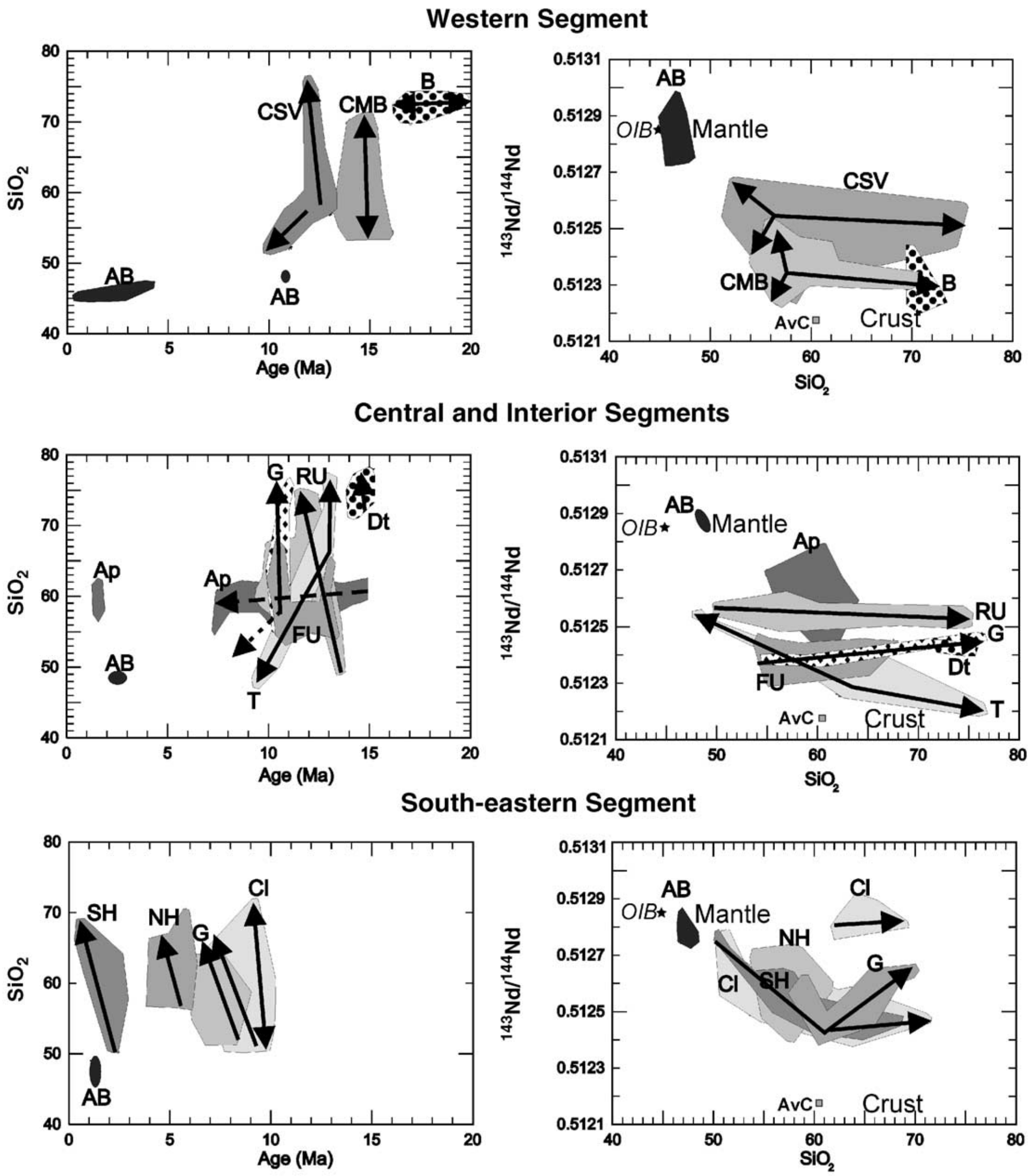

Fig. 3. SiO_2 vs. Age (Ma) and $^{143}Nd/^{144}Nd$ variation for Carpathian–Pannonian volcanic rocks in *Western*, *Central*, *Interior*, and *South-Eastern segments*, to distinct source processes (mantle or crustal melting and their various mixing processes) from various differentiation processes (fractional crystallization or assimilation—fractional crystallization). Data, fields and abbreviations as in Fig. 2. Abbreviation: AvC–average local crust (Mason et al., 1996).

gests a lower crust/upper lithospheric mantle reservoir (Roşu et al., 2001, 2005). Early South-Eastern Segment magmas (Cl) display variable and some of the most depleted mantle (asthenospheric?) reservoir in CPR (higher $^{143}Nd/^{144}Nd$ ratio), influenced by a small amount of subduction-related sediment involvement (Mason et al., 1996; Seghedi et al., 2004a). Lower and upper crustal fractionation and assimilation are responsible for Cl, G, NH and SH trends (Seghedi et al., 1995; Mason et al., 1995, 1996; Seghedi et al., 2004a, 2005). The younger SH magmas were derived from a different subduction-affected mantle reservoir, similar with contemporaneous local alkali basalt magmas, mainly derived from an OIB-source asthenosphere (Downes et al., 1995b; Vaselli et al., 1995; Seghedi et al., 2004a,b).

3.3. Constraining magma fractionation and fluid contribution to the source

A combination of the ratios Ba/Nb and La/Y and age (Ma) can provide information about the fluid contribution to the mantle source of the magmas in the Carpathian–Pannonian region (Fig. 4). This gives information about the contamination of the source by subducted fluids and/or melts and can reveal unusual melting processes resulting in adakite-like magmas (e.g., Drummond et al., 1996; Kapezhinskas et al., 1997; Roşu et al., 2001, 2005; Seghedi et al., 2004a). However, these ratios can also be affected by fractional crystallization, recharge, magma mixing and assimilation in shallow crustal magma chambers. Values of La/Y > 2 and Ba/Nb > 30 can be produced by high-pressure garnet–(olivine–pyroxene) and/or hornblende fractionation (e.g., Harangi, 2001a). Variable Ba/Nb and La/Y ratios of the magnitude seen in the CMB (Western Segment) magmas are too large to only be controlled by these low-pressure processes. Both crustal (higher La/Y and Ba/Nb) and upper mantle sources (lower La/Y and Ba/Nb) are required to explain these ratios. The oldest Bükk rhyolite magmas (B) have ratios similar to CMB magmas that mixed with lower crustal melts (e.g., Harangi, 2001a). The deviated trend to low La/Y com-

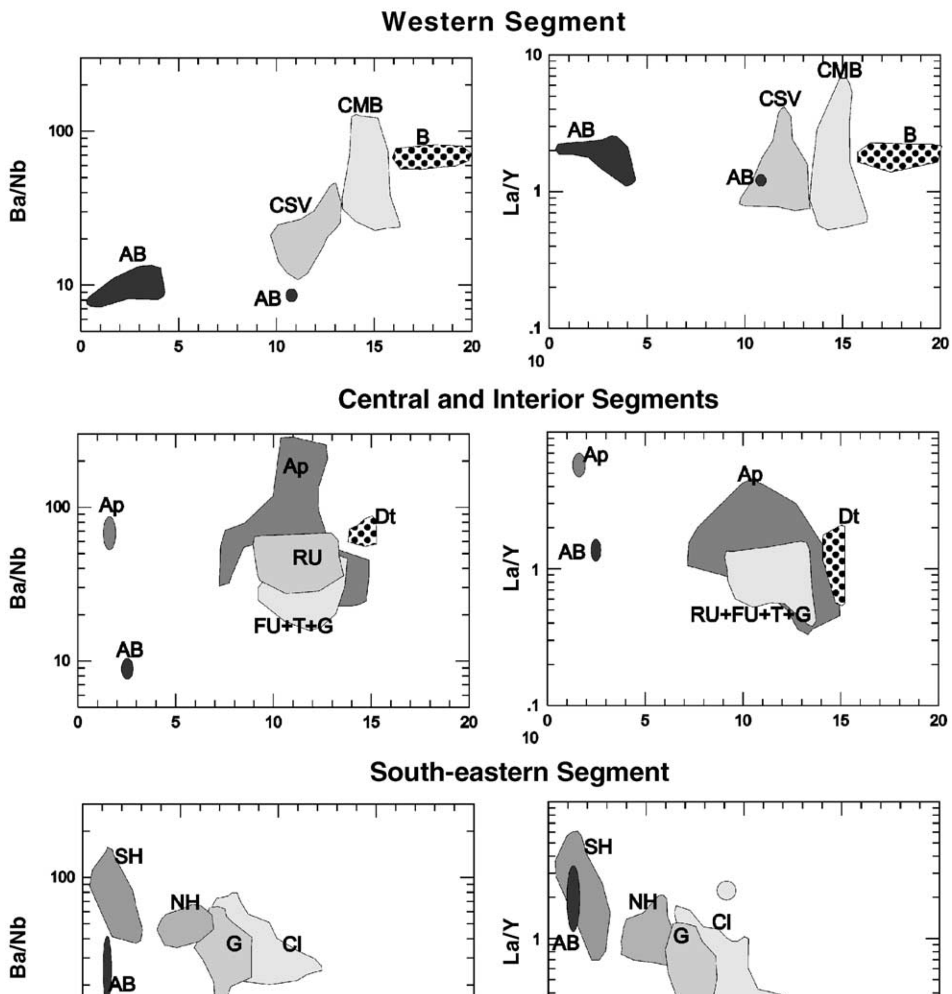

Fig. 4. Ba/Nb and La/Y ratios vs. Age (Ma), for Carpathian–Pannonian volcanic rocks separated in *Western*, *Central*, *Interior* and *South-Eastern segments* suggesting the influence of fluid contribution and high pressure fractionation. Data, fields and abbreviations as in Fig. 2.

bined with lower Ba/Nb for the younger CSV magmas, along with the behaviour of their Sr and Nd isotopic ratios (Fig. 2) may suggest two different mantle sources, one older (lithospheric or asthenospheric) variably affected by subducted components and another younger less contaminated asthenospheric source closer to OIB. However, fractionation processes could also have significantly affected these ratios.

Rather restricted range of La/Y ratios for the Central Segment magmas and a positive correlation with Ba/Nb are consistent with low-pressure fractionation of magmas derived from a subduction-modified mantle source (Seghedi et al., 2001). Rhyolites from the Dej Tuff complex (Dj) show similar or higher La/Y and Ba/Nb ratios compared with other volcanic areas of Central Segment, interpreted as derived by fractionation of a mantle-derived magma in large magma chambers situated in the lower to middle crust (Szakács, 2000). The large range of La/Y, combined with high Ba/Nb, for Interior Segment magmas, mainly between 10–12 Ma is inconsistent with a homogeneous source and low-pressure fractionation, but supports some high-pressure amphibole and/or garnet fractionation (La/Y > 2) and additional fluid involvement (Ba/Nb > 80), supporting a possible calc-alkaline adakite-like origin (Roşu et al., 2001, 2005; Seghedi et al., 2004a).

Magmas in the South-Eastern Segment show a similar trend of La/Y and Ba/Nb for Cl, G, narrower for NH, suggesting dominant mid-crustal depth fractionation then upper crustal fractionation, with the exception of the youngest Cãlimani lavas (Mason et al., 1995, 1996; Seghedi et al., 2005). This is also supported by their Sr and Nd isotope ratios trend (Fig. 2). South Harghita magmas show a similar trend, but at higher La/Y ratios. High Ba/Nb ratios suggest an additional involvement of fluid (Ba/Nb > 80) and high-pressure fractionation (La/Y > 2), implying slab-melting processes in the generation of calc-alkaline adakite-like magmas (Seghedi et al., 2004a).

The elemental signature of Pannonian Basin younger alkali basalts is largely similar to that of OIB (e.g. Embey-Isztin et al., 1993) and differs from that in the Per°ani Mountains, where a higher Ba/Nb ratio suggests clear influence of subduction-modified material (via melting or mixing) in the magma generation (Downes et al., 1995b; Seghedi et al., 2004b). It is significant from the geodynamic point of view that the Per°ani Mountains basalts were erupted contemporaneously with calc-alkaline and adakite-like calc-alkaline and shoshonitic magmas (Seghedi et al., 2004a), between 1.5 and 0.5 Ma (Panaiotu et al., 2004).

4. Implications for subduction processes

During Miocene–Quaternary times the CPR experienced both subduction and back-arc extension (e.g. Royden, 1988; Horvath, 1993; Csontos, 1995). These processes happened during Early Miocene block collision due to the uneven roll-back of the subduction zone (e.g. Royden and Burchfiel, 1989). This caused lithosphere thinning in the Pannonian basin, mostly along the mid-Hungarian belt, which was most significant in the Little Hungarian Plain-Bakony region (Alcapa block) and in the Great Hungarian Plain (Tisia block). The rotation of the two blocks in opposite senses may also have contributed to crustal thinning. Csontos and Nagymarosy (1998) suggested that rotation around the external rotation poles of the two major blocks led to extensional deformation along the mid-Hungarian line, causing tangential extension, lithosphere thinning and generation of wedge-shaped basins toward Tisia (Fig 1). Westward-dipping subduction zones become steeper due to slab roll-back, compared with Eastward-dipping subduction zones which display gentle angles of subduction, perceived as related to relative eastward mantle flow or westward drift of the lithosphere (Doglioni et al., 1999). The westward-directed Miocene subduction zone of the Carpathians which shows evidence of slab-roll-back, may not only be due to slab pull (Royden, 1993) or marginal block shifting, but also to eastward mantle flow and/or opposite drift of the European Plate (Doglioni et al., 1999).

It is very difficult to determine the relationship between extension and volcanism in the CPR. Most of the Western Segment volcanism (20–11 Ma) generated in the Alcapa Block is attributed to back-arc extension and between 10–9 Ma by NW–SE extension (e.g. Sperner et al., 2002), at its initial stage being represented by "areal-type silicic volcanics" (mainly located along the Mid-Hungarian Line) and in the intense back-arc extension stage by "areal-type andesitic volcanics" (mainly located south of the CSV) (Lexa and Konečny, 1999). Most of this volcanism was directly associated with Miocene sedimentation in the Pannonian Basin (Vass, 1995; Kováč et al., 1998), as it is largely buried by sediments. Middle to late Miocene volcanism was a response to the transtension and extension around the Transcarpathian basin (e.g. Central Segment rhyolites) (Lexa and Konečny, 1999; Seghedi et al., 1998; Seghedi et al., 2001; Konečny et al., 2002), which is considered as a second phase of extension (Huismans et al., 2001). The geochemical and isotopic interpretations suggest a larger crustal melt contribution for the Dej tuff complex rhyolites, compared to the younger ones, associated to the calc-alkaline andesitic volcanism and mainly formed by differentiation (Figs. 2 and 3). Furthermore, some of the younger Central Segment rhyolites represent fractionated products of a mantle source variably enriched in OIB-like components (Fig. 3). Downes et al. (1995b) and Seghedi et al. (2001) suggested that the asthenospheric influx became geochemically perturbed adjacent to the bend in the slab. The spatial and temporal change in the back-arc evolution in front of the Alcapa block, also indicated by lateral depocenter migration, as well as slight west to east migration of volcanism, probably corresponds to changes in the roll-back-induced pull at the front and counter-clockwise rotation (Pătraşcu et al., 1994; Panaiotu, 1998; Márton et al., 2000; Meulenkamp et al., 1996). Extension-related calc-alkaline volcanism in the western segment was suggested also by Harangi et al. (1998, 2001) and Harangi (2001a) based on the temporal variation of the geochemical characters of the volcanic rocks and the occurrence of the garnet-bearing magmas at the initial stage of the calc-alkaline volcanism.

This change in direction was coeval with the eastward translation and fast clockwise rotation (>60°) of the Tisia block between 14.5 and 12 Ma (Csontos, 1995; Panaiotu, 1999). The style of extension of Tisia, corresponding to the Apuseni Mts, does not resemble genuine back-arc development. Instead, basins showing NW–SE trending graben-like features (e.g. Royden, 1988) were related to the generation of a special type of extension-related magmatism, including adakite-like calc-alkaline type (Roşu et al., 2001, 2005; Seghedi et al., 2004a). These basins could also be explained as due to lithosphere thinning at the external hinge (along the mid-Hungarian belt) during counter-clockwise rotation around a pole situated in western Moesia (Csontos and Nagymarosy, 1998) and/or en-echelon brittle crustal fragmentation during fast clockwise rotations and coupled with local decompressional melting processes (Seghedi et al., 2004a).

Calc-alkaline volcanism in the CPR was contemporaneous with collisional and post-collisional processes in Carpathians, with earlier phases related to successive development of back-arc extension processes and asthenospheric upwelling (Western and Central Segment) (Harangi et al., 1998, 2001; Harangi, 2001a; Konečny et al., 2002), fast rotation-related extension and decompressional melting (Interior Segment) and finally restrained to the collision boundaries, triggered by along-arc break-off and tearing in the final stage, enabling local mantle upwelling (South Eastern Segment). We already acknowledged that the mantle was affected by subduction metasomatism prior to magma generation (Rosenbaum et al., 1997), however it is difficult to appreciate to what extent the asthenosphere and lithosphere were polluted to a greater distance from the trench. In any case, a larger amount of lithosphere may have been affected closer to the trench (e.g. front-arc Central Segment magmas).

Another puzzling problem is whether there are any genuine subduction-type magmas in CPR, of the kind generated above a down-going slab, which passed through the magma generation window? Since subduction was already active in Early Miocene times, before the onset of roll-back, such processes would be expected to have occurred. However, there is no clear subduction-related magmatism prior the Early Miocene – Harangi (2001a) suggested that this amagmatic period could be explained by flat subduction followed by retreated style of subduction, when lithospheric extension could have been the main cause of melt generation at least at the western segment. However, later tectonic developments that led to back-arc formation, changed the triggering mechanism of melting and initiated a variety of asthenospheric mantle upwelling processes, related to the last stage of roll-back, delamination, break-off or tearing.

The geochemical and isotopic data confirm the diminution of subduction-modified mantle with time, in favor of less affected asthenospheric OIB-like mantle, as in the Western Segment and in the Tokaj Mts. of the Central Segment (Figs. 1 and 2).

Alkalic mafic volcanism has chiefly an uncontaminated mantle origin (OIB-like; e.g. Embey-Isztin et al., 1993), but was partly affected by subduction metasomatism, especially when close temporally with the generation of calc-alkalic magmatism (e.g. Downes et al., 1995b; Seghedi et al., 2004b).

5. Geodynamic implications

Various geodynamic models have been proposed to explain the complex situation of the CPR, all of them involving subduction. Since Early Miocene times, retreating subduction and extrusion have been active as shown by Ratschbacher et al. (1991); Royden, (1993); Sperner et al. (2002).

5.1. Western segment

Along the Western Segment collision was an early Middle Miocene event, marked by counter-clockwise rotations of the Alcapa block (e.g. 80–90° during 21–18.5 Ma and 30° during 17.5–16 Ma) (Pécskay et al., 1995a; Márton and Pécskay, 1998) (Fig. 1). As 21–18 Ma was the time of generation of large volumes of felsic magma, crustal rotations may have led to localized extension that favoured eruption. Predominantly intermediate volcanic activity show climaxes between 17–14 Ma in CMB and 16–12 Ma in CSV, implying migration toward the north (Pécskay et al., 1995a; Lexa and Konečny, 1999). Variable time-related geochemical features towards the north suggest that Western Segment magmas were generated with a large initial contribution of crustal melts, which decreased with time (Harangi, 2001a). The question is whether the crustal melts were generated independently from the mantle melts or contemporaneously, with a direct influence of the mantle melts on crustal melting generation. Trace elements and isotopic trends suggest that upper and lower crust melts were variably mixed with mantle-derived arc magmas (Figs 2–4). Mantle-type magmas affected by subduction components were probably derived from lithosphere and adjacent asthenosphere, as lithospheric mantle in the central part of the Pannonian Basin displays evidence of subduction-related enrichment by silicate melts and aqueous fluids (Rosenbaum et al., 1997).

Two mechanisms of magma generation have been invoked:

(1) Subduction-related diapiric uprise of large-volume partial melts from the metasomatized mantle caused underplating and crustal anatexis; then mixing of crustal melts with mantle-derived magmas (e.g. Bükk rhyolites; Harangi, 2001). Further delamination processes (e.g. de Boorder et al., 1998; Seghedi et al., 1998) favored the generation of magma from an asthenospheric material less affected by subduction metasomatism.
(2) Slab-roll-back processes may lead to invasion of hot asthenospheric mantle under the thinned lithosphere, causing extensive partial melting in the upper continental crust (Lexa and Konečny, 1999; Huismans et al., 2001; Konečny et al., 2002).

The currently available trace element and isotopic data cannot sufficiently constrain the mechanisms of mixing and crustal melting required to identify the most likely of these two processes.

At the termination of calc-alkaline magmatism (~10 Ma) and between 8 and 0.1 Ma, further mafic alkalic volcanism occurred, suggesting local asthenospheric upwelling and related adiabatic partial melting of a mantle source (Embey-Isztin et al., 1993; Dobosi et al., 1995; Harangi et al., 1995; Konečny et al., 1995; Harangi 2001b). Alkalic mafic volcanism may have been generated by finger-like mantle plumes (e.g. Seghedi et al., 2004b), under various local extensional or rotational conditions during Pliocene times (Márton and Fodor, 2003), which caused brittle deformations of the lithosphere.

5.2. Central segment

In front of the Central Segment collision ended in upper Middle Miocene times with simultaneous counter-clockwise rotation of the easternmost Alcapa (Zemplin) lithospheric block (Panaiotu, 1998; Márton et al., 2000) and clockwise rotation of Tisia with a change of the slab pull towards the northeast. Magmatism was generated between 15 and 8 Ma, in front of the Zemplin and Tisia blocks, in a complex extensional–transtensional regime (Fodor et al., 1999). A transpressive regime along the Drago° Voda fault (Zweigel, 1997; Ciulavu, 1999) caused shallow-level magmatic intrusions instead of surface volcanism.

In front of the Zemplin block calc-alkaline magmas were erupted, whose geochemical features (Figs. 2–4) suggest initial source contamination of the asthenosphere during slab roll-back of the subducted lithosphere (as related to collisional processes), then thermal disturbance caused by ascent of hot asthenospheric mantle during the late-stage back-arc opening of the Transdanubian Basin.

The mechanisms of magma generation were associated with asthenospheric influx and consequently a thermal input, as a result of the earlier trench-ward roll-back and break-off processes, which yield concomitant generation of magmas at the asthenosphere/lithosphere bulged boundary, and all along ~100 km of back-arc and trench (Seghedi et al., 1998, 2001; Kovacs, 2002). In front of the Tisia block, various intrusions suggest generation via melting of a heterogeneous mantle wedge and lower crust (Papp et al., 2005), however triggering mechanisms are still uncertain.

5.3. Interior segment

In the *Interior segment*, corresponding to the Apuseni Mts. area, there was a complex development between typical calc-alkaline and adakite-like calc-alkaline magmas at 15–8 Ma, clearly different geochemically (Figs. 2–4) from magmas generated contemporaneously in front of the Central Segment (Fig. 1), in a period of major rotations and roll-back processes.

Magma generation occurred in an extensional regime (Royden, 1988; Csontos and Nagymarosy, 1998;

Ciulavu, 1999; Balintoni and Vlad, 1998) and was therefore probably related to decompressional melting during eastward translation and clockwise rotation of the Intracarpathian blocks during middle Miocene times (Seghedi et al., 1998; Roşu et al., 2001; Seghedi et al., 2004a). Variable fluid involvement in magma generation (Fig. 4), sometimes time dependent, characterise a heterogeneous, variably fluid-rich source, most probably the lower crust or upper lithospheric (Roşu et al., 2001, 2005; Seghedi et al., 2004a). After a time gap at ~2.5 Ma, eruption of alkali basalts and ~1.5 Ma shoshonites suggests a hot mantle upwelling in a local extensional environment (Seghedi et al., 2004a).

5.4. South-eastern segment

In front of the South-eastern Segment post-collisional volcanism developed from north to south along the Carpathian accretionary prism between 10 Ma and < 1 Ma. It is assumed to be related to upper middle Miocene oblique subduction and roll-back bending of a narrow slab connected to East European plate (Mason et al., 1998), which created the necessary geotectonic conditions for along-arc magma generation by progressive break-off processes. Based on kinematic data Linzer (1996) has imagined a model of magma generation, by continuous migration toward east, as triggered by a west-to-east subduction rollback of Moesian plate subduction slab, currently in a vertical position in the Vrancea zone.

Early volcanic activity in Cãlimani shows large source variability (Figs. 2–4); this is also seen at the inception of South Harghita magmatism. This may have implications for the tectonic processes, such as break-off initiation (Cãlimani) or slab tearing (South Harghita). South Harghita magmas were generated after a time gap (~0.5 Ma) suggesting a different mechanism. A contribution from a slab melt produced in the eclogite field is suggested for the youngest magmatism in the South Harghita area. Adakite-like magmas were generated due to increased temperature by OIB-source mantle upwelling, which itself produced alkali basalt magmas via decompressional melting (Downes et al., 1995b; Seghedi et al., 2004a). Here, the late-stage complex oblique subduction and break-off processes were followed by tearing of the slab (Maţenco et al., 1997; Gvirtzman, 2002). Towards the south the underthrusted East European/Scythian and Moesian blocks are delimited by the Trotu° fault system and indicate an unusual subduction mechanism associated with a special development of overlying foredeep basins (Maţenco et al., 2003; Bertotti et al., 2003; Cloething et al., 2004). Contemporaneous eruption of normal and adakite-like calc-alkaline, shoshonitic and alkali basaltic magmas at ~1.5 Ma (Pécskay et al., 1995b; Panaiotu et al., 2004; Seghedi et al., 2004a) point to the lateral variation of lithospheric elastic properties (Maţenco et al., 1997), the timing of transition between along-arc break-off and tearing and/or delamination processes (Mason et al., 1998; Sperner et al., 2001; Gvirtzman, 2002) at the transition from East European/Scythian to Moesian block as lower plate.

6. Conclusions

Analysis of the literature data from the CPR magmatism between 20–0.1 Ma has led us to conclude that there is interdependence between geochemical and isotopic composition of magmas, timing and the tectonic setting in which they were generated. Isotope geochemistry is a powerful tool and together with major and trace element geochemistry reflects the characteristics and processes in the source regions of different magma types generated. Most of the calc-alkaline melts in CPR are not a direct product of west-driving subduction processes, but are collisional or post-collisional extension-related melts. Various extension processes generated either crustal melts or melting of already metasomatized overlying mantle, after the active subduction ceased. The data show evidence that an inherited subduction signature is preserved in the mantle after cessation of subduction, being reactivated by asthenosphere uprise via subduction roll-back, slab detachment, slab-break-off or tearing. The subduction components have been progressively consumed during the magma generation processes in the mantle, so their effect diminished with time, and even some of the alkalic basaltic magmas (generated contemporaneously or after calc-alkali magmas) still keep a slight slab signature.

This situation is comparable with other areas in the world, as Indonesia (e.g. Elburg and Foden, 1998), Italy (e.g. Serri, 1990; Doglioni et al., 1999) or Taiwan (e.g. Wang et al., 2004), which suggests that there is a geochemical response to continental collision, that could show similarities in different regions, despite the differences in the dominant tectonic processes, specific in each region (back-arc opening, extension by transtensional faulting, along-arc break-off and tearing), all of which are connected with mantle upwelling. Many problems remain to be solved or refined, from both the petrological and tectonic point of view. We consider that it is essential to use a combination of tectonic and petrologic approaches to solve these problems, in order to develop new models to improve existing geodynamic interpretations.

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References

Balla, Z., 1987. Tertiary paleomagnetic data for the Carpatho-Pannonian region in the light of Miocene rotation kinematics. Tectonophysics 139, 67–98.

Balintoni, I., Vlad, S., 1998. Tertiary magmatism in the Apuseni Mountains and related tectonic setting. Studia Univ Babeş-Bolyai. Geologie IX, 1–11.

Bertotti, G., Maţenco, L., Cloetingh, S., 2003. Vertical movements around the south-east Carpathians foredeep: lithospheric memory and stress field control. Terra Nova 15, 299–305.

de Boorder, H., Spakman, W., White, S.H., Wortel, M.J.R., 1998. Late Cenozoic mineralization, orogenic collapse and slab detachment in the European Alpine Belt. Earth Planet. Sci. Lett. 164, 569–575.

Ciulavu D., 1999. Tertiary tectonics of the Transylvanian basin. PhD Thesis, Vrije Universiteit, Faculty of Earth Sciences, Amsterdam. 154 pp.

Cloething, S.A.P.L., Burov, E., Maţenco, L., Toussaint, G., Bertotti, G., Andriessen, P.A.M., Wortel, M.J.R., Spakman, W., 2004. Thermo-mechanical controls on the mode of continental collision in the SE Carpathians. Earth Planet. Sci. Lett. 218, 57–76 (Romania).

Csontos, L., 1995. Tertiary tectonic evolution of the intra-Carpathian area: a review. Acta Vulcanol. 7, 1–13.

Csontos, L., Nagymarosy, A., 1998. The mid-Hungarian line: a zone of repeated tectonic inversion. Tectonophysics 297, 51–71.

Csontos, L., Nagymarosy, A., Horvath, F., Kováč, M., 1992. Tertiary evolution in the Intracarpathian area: a model. Tectonophysics 208, 221–241.

Davidson, J.P., 1987. Crustal contamination versus subduction zone enrichment: examples from the Lesser Antilles and implications for mantle source compositions of island arc volcanic rocks. Geochim. Cosmochim. Acta 51, 2185–2198.

Davidson, J.P., 1996. Deciphering mantle and crustal signature in subduction zone magmatism. In: Bebout, G.E., Scholl, D.W., Kirby, S.H., Platt, J.P. (Eds.), Subduction Top to Bottom. Geophysical Monograph, 96, pp. 251–262.

Defant, M.J., Drummond, M.S., 1990. Derivation of slab arc magmas by melting of young subducted lithosphere. Nature 347, 662–665.

Dobosi, G., Jenner, G.A., 1999. Petrologic implications of trace element variation in clinopyroxene megacrysts from the Nograd volcanic province, north Hungary: a study by laser ablation microprobe-inductively coupled plasma-mass spectrometry. Lithos 46, 731–749.

Dobosi, G., Fodor, R.V., Goldberg, S.A., 1995. Late Cenozoic alkalic basalt magmatism in Northern Hungary and Slovakia: petrology, source composition and relationships to tectonics. Acta Vulcanol. 7, 199–207.

Doglioni, C., Harabaglia, P., Merlini, S., Mongelli, F., Peccerillo, A., Piromallo, C., 1999. Orogens and slabs vs. their direction of subduction. Earth Sci. Rev. 45, 167–208.

Downes, H., Pantó Gy. Póka, T., Mattey, D.P., Greenwood, P.B., 1995a. Calc-alkaline volcanics of the Inner Carpathian arc, Northern Hungary: new geochemical and oxygen isotopic results. Acta Vulcanol. 7, 29–41.

Downes, H., Seghedi, I., Szakács, A., Dobosi, G., James, D.E., Vaselli, O., Rigby, I.J., Ingram, G.A., Rex, D., Pécskay, Z., 1995b. Petrology and geochemistry of the late Tertiary/Quaternary mafic alkaline volcanism in Romania. Lithos 35, 65–81.

Drummond, M.S., Defant, M.J., Kapezhinskas, P.K., 1996. Petrogenesis of slab-derived trondhjemite–tonalite–dacite–adakite magmas. Trans. Royal Soc. Edinburgh Earth Sci. 87, 205–215.

Elburg, M.A., Foden, J., 1998. Temporal changes in arc magma geochemistry, Northern Sulawesi, Indonesia. Earth Planet. Sci. Lett. 163, 381–398.

Ellam, R.M., Hawkesworth, C.J., 1988. Elemental and isotopic variation in subduction related basalts: evidence for three component model. Contrib. Mineral. Petrol. 98, 72–80.

Embey-Isztin, A., Downes, H., James, D.E., Upton, B.G.J., Dobosi, G., Ingram, G.A., Harmon, R.S., Scharbert, H.G., 1993. The petrogenesis of Pliocene alkaline volcanic rocks from the Pannonian Basin, Eastern Central Europe. J. Petrol. 34, 317–343.

Embey-Isztin, A., Dobosi, G., 1995. Mantle source characteristics for Miocene–Pleistocene alkali basalts, Carpathian–Pannonian Region: a review of trace elements and isotopic composition. Acta Vulcanol. 7, 155–166.

Fodor, L., Csontos, L., Bada, G., Gyorfy, I., Benkovics, L., 1999. Tertiary tectonic evolution of the Pannonian Basin system and neighboring orogens: a new synthesis of paleostress data. In: Durand, B., Jolivert, L., Horvath, F., Seranne, M. (Eds.), “The Mediterranean Basins: Tertiary extensions within the Alpine orogen”. Geol. Soc. London. Spec. Publ., 156, pp. 295–334.

Gîrbacea, R.A., 1997. The Pliocene to Recent tectonic evolution of the Eastern Carpathians (Romania). Tub. Geowisse. Arb., Rheihe A, vol. 35 (136 pp.)

Gîrbacea, R.A., Frisch, W., 1998. Slab in the wrong place: lower lithospheric mantle delamination in the last stage of the Eastern Carpathians subduction retreat. Geology 26, 611–614.

Gvirtzman, Z., 2002. Partial detachment of a lithospheric root under the southeast Carpathians: toward a better definition of the detachment concept. Geology 30, 51–54.

Harangi, Sz., 2001a. Neogene to Quaternary volcanism of the Carpatho-Pannonian Region – a review. Acta Geol. Hung. 44, 223–258.

Harangi, Sz., 2001b. Neogene magmatism in the Alpine–Pannonian Transition zone – a model for melt generation in a complex geodynamic setting. Acta Vulcanol. 13, 1–11.

Harangi, Sz., Vaselli, O., Tonarini, S., Szabó, Cs., Harangi, R., Coradossi, N., 1995. Petrogenesis of Neogene extension-related alkaline volcanic rocks of the Little Hungarian Plain Volcanic field (Western Hungary). Acta Vulcanol. 7, 173–187.

Harangi, Sz., Downes, H., Kósa, L., Szabó, Cs., Thirlwall, M.F., Mason, P.R.D., Mattey, D., 2001. Almandine garnet in calc-alkaline volcanic rocks of the Northern Pannonian Basin (Eastern-Central Europe): geochemistry, petrogenesis and geodynamic interpretations. J. Petrol. 42, 1813–1843.

Harangi Sz., Downes H., Thirlwall M.F., Geochemistry and petrogenesis of Miocene calc-alkali volcanic rocks in the western Carpathians arc, eastern central Europe: evidence for an enriched mantle source. J. Petrol., submitted.

Hawkesworth, C.J., O'Nions, R.K., Pankhurst, P.J., Hamilton, P.J., Evensen, N.M., 1977. A geochemical study of island-arc and back-arc tholeiites from the Scotia Sea. Earth Planet. Sci. Lett. 36, 253–262.

Horváth, F., 1993. Towards a mechanical model for the formation of the Pannonian Basin. Tectonophysics 226, 333–357.

Huismans, R.S., Podladchikov, Y.I., Cloething, S., 2001. Dynamic modelling of the transition from passive to active rifting, application to the Pannonian basin. Tectonics 20, 1021–1039.

Kapezhinskas, P., McDermott, F., Defant, M.J., Hochstaedter, A., Drummond, M.S., Hawkesworth, C.J., Koloskov, A., Maury, R.C., Bellon, H., 1997. Trace element and Sr-Nd isotopic constraints on a three-component model of Kamchatka Arc petrogenesis. Geochim. Cosmochim. Acta 61, 577–600.

Konečny, V., Lexa, J., Hojstrièová, V., 1995. The Central Slovakia Neogene volcanic field: a review. Acta Vulcanol. 7, 63–79.

Konečný, V., Kováč, M., Lexa, J., Šefara, J., 2002. Neogene evolution of the Carpatho-Pannonian region: an interplay of subduction and back-arc diapiric uprise in the mantle. EGS Spec. Publ. Ser. 1, 165–194.

Kováč, M., Nogymarossy, A., Oszczypko, N., Ślączka, A., Csontos, L., Mărunţeanu, M., Maţenco, L., Márton, M., 1998. Palinspastic reconstruction of the Carpathian Pannonian region during the Miocene. In: Rakus, M. (Ed.), Geologic Development of the Western Carpathians. GSSR, Bratislava, pp. 189–217.

Kovacs, M., 2002. Petrogenesis of subduction-related magmatic rocks in the central-south-east area of Gutâi Mountains. In: Dacia, M. (Ed.), Cluj-Napoca (in Romanian) 201 pp.

Lexa, J., Konečny, V., 1999. Geodynamic aspects of the Neogene to Quaternary volcanism. In: Rakus, M. (Ed.), Geologic Development of the Western Carpathians. GSSR, Bratislava, Bratislava, pp. 219–240.

Linzer, H.-G., 1996. Kinematics of retreating subduction along the Carpathian arc, Romania. Geology 24, 167–170.

Linzer, H.-G., Frisch, W., Zweigel, P., Gîrbacea, R., Hann, H.-P., Moser, F., 1998. Kinematic evolution of the Romanian Carpathians. Tectonophysics 297, 133–156.

Márton, E., Fodor, L., 2003. Tertiary paleomagnetic results and structural analysis from the Transdanubian Range (Hungary): rotational desintegration of the Alcapa unit. Tectonophysics 363, 201–224.

Márton, E., Márton, P., 1996. Large scale rotations in North Hungary during the Neogene as indicated by paleomagnetic data. In: Morris, A., Tarling, D.H. (Eds.), Paleomagnetism and Tectoncs of the Mediterranean Region. Geol. Soc. London. Spec. Publ., vol. 105, pp. 153–173.

Márton, E., Pécskay, Z., 1998. Correlation and dating of the Miocene ignimbritic volcanics in the Bükk Foreland, Hungary: complex evaluation of paleomagnetic and K/Ar isotope data. Acta Geol. Hung. 41, 467–476.

Márton, E., Vass, D., Tunyi, I., 2000. Counterclockwise rotations of the Neogene rocks in the East Slovak Basin. Geol. Carpath. 51, 159–168.

Mason, P., Downes, H., Seghedi, I., Szakács, A., Thirlwall, M.F., 1995. Low-pressure evolution of magmas from the Călimani, Gurghiu and Harghita Mountains. Acta Vulcanol. 7, 43–53.

Mason, P., Downes, H., Thirlwall, M.F., Seghedi, I., Szakács, A., Lowry, D., Mattey, D., 1996. Crustal assimilation as a major petrogenetic process in the East Carpathian Neogene and Quaternary continental margin arc, Romania. J. Petrol. 37, 927–959.

Mason, P.R.D., Seghedi, I., Szakács, A., Downes, H., 1998. Magmatic constraints on geodynamic models of subduction in the Eastern Carpathians, Romania. Tectonophysics 297, 157–176.

Maţenco, L., Bertotti, G., 2000. Tertiary tectonic evolution of the external East Carpathians (Romania). Tectonophysics 316, 255–286.

Maţenco, L., Zoetemeijer, R., Cloetingh, S., Dinu, C., 1997. Lateral variations in mechanical properties of the Romanian external Carpathians: inferences of flexure and gravity modelling. Tectonophysics 282, 147–166.

Maţenco, L., Bertotti, G., Cloetingh, S., Dinu, C., 2003. Subsidence analysis and tectonic evolution of the external Carpathian–Moesian platform region during Tertiary times. Sediment. Geol. 156, 71–94.

Meulenkamp, J.E., Kováč, M., Chica, I., 1996. On Late Oligocene depocentre migration and the evolution of the Carpathian–Pannonian system. Tectonophysics 266, 301–317.

Nemčok, M., Pospisil, L., Lexa, J., Donelik, R.A., 1998. Tertiary subduction and slab breakoff model of the Carpathian Pannonian region. Tectonophysics 295, 307–340.

Panaiotu, C., 1998. Paleomagnetic constraints on the geodynamic history of Romania. Reports on Geodesy, vol. 7. Warsaw University of Technology, pp. 205–216.

Panaiotu C., 1999. Paleomagnetic studies in Romania. Tectonophysics implications. PhD Thesis, University of Bucharest (in Romanian). 265 pp.

Panaiotu, C.G., Pécskay, Z., Hambach, U., Seghedi, I., Panaiotu, C.E., Tetsumaru, I., Orleanu, M., Szakács, A., 2004. Short-lived Quaternary volcanism in the Perşani Mountains (Romania) revealed by combined K-Ar and paleomagnetic data. Geol. Carpath. 55, 333–339.

Papp, D.P., Ureche, I., Seghedi, I., Downes, H., Dallai, L., 2005. Petrogenesis of convergent margin calc-alkaline rocks and the significance of low-isotope oxygen ratio: the Rodna-Bârgău Neogene subvolcanic area (Eastern Carpathians). Geol. Carpath. 56, 77–90.

Pătraşcu, S., Panaiotu, C., Şeclăman, M., Panaiotu, C.E., 1994. Timing and rotational motions of Apuseni Mountains, Romania: palaeomagnetic data from Tertiary magmatic rocks. Tectonophysics 233, 163–176.

Pécskay, Z., Lexa, J., Szakács, A., Balogh, Kad., Seghedi, I., Konečny, V., Kovacs, M., Márton, E., Széky-Fux, V., Póka, T., Gyarmaty, P., Edelstein, O., Roşu, E., Žec, B., 1995a. Space and time distribution of Neogene–Quaternary volcanism in the Carpatho-Pannonian Region. Acta Vulcanol. 7, 15–29.

Pécskay, Z., Edelstein, O., Seghedi, I., Szakács, A., Kovacs, M., Crihan, M., Bernad, A., 1995b. K-Ar datings of the Neogene–Quaternary calc-alkaline volcanic rocks in Romania. Acta Vulcanol. 7, 53–63.

Pécskay, Z., Seghedi, I., Downes, H., Prychodko, M., Mackiv, B., 2000. Geochronological and volcanological study of calc-alkaline volcanic rocks from Transcarpathia, SW Ukraine. Geol. Carpath. 51 (2), 83–89.

Póka, T., Zelenka, T., Szakács, A., Seghedi, I., Nagy, G., Simonits, A., 1998. Petrology and geochemistry of the Miocene acid explosive volcanism of the Bükk Foreland, Pannonian Basin, Hungary. Acta Geol. Hung. 41/4, 437–467.

Ratschbacher, L., Frisch, W., Linzer, H.-G., Merle, O., 1991. Lateral extrusion in the Eastern Alps: Part 2. Structural analysis. Tectonics 10, 257–261.

Rosenbaum, J.M., Wilson, M., Downes, H., 1997. Multiple enrichment of the Carpathian–Pannonian mantle: Pb-Sr-Nd isotope and trace element constraints. J. Geophys. Res. 102 (B7), 14,947–14,961.

Roşu, E., Pécskay, Z., Stefan, A., Popescu, G., Panaiotu, C., Panaiotu, C.E., 1997. The evolution of the Neogene volcanism in the Apuseni Mountains (Romania): constraints from new K/Ar data. Geol. Carpath. 48 (6), 353–359.

Roşu, E., Szakács, A., Downes, H., Seghedi, I., Pécskay, Z., Panaiotu, C., 2001. The origin of Neogene calc-alkaline and alkaline magmas in the Apuseni Mountains, Romania: the adakite connection. Rom. J. Miner. Depos. 71 (suppl. 2), 3–23 (ABCD-Geode 2001 workshop).

Roşu, E., Seghedi, I., Downes, H., Alderton, D.H.M., Szakács, A., Pécskay, Z., Panaiotu, C., Panaiotu, C.E., Nedelcu, L., 2005. Extension-related Miocene calc-alkaline magmatism in the Apuseni Mountains, Romania: origin of magmas. Swiss Bull. Mineral. Petrol. 84 (1–2), 153–172.

Royden, L.H., 1988. Late Cenozoic tectonics of the Pannonian basin system. In: Royden, L., Horvath, F. (Eds.), The Pannonian Basin: A study in Basin evolution. AAPG Memoir, vol. 45, pp. 27–48.

Royden, L.H., 1993. The tectonic expression slab pull at continental convergence boundaries. Tectonics 12, 303–325.

Royden, L.H., Burchfiel, B.C., 1989. Are systematic variations in thrust-belt style related to plate boundary processes? Tectonics 8, 51–61.

Royden, L.H., Horvath, F., Burchfiel, B.C., 1982. Transform faulting, extension and subduction in the Carpatho-Pannonian region. Bull. Geol. Soc. Am. 93, 717–725.

Salters, V.J.M., Hart, S.R., Pantó, Gy., 1988. Origin of Late Cenozoic volcanic rocks of the Carpathian arc, Hungary. In: Royden, L., Horvath, F. (Eds.), The Pannonian Basin: A study in Basin evolution. AAPG Memoir, 45, pp. 279–292.

Săndulescu, M., 1988. Cenozoic tectonic history of the Carpathians. In: Royden, L., Horvath, F. (Eds.), The Pannonian Basin: A study in Basin evolution, AAPG Memoir, 45, pp. 17–25.

Seghedi, I., Szakács, A., Mason, P.R.D., 1995. Petrogenesis and magmatic evolution in the East Carpathians Neogene volcanic arc (Romania). Acta Vulcanol. 7, 135–145.

Seghedi, I., Balintoni, I., Szakács, A., 1998. Interplay of tectonics and Neogene post-collisional magmatism in the Intracarpathian area. Lithos 45, 483–499.

Seghedi, I., Downes, H., Pécskay, Z., Thirlwall, M.F., Szakács, A., Prychodko, M., Mattey, D., 2001. Magmagenesis in a subduction-related post-collisional volcanic arc segment: the Ukrainian Carpathians. Lithos 57, 237–262.

Seghedi, I., Downes, H., Szakács, A., Mason, P.R.D., Thirlwall, M.F., Roşu, E., Pécskay, Z., Márton, E., Panaiotu, C., 2004a. Neogene–Quaternary magmatism and geodynamics in the Carpathian–Pannonian region: a synthesis. Lithos 72, 117–146.

Seghedi, I., Downes, H., Vaselli, O., Szakács, A., Balogh, K., Pécskay, Z., 2004b. Post-collisional Tertiary–Quaternary mafic alkalic magmatism in the CarpathianPannonian region: a review. Tectonophysics 393, 43–62.

Seghedi, I., Szakács, A., Pécskay, Z., Mason, P.R.D., 2005. Eruptive history and age of magmatic processes in the Călimani volcanic structure (Romania). Geol. Carpath. 56, 67–75.

Serri, G., 1990. Neogene–Quaternary magmatism of the Tyrhenian region: characterization of the magma source and geodynamic implication. Geol. Soc. It. Mem. 41, 219–242.

Sperner, B., Lorenz, F., Bonjer, K., Hettel, S., Muller, B., Wenzel, F., 2001. Slab break-off-abrupt cut or gradual detachment? New insights from the Vrancea Region (SE Carpathians, Romania). Terra Nova 13, 172–179.

Sperner, B., Ratschbacher, L., Nemčok, M., 2002. Interplay between subduction retreat and lateral extrusion: Tectonics of the Western Carpathians. Tectonics 21 (6), 1051. doi:10.1029/2001TC901028.

Szabó, Cs., Harangi, Sz., Csontos, L., 1992. Review of Neogene and Quaternary volcanism of the Carpathian–Pannonian region. Tectonophysics 208, 243–256.

Szakács A., 2000. Petrologic and tephrologic study of Lower Badenian volcanic tuffs from NW of Transylvanian Basin, PhD Thesis, University of Bucharest (in Romanian), 168 pp.

Tari, G., Dövényi, P., Dunkl, I., Horváth, F., Lenkey, L., Stefănescu, M., Szafián, P., Tóth, T., 1999. Lithospheric structure of the Pannonian Basin derived from seismic, gravity and geothermal data. In: Durand, B., Jolivet, L., Horváth, F., Séranne, M. (Eds.), The Mediterranean Basins: Tertiary Extension within the Alpine Orogen, 156. Geological Society, London, pp. 215–250 (Spec. Publ.)

Tatsumi, Y., Eggins, S., 1995. Subduction Zone Magmatism. Blackwell Science, Cambridge, Massachusetts. 211 pp.

Thirlwall, M.F., Graham, A.M., Arculus, R.J., Harmon, R.S., Macpherson, C.G., 1996. Resolution of the effects of crustal assimilation, sediment subduction and fluid transport in island arc magmas: Pb-Sr-Nd-O isotope geochemistry of Grenada, Lesser Antilles. Geochim. Cosmochim. Acta 23, 4785–4810.

Vaselli, O., Downes, H., Thirlwall, M., Dobosi, G., Coradossi, N., Seghedi, I., Szakács, A., 1995. Ultramafic xenoliths in Plio-Pleistocene alkali basalts from the Eastern Transylvanian Basin: depleted mantle enriched by vein metasomatism. J. Petrol. 36, 23–53.

Vass, D., 1995. The origin and disappearance of Hungarian Paleogene basin and short-term Lower Miocene basins in Northern Hungary and southern Slovakia. Slovak Geol. Mag. 1–1, 81–95.

Wang, K.-L., Chung, S.-L., O'Reilly, S.Y., Sun, S.-S., Shinjo, R., Chen, C.-H., 2004. Geochemical constraints for the genesis of post-collisional magmatism and the geodynamic evolution of the Northern Taiwan region. J. Petrol. 45, 975–1011.

Wortel, M.J.R., Spakman, W., 2000. Subduction and slab detachment in the Mediterranean–Carpathian region. Science 290, 1910–1917.

Zweigel, P., 1997. The Tertiary tectonic evolution of the Eastern Carpathians (Romania): orogenic arc formation in response to microplate movements. Tüb. Geowiss. Arb. 33 (127 pp.).