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Tectonic significance of changes in post-subduction Pliocene-Quaternary magmatism in the south east part of the Carpathian-Pannonian Region

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Abstract

The south-eastern part of the Carpathian-Pannonian region records the cessation of convergence between the European platform/ Moesia and the Tisza-Dacia microplate. Magmatic activity in this area, in close proximity to the 'Vrancea zone', shows a shift from normal calc-alkaline to much more diverse compositions (adakite-like calc-alkaline, K alkalic, mafic Na-alkaline and ultrapotassic) in the Pliocene-Quaternary, suggesting a significant change in geodynamic processes at approximately 3 Ma. We review the tectonic setting, timing, petrology and geochemistry of the post-collisional volcanism to constrain the role of geodynamics on melt production and migration. The calc-alkaline volcanism (5.3-3.9 Ma) marks the end of normal subduction-related magmatism along the post-collision Călimani-Gurghiu-Harghita volcanic chain in front of the European convergent plate margin. At ca. 3 Ma magma compositions changed in South Harghita to adakite-like calc-alkaline and continued until recent times (< 0.03 Ma) interrupted at 1.6-1.2 Ma by generation of Na and K alkalic varieties, signifying changes in the source and melting mechanism. We attribute the progressive change in magma composition in front of the Moesian platform to two main geodynamic events: (1) slab-pull and steepening with opening of a tear window (adakite-like calc-alkaline magmas) and (2) inversion tectonics (Na and K alkalic magmas). Contemporaneous post-collision volcanism at the eastern edge of the Pannonian Basin at 2.6-1.3 Ma was dominated by Na alkalic and ultrapotassic magmas, suggesting a close relationship with thermal rifting and inversion tectonics. Similar timing, magma chamber processes and volume for K-alkalic (shoshonitic) magmas in the South Apuseni Mountains (1.6 Ma) and South Harghita area at a distance of ca. 200 km imply a regional connection with the inversion tectonics.

Key words: Post-collisional slab mechanics, calc-alkaline, adakite-like, Na-alkalic, K-alkalic and ultrapotassic magmas.

1. Introduction

Post-collision magmatism at convergent plate boundaries is very complex and is usually characterized by the presence of adakite-like and/or alkaline magmas, e.g. in the Mediterranean (Duggen et al., 2005), Tibet (Turner et al., 1996; Mo et al., 2006) and Baja California (Negrete-Aranda and Cañon-Tapia, 2008). The existence of such magmas may be associated with the post-collisional evolution of inherited slabs. A typical Africa-European collision zone includes a subduction stage characterized by roll-back associated with extensional back-arc volcanism in highly arcuate orogenic settings (Faccenna et al., 2004; Harangi et al., 2006). The SE Carpathians is a region where the post-collisional stage of a highly arcuate orogen is associated with unusual volcanism, where the final stage of roll-back of the slab can be seen in the high-velocity intermediate-depth mantle anomaly detected by seismic tomography studies (e.g., Martin et al., 2006), associated with the Vrancea seismic zone (e.g., Oncescu and Bonjer, 1997).

After the collision at 11 Ma (Mațenco and Bertotti 2000), volcanism occurred in the SE Carpathians and in the Pannonian Basin (Fig. 1). The large amount of research in recent decades related to deciphering the lithospheric structure of the Carpathians (e.g., Cloetingh et al., 2006; Schmid et al., 2008 and references therein) resulted in a vast structural database that is relevant to the interpretation of magma generation episodes. Furthermore, the foreland of the SE Carpathians has striking contrasts in mechanical properties distributed along the orogen which have been proven to impact the earlier subduction stage (e.g. Cloetingh et al., 2004) and have the potential to affect magma generation. Changes in the stress regimes within the Pannonian-Carpathian system (Bada et al., 2007; Jarosinski et al., 2007) can partition strain along particular fault structures which might function as magma pathways. In particular, reactivated large fault systems such as transcurrent zones or transform faults can facilitate rapid ascent of magma.

In the SE Carpathians and Transylvanian Basin, post-collisional magmas include adakite-like calc-alkaline, K-alkalic and Na-alkalic varieties (e.g. Mason et al, 1996, 1998; Pécskay et al., 1995, 2006; Seghedi et al, 2004a, b; Harangi et al., 2006) whereas isolated occurrences of K-alkalic, Na-alkalic and ultrapotassic rocks are present in the SE Pannonian Basin, near the contact with the Apuseni Mountains and South Carpathians (Downes et al., 1995; Harangi et al., 1995; Roşu et al., 2004; Pécskay et al., 2006; Seghedi et al., 2008). Using recently published geochemical and structural data, we critically examine the tectonic models, proposing a novel explanation for the origin of post-collisional volcanism that encompasses an understanding of the geodynamic evolution of the region. We demonstrate a clear relationship between the mechanism of Pliocene-Quaternary magma generation and coeval tectonic processes in the Carpathians.

2. Constraints from the post-collisional evolution of the SE Carpathians

The evolution of the entire Carpathian region during Middle-Late Miocene times was characterized by coeval back-arc extension in the Pannonian Basin and contraction at the exterior of the arc (e.g. Horváth et al., 2006). Back-arc extension took place over an inherited orogenic structure composed of basement and cover nappes, sutured during episodes of successive shortening during Albian-Palaeogene times (Csontos and Vörös, 2004 and references therein). This structure includes three presently internal Carpathian blocks: Tisza to the south-west and Dacia to the south-east that were sutured during intra-Turonian times, and subsequently sutured to the ALCAPA block to the north in early Miocene times (Schmid et al., 2008) (Fig. 1). During Palaeogene-Miocene times, these blocks moved into the so-called Carpathian embayment, a gulf into the stable foreland platforms of Palaeozoic/Proterozoic Europe (i.e. the East European/Scythian and Moesian platforms) (Balla 1987; Pharaoh et al., 2006; Ustaszewski et al., 2008 and references therein). In between these internal blocks and the external foreland, the Carpathian nappes experienced 160-220 kms of shortening (e.g. Morley 1996) by the time contraction ceased at 11 Ma.

2.1 Tectonic constraints

Post-dating nappe emplacement, two different periods can be defined in the tectonic evolution of the SE Carpathians (Fig. 2). The first period is latest Miocene-Pliocene when subsidence is recorded in all areas overlying the Moesian platform, commonly interpreted as a slab-pull effect (Maţenco et al., 2007). The second period (latest Pliocene-Quaternary) was characterized by differential vertical movements associated with ~5km of contraction restricted roughly to the area located between the Trotuş and Intramoesian faults (Fig. 1, Leever et al., 2006). This is interpreted as foreland-coupling (sensu Ziegler et al., 1995), exhumation related to high-angle reverse faulting in the central part of the orogen being associated with enhanced subsidence in the foreland (Maţenco et al., 2007). This interpretation is supported by the apparently folded, shallow Moho beneath the orogen (Hauser et al., 2007, see Schmid et al., 2008 and their East Carpathians profile in Plate 3). At the regional scale, this was coeval with the Plio-Quaternary inversion recorded in the Pannonian Basin, associated with fault reactivation, large-scale folding and present-day seismicity, generally interpreted as an effect of the push from the Adriatic indenter (e.g. Pinter et al., 2005).

The present-day geometry of the lithosphere-asthenosphere boundary (the probable magma generation zone) is a result of two diachronous mechanisms. Firstly the widely distributed Miocene crustal extension (Tari et al., 1999) is associated with much larger thinning of the mantle lithosphere in the Pannonian Basin (Lenkey and Horvath 2006), reaching thicknesses as low as 60 km (Horvath et al., 1995). Secondly, gravitational sinking of the slab beneath the Vrancea region induces convection in the asthenospheric mantle with downwelling adjacent to the sinking slab and upwelling beneath the eastern part of the Transylvanian Basin (Ismail-Zadeh et al., 2005). The upwelling part is demonstrated by seismic attenuation beneath the internal part of the Carpathian bend zone (Russo et al., 2005; Popa et al., 2005; Ivan 2008), by the low velocity anomaly observed in seismic tomography beneath the Transylvanian Basin (Martin et al., 2006), and by high ^{3}He/^{4}He values of post-volcanic gas emanations (Vaselli et al., 2000). The neighboring high velocity anomaly coincides with a series of frequent and strong intermediate mantle-level earthquakes clustered in a narrow zone which extends almost vertically from around 70 to 170km in depth, known as the Vrancea mantle seismic zone (Fig. 1) (Oncescu et al., 1984; Oncescu and Bonjer, 1997). In contrast, the area between the Pannonian Basin and the Vrancea zone, i.e. the Transylvanian Basin and the eastern part of the Apuseni mountains, displays only minor Miocene upper crustal extension (Krézsek and Bally, 2006; Szakács and Krézsek, 2006). This transitional area has a rather low surface heat-flux (30-60mW/m^2) which may indicate crust and lithosphere of normal thicknesses (Demetrescu and Andreescu, 1994; Demetrescu et al., 2001; Dererova et al., 2006).

Significant differences exist between the northern (East European and Scythian Platforms) and southern (Moesian Platform) parts of the foreland (Cloetingh et al., 2004 and references therein), north and south of the Trotus fault. In the north, collision was oblique, being accommodated by orogenic exhumation in the order of 6 km (Gröger et al., 2008). The coeval collision in the south was associated with somewhat reduced uplift (Sanders et al., 1999) and by subsidence in the foreland, with up to 6 km of sediments being recorded (Tărăpoancă et al., 2003).

Most geodynamic models for the East Carpathians start from a common point: the Miocene roll-back of the distal (presumed oceanic) parts of the European lithosphere (*sensu* Royden and Burchfiel, 1989). Ideas diverge when discussing the post-collisional times, in an effort to explain the origin of the Carpathian volcanism and Vrancea seismicity in a consistent manner. Most models assume that the current geodynamic situation is the result of subduction, probably of oceanic character (e.g. Linzer et al., 1998). Other models assume that slab detachment, initiated at 16 Ma in the area of the Western Carpathians, had migrated towards the SE, allowing movement of the intra-Carpathian blocks into the Carpathian embayment (Nemčok et al., 1998; Wortel and Spakman, 2000), potentially associated with tearing of previously subducted slab fragments (Sperner et al. 2001). The overall detachment would explain the gradual migration in time of emplacement of volcanic structures along the Călimani-Gurghiu-Harghita (CGH) volcanic chain in the East Carpathians (e.g., Seghedi et al., 2005) (Fig.1). Different types of delamination (sensu Sacks and Secor, 1990), potentially associated with detachment, could have taken place during or after collision (Gîrbacea and Frisch, 1998; Gwirtzman, 2002; Knapp et al., 2005). This could provide an alternatively explanation for the asthenospheric upwelling in the hinterland (NW) of the present-day slab. Finally the model of Houseman and Gemmer (2007) suggests that the present-day situation can also be obtained by gravitational instability of the mantle lithosphere by viscous flow towards the Vrancea high velocity anomaly.

2.2 Constraints from magmatic products

While post-11 Ma shortening in the foreland was minor, in the same time interval large volumes of calc-alkaline volcanic rocks (~1400 km^3) were emplaced in the CGH volcanic chain (Szakács and Seghedi, 1995). Volcanic centers seem to be concentrated along individual faults and/or at intersections of faults, the age of volcanism becoming gradually younger southwards between 10.5-0.03 Ma (Pécskay et al., 1995; Seghedi et al., 1994; Fielitz and Seghedi, 2005). In the north, this volcanism was coeval with the opening of small-scale hinterland basins, which are interpreted as either extensional (Fielitz or Seghedi, 2005) or shallow volcanic sag structures (Szakács and Krézsek, 2006). In the south, part of the magmatism was coeval with or post-dated the subsidence of the Braşov (<5.8 Ma, Ciulavu et al., 2000), Gheorgheni and Ciuc basins (Gîrbacea et al., 1998; Fielitz and Seghedi, 2005). The geometry of the faults and alignment of volcanic centers indicate both strike-slip and normal faulting and permitted the ascent of magmas generated in the upper mantle and lower crust (see Mason et al., 1995, 1996; Seghedi et al., 2004a).

Pliocene-Quaternary magmatism occurred in the South Harghita Mountains which form part of the CGH volcanic chain (Szakács et al., 1993; Szakács & Seghedi, 1995) (Figs. 1 and 2). Calc-alkaline volcanism developed here between 5.3 and 0.3 Ma with a major gap at 3.9 - 2.8 Ma and another gap at 1.6-1.0 Ma. However, in spite of these interruptions, the partial spatial overlap of individual volcanoes shows continuity along the NW-SE direction although row of South Harghita volcanic edifices crosscuts the easternmost tip of the Dacia unit (Szakács et al., 1993) (Figs. 1 and 2). The 1.6-1.0 Ma time gap along the CGH chain is a period when K-alkalic volcanism (1.6-1.4 Ma) developed at Bicsad/Malnaş close to the southward extension of the South Harghita chain, whilst Na-alkalic volcanism (1.5-1.2 Ma) developed 40 km to the west in the Perşani Mountains (Downes et al., 1995; Panaiotu et al., 2004) (Figs. 1 and 2). These volcanic centers are arranged parallel to a ~ NNE-SSW normal fault system with the same orientation as the main normal faults of the Braşov basin crossing with an E-W system (Ciulavu et al., 2000; Gîrbacea, 1997). A final stage of Na-alkalic magmatism occurred in the Perşani Mts. at 0.6 Ma (Panaiotu et al., 2004). In the eastern part of the Pannonian Basin (Fig. 1), Na-alkalic volcanism at Lucareț is older, occurring at 2.4-2.6 Ma. In the south Apuseni area, an isolated 1.6 Ma old K-alkalic body at Uroi (Roşu et al., 2004) was emplaced at the same time as the K-alkalic rocks in the SE Carpathian. Ultrapotassic magmatism is older (2.1 Ma) at Bar in the Pannonian Basin (Harangi et al, 1995; Pécskay et al., 1995) and younger (1.35 Ma) at its eastern margin at Gătaia (Seghedi et al., 2008).

3. Petrological and geochemical features of the Plio-Quaternary post-collisional volcanism

Detailed petrological characteristics of South Harghita and Perşani volcanic rocks were described by Downes et al. (1995), Mason et al. (1996, 1998) and Seghedi et al. (2004 a, b). The youngest volcanic products in South Harghita, according to the total alkali vs. silica classification diagram (Fig. 3a), are shoshonitic and high-K calc-alkaline basaltic andesites, andesites and dacites, with a gradual increase in K_2O and decrease in SiO_2 for the youngest rocks (Peccerillo and Taylor, 1976; Seghedi et al., 1987, Szakács et al., 1993) (Fig. 3a). This increase in K_2O, associated with H_2O enrichment, is reflected in a change of phenocryst composition from pyroxene, through hornblende, to biotite. The calc-alkaline rocks are intermediate to acidic, derived from a mafic parental magma by fractional crystallization associated with some crustal assimilation (Seghedi et al., 1986; Szakács and Seghedi, 1986; Mason et al., 1996). These magmas differ in chemical composition from the older calc211 alkaline magmas of the CGH chain in having high Ba and Sr and low Y and B concentrations (1000-2000 ppm Ba, 1000-1600 ppm Sr, 5-15 ppm Y, 10–30 μg/g B) (Mason et al., 1996, 1998; Seghedi et al., 1987; Szakács et al., 1993; Vinkler et al., 2007; Gméling et al., 2007). These compositions show strong similarities to adakites and hence are termed “adakite-like” (Seghedi et al., 2004a).

The K-alkalic volcanic dome at Uroi in the southern part of the Apuseni Mountains and two small-volume K-alkalic volcanic domes (Malnaş, Murgul/Bicsad) in the southernmost part of South Harghita Mts., are shoshonitic andesites with high K_2O and low SiO_2 contents (Fig. 3a) and a mineralogical assemblage of olivine, clinopyroxene, orthopyroxene and hornblende, showing a hybrid composition resulting from mixing processes during ascent (Mason et al., 1996; Roşu et al., 2004; Seghedi et al., 2007). The petrographic and chemical similarities between these bodies of similar age but situated 200 km apart indicate that similar processes were responsible for their generation. It seems likely that these magmas resided in crustal magma chambers where differentiation and mixing occurred.

Na-alkalic basaltic rocks from Perşani Mts. plot in the trachybasaltic field of Fig. 3a (Downes et al., 1995) but have distinctively higher La/Nb and lower Ce/Pb ratios than the other alkaline basalts in the Pannonian Basin, suggesting a subduction-related component in their source region (Embey-Isztin and Dobosi, 1995; Downes et al., 1995; Seghedi et al., 2004b).

In the eastern part of the Pannonian Basin, three post-collisional monogenetic volcanoes are known (Fig. 1). Na-alkaline magmas erupted at Lucareț plot in the same field as the Na-alkaline basalts of the Perşani Mts. (Fig. 3a) and most of the Pliocene alkali basalts in the western part of the Pannonian Basin (Embey-Isztin et al., 1993; Downes et al., 1995; Harangi, 2001). Two occurrences of ultrapotassic volcanism (Bar and Gătaia) plot in the highly alkaline field (Fig 3a). The ΔQ vs. K_2O/Na_2O classification diagram (acc. Peccerillo, 2003) clearly differentiates potassic and ultrapotassic magmas from normal calc-alkaline ones by higher K_2O/Na_2O ratio and their greater silica undersaturation (Fig. 3b), whereas the Na-alkalic magmas are distinguished by their negative ΔQ values. All are clearly distinct from the CGH magmas.

In Figure 4, we use particular trace element ratios such as Nb/Y, Ba/Nb, La/Y, which remain relatively unaffected by crystal fractionation processes, to reveal magma sources. The calc-alkaline magmas of South Harghita show an increase in Nb/Y with time (Fig, 4a), starting from the normal varieties erupted before 3.9 Ma to the adakite-like calc-alkaline and K-alkalic ones which were erupted until recent times. Na-alkalic basalts from Lucareț and ultrapotassic magmas from Bar and Gataia show Nb/Y ratios >2 as do the Na-alkalic magmas from the rest of the Pannonian Carpathian Region. Na-alkalic basalts from the Perşani Mts. and the Uroi K-alkalic magmas fall between these two groups.

The SiO_2-Nb/Y diagram (Fig 4b) separates source processes (various types of mantle source and inferred degrees of partial melting) from various differentiation processes (e.g., fractional crystallization – labeled as FC in Fig 4b). The South Harghita calc-alkaline magmas show slightly different fractionation trends for each volcanic structure, with slightly increasing Nb/Y ratios resulting from partial melting of a heterogeneous mantle source (Fig. 4b). This source trends towards Na-alkalic basalt magmas from the Persani Mountains, which are dominantly derived from an asthenospheric source (Downes et al., 1995; Vaselli et al., 1995; Seghedi et al., 2004b, 2005). K-alkalic magmas from South Harghita and Uroi show similar Nb/Y ratios as the Perşani Na-alkalic basalts, whereas the ultrapotassic ones from Bar and Gătaia have similar values to Na-alkalic basalts from elsewhere in the Carpathian-Pannonian Region (see Embey-Isztin et al., 1993).

In the Ba/Nb-La/Y diagram (Fig. 4c) the South Harghita calc-alkaline and K-alkalic magmas show a positive correlation that suggests an important involvement of fluid components (Ba/Nb>60) and high-pressure fractionation (La/Y>2), probably related to slab melting processes in the generation of adakite-like calc-alkaline magmas (Seghedi et al., 2004a, 2005). Higher La/Y at lower Ba/Nb is characteristic for ultrapotassic and K-alkalic magmas from the eastern part of the Pannonian Basin and Apuseni Mts. The younger Na-alkalic basalts in the Pannonian Basin differ from those in the Perşani Mountains, which show a higher Ba/Nb ratio that suggests the influence of subduction-modified material in magma generation (Downes et al., 1995).

Adakite-like magmas from South Harghita show an unusual trend in their Pb–Sr isotope ratios (Fig. 4d) that contrasts strongly with the general CGH trend (in which crustal assimilation was linked with fractionation). Their adakite-like trend is parallel to that of the Perşani Na-alkalic magmas. This is closely associated with an increase of Nb/Y towards values more typical of alkaline melts (resembling Ocean Island Basalts - OIB) and is directed toward an enriched mantle component (EM1). Enrichments in La over Y and Ba over Nb suggest an influx of fluids from the mantle source, which also affected Pb-isotope ratios, whereas the HREE-depletion (low La/Y) implies the gradual increase of garnet in the source

(Mason et al., 1996) and/or high-pressure amphibole fractionation (Harangi and Lenkey 2007).

4. A combined tectono-magmatic scenario

Calc-alkaline magma compositions throughout the CGH chain suggest a rather homogeneous subduction-related source (**CA source**) (Mason et al., 1996). In contrast the highly variable characteristics of post-collisional Plio-Quaternary magmatism in the SE Carpathians and eastern Pannonian Basin call for magma generation processes in a wide variety of settings. Heterogeneity of Sr, Nd and Pb isotopic ratios, combined with a great heterogeneity of trace element patterns (Seghedi et al., 2008), is probably a source effect (e.g. Chalot-Prat and Gîrbacea, 2000; Seghedi et al., 2004a), likely including previously metasomatised subcontinental mantle. The 5.3-3.9 Ma Pliocene calc-alkaline volcanism discussed here are similar to all CGH volcanism (11-5.3 Ma) (Mason et al., 1996); however the younger Pliocene (2.8-1.6 Ma) and Quaternary (1-0.03 Ma) rocks show increasing adakitic tendencies, i.e. increasing Sr/Y, Nb/Y and decreasing ^{206}Pb/^{207}Pb isotopic ratio (**CA-a source**) (Mason et al., 1998; Seghedi et al., 2004a, 2005) (Fig. 4b, d). Although the South Harghita calc-alkaline and K-alkalic (shoshonitic) rocks have many geochemical characteristics in common (e.g., high LILE/HFSE ratios), they display different extents of enrichment in incompatible elements as well as different major element characteristics. The shoshonitic rocks were derived from anomalous mantle sources, most likely enriched lithosphere affected by asthenospheric melt components (**AK source)**. The Na-alkalic rocks from Perşani Mts. and Lucareț were most probably generated in an asthenospheric mantle source similar to that of oceanic island basalts (**ANa source**) (Downes et al., 1995), whereas the ultrapotassic rocks clearly show a different source component with very high Nb/Y coupled with high La/Y (**UK source**), considered to be situated deep in the metasomatized lithosphere (Harangi et al., 1995; Seghedi et al., 2008). This may indicate contemporaneous generation of melts from different mantle sources and/or a change in tectonic regime over a short period of time with multiple sourcing events. The main issue is to relate these magmatic source components to the tectonic setting in which the magmas were generated. In this respect we examine in a geodynamic context the volcanic events and the relationship between the timing and direction of displacement along the fault system, considering two periods marked by sudden changes in magma composition and geochemistry, 2.8 and 1.6 Ma, respectively (Figs. 2 and 4).

4.1. Magmatism with typical subduction signature (until 3.9 Ma)

The typical calk-alkaline magmatism is concentrated in the final phases of Carpathians collision and during post-collisional times. Subduction is documented since the intra-Albian phase of thrusting over the Ceahlău-Severin domain (Fig. 5) or the Măgura-Piennides oceans further to the north (Săndulescu, 1988; Plasienka, 1997), but subduction-related magmatism started in the intra-Carpathians units only during the Middle Miocene (Pécskay et al., 1995; 2006), when the (thinned) continental parts of the lower plate reached the subduction zone (e.g., Ustaszewski et al., 2008). Therefore, a genetic link is likely between the CGH subduction-related magmatism and the arrival of continental crust at the subduction zone. Magmas generated between 11.0 and 3.9 Ma (Fig. 5) in the CGH chain are normal calc-alkaline in composition (Mason et al., 1996, 1998). They show homogeneous Sr–Nd–Pb isotopic compositions that reflect a common mantle source considered to be the subduction metasomatised mantle wedge above the subducting slab (Mason et al., 1996, 1998; Seghedi et al., 2004a). The volcanoes are located roughly parallel to the Carpathians and become younger southwards, along a southward propagating fault system (Pécskay et al., 1995; Szakács and Seghedi, 1995). This along-arc temporal distribution of the volcanism has been explained by gradual slab detachment following an oblique subduction stage (Mason et al., 1998, Seghedi et al., 1998). However, this along-arc temporal distribution of the calc-alkaline volcanism is not associated with a similar migration in time of near-surface vertical movements, as would be theoretically required by the slab-detachment mechanism (Bertotti et al., 2003). This discrepancy still remains to be explained, but the age of the magmatism suggests that, if slab-detachment occurred, it must postdate the cessation of major thrusting at 11 Ma and the 9 Ma thickening in the core of the orogen, as suggested by the exhumation of the Transylvania basin at around 9 Ma (Krézsek and Bally, 2006). In this situation the hypothesis of magma generation during an oblique collision with the thick continental parts of East-European and Scythian lower plate (see Mason et al., 1998) does not explain the rather large time lag between the last possible moment of orogenic shortening (9 Ma) and the youngest normal calc-alkaline volcanism (3.9 Ma).

Magma ascent in the CGH chain was facilitated by the existence of inherited or coeval fractures. Normal faulting and/or transtensional zones are inferred below the volcanic edifices both during the Late Cretaceous (Gröger et al., 2008) and possibly during the latest Miocene-Pliocene (Fielitz and Seghedi, 2005) (Fig. 5).

4.2. Magmatism related to slab corners, asthenospheric uprise and slab steepening (2.8-0.03 Ma)

In the SSE-ward continuation of the CGH volcanic chain, the South Harghita volcanism is oriented oblique, crossing the trend of the East Carpathians (Figure 5a). After a gap of ca. 1 Ma, it records the transition from normal calc-alkaline magmas (up to 3.9 Ma) (**CA source**) to adakite-like calc-alkaline magmas (**CA-a source**), erupting during two time intervals at 2.8-1.6 Ma and 1-0.03 Ma, respectively (Pécskay et al., 1995, 2006; Seghedi et al., 2005; Szakács et al., 1993). This sudden change in magma composition has previously been interpreted as being related to the processes in the hanging slab beneath the Vrancea zone as the expression of the latest stage of subduction along the Carpathians (Mason et al., 1998; Nemčok et al., 1998; Wortel and Spakman, 2000; Konečný et al, 2002; Seghedi et al., 2004a). However, two other processes have previously received much less attention in the effort to link magma generation with geodynamic processes: (1) the existence of a rheologically different domain as the lower plate in the SE Carpathians (i.e. the Moesian Platform and its distal margins, Fig. 6a), and (2) the inversion recorded in the SE Carpathians which started at the beginning of the Quaternary.

The change in subduction mechanics in the Moesian domain changed the process of magma generation. The reduced rates of collision and the gradual steepening of the slab inherited from the roll-back collision continued with a thermal resettlement and viscous re362 equilibration in the asthenosphere of the long-lasting Cretaceous slab (Cloetingh et al., 2004). The pronounced sinking of the slab into the asthenosphere, as inferred from the character of the earthquakes and the geometry of the high velocity body (e.g., Heidbach et al., 2007 and referenced therein), created localized convection currents of asthenospheric material, as derived by numerical modeling of the thermal effects associated with its geometry (Ismail-Zadeh et al., 2005). A significant feature of the local tomography is the striking low velocity anomaly observed beneath the central and eastern part of the Transylvania basin (Fig. 6a). The coincidence in space of the upwelling part of the asthenospheric convection cell with the presence of the low velocity body must indicate a genetic link. This process involves a long residence time of the distal parts of the Moesian slab in the asthenosphere that would lead to slab melting in the eclogite field, generating adakite-like calc alkaline magmas (**CA-a source**) due to increased temperatures related to asthenosphere upwelling or "suction", which itself generated contemporaneous Na-alkalic basalt magmas via decompressional melting (Downes et al, 1995; Mason et al., 1998; Seghedi et al., 2004b, 2005). A downward force (slab-pull) was exerted by this thermally re-equilibrating lithospheric body (e.g., Cloetingh et al., 2004), which can be interpreted in any of the existing Vrancea geodynamic scenarios, from a remnant slab to an inherited and delaminated cold block (*senso* Schott and Schmelling, 1998) from the Moesian lithosphere. In any of these situations, the Moesian block was decoupled (tearing) from the European-Scythian Plate along the Trotuş fault system during the late Miocene collision (see also Seghedi et al., 1998). In the case of delamination of its eclogitic keel and partial melting of this material at mantle depths may explain the peculiar chemistry of shoshonites and adakite-like rocks as a consequence of elevated K_2O/Na_2O in the protolith and high pressure conditions of partial melting (e.g. Xiao and Clemens, 2006). Similar examples have been recognized elsewhere in Baja California by Pallares et al. (2007) and in Italy by Rosenbaum et al. (2008).

In the next sections we relate the three types of magmas (adakite-like calc-alkaline, K388 alkalic and Na-alkalic) as being generated in the transition region between the European-Scythian Plates and the Moesian Plate and specifically within the Moesian plate domain.

4.2.1. *Adakite-like calc-alkaline magmatism associated with corner-flow effect*

The change of magmatism from normal calc-alkaline type in the CGH chain to the large variety found to the south occurred at the contact between the East-European/Scythian and Moesian platforms along the extension of the Trotuş fault (Fig. 5). In the same place, a significant change in the geometry of the lower plate is observed, from normal sub-horizontal inclinations to the north, to the vertical position of the Vrancea slab (Cloetingh et al., 2004). This geometry suggest a tear in the lower plate perpendicular to the strike of the orogen (i.e. the Trotuş fault and its extension), its offset increasing westwards to a situation where the asthenosphere can flow around and into the tear (see Maţenco et al., 1997), using a mechanism similar to the corner flow effects interpreted around the Calabrian slab (Faccenna et al., 2005). The metasomatised lithosphere heated during the horizontal asthenospheric flow around the steepening Vrancea slab is the source of the adakite-like calc-alkaline volcanism recorded exactly on the surface projection of its northern margin. The pathways used by the magmas during their ascent are most likely situated at the structural intersection between the major E-W Trotuş contact and the N-S oriented normal faults system, which was active from approximately 4 Ma (Fig. 5, see also Gîrbacea et al., 1998 for the kinematics and timing of the normal faults system). The second order feature of the observed adakite-like calc-alkaline magmatism, i.e. decreasing emplacement ages and volumes in an SE-ward direction, can be explained by the gradual opening of the lithospheric tear during slab-steepening. Near the surface, this is associated with the westward migration of the late Pliocene-Quaternary depocenters in the Focşani basin (Leever et al., 2006). At greater depths, this may allow asthenosphere "suction", lithosphere stretching and generate magmas (**CA-a source**) in the metasomatized regions of the asthenospheric mantle.

4.2.2. Na- and K-alkalic magmatism associated with localised asthenospheric convection

At greater distances along the strike of the orogen from the northern margin of the Moesian platform, coeval generation of Na- and K-alkalic magmas is recorded along the same N-S oriented normal fault system (Figs. 4, 5 and 6a, see also Ciulavu et al., 2000). At depth, the size and amplitude of the recently discovered low velocity anomaly associated with seismic wave attenuation are unlikely to be the effect of a lithospheric high-temperature body, such as a magmatic chamber (Fig. 6a). Although its western margins are less precise in seismic tomographic images, this low velocity zone must be the effect of hot asthenospheric uprising beneath the center and eastern part of the Transylvania basin. We have, therefore, corrected the lithospheric configuration (Horvath et al., 2006; Dererova et al., 2006) taking into account the results of recent local tomography studies (Martin et al., 2006) (Fig. 6a).

The Na-alkalic mafic magmas were derived from an asthenospheric mantle-source partly affected by subduction metasomatism (**ANa source**), resulted most probably by decompressional melting during asthenospheric uprise (Fig. 6a, Downes et al., 1995; Seghedi et al., 2004a). This asthenospheric upwelling correlates well with the described low-velocity anomaly, which coincides with a high attenuation volume (Popa et al., 2005; Russo et al. 2005; Martin et al., 2006). Mantle xenoliths in the Na-alkalic basalts of the Perşani Mts. point to a refertilised lithospheric mantle which resulted from interaction with an hydrous LREE434 poor, HREE-rich, silica-saturated melt with high Sr contents (Coltorti et al., 2007), the same melts that have favoured generation of adakite-like calc-alkaline magma in this unusual context thermally re-equilibrating slab.

The primitive K-alkalic magmas (**AK source**), which mixed thoroughly with more evolved similar magmas in crustal reservoirs generating hybrid magmas as lava flows or shallow intrusions (Figs. 3 and 6a), must be linked with the same process of hot asthenospheric uprise, but this time the magmas were generated at the base of the lithosphere, that has been previously fertilized by the adakite-like silica-saturated melts (see Coltorti et al., 2007).

The obvious geochemical and isotopic similarities of all magmatic rocks associated with the Carpathian bend area at 2.8-0.03 Ma suggest that asthenospheric uprise might also have mobilized subduction-related fluids/melts from the neighboring lithosphere (e.g., Mason et al, 1998). Alternatively, subduction-related components may have resided in the asthenosphere, where alkaline mafic magmas were generated (Harangi and Lenkey, 2007).

4.3. A distinct mantle source for the Pannonian basin post-collision magmas

The ultrapotassic rocks at Bar (2.1 Ma) in the Pannonian basin and at Gătaia (1.36 Ma) close the eastern border of the Pannonian basin (Figs. 1 and 6a) were derived from a distinct mantle source (**UK source**), in a profoundly metasomatized lithospheric mantle (Harangi et al., 2005; Seghedi et al., 2008). Isolated occurrences of Na-alkalic lavas at Lucareț (**ANa source**) on the eastern border of the Pannonian basin (Downes et al., 1995) are similar to the Pannonian asthenospheric mantle source, which is similar to that described in other parts of Europe (e.g. Lustrino and Wilson, 2007*)*. In the case of the Lucareț (**ANa source**) and Uroi bodies (**AK source**), uprise of the magmas was facilitated by close proximity to a major, almost vertical contact inherited from the Jurassic-Cretaceous evolution of the Eastern Vardar ocean, i.e. the contact between the Apuseni Mountains and the South Carpathians along the

South Transylvania fault (Fig. 6b, see Schmid et al., 2008 for the kinematics, timing and paleogeographic significance of this contact). The magmas certainly have different sources, but have used the same fault as pathways to the surface, in different locations along its strike. At the shallow asthenospheric level the two sources of Na-alkalic magmas (**ANa source**) are also different: that of the Pannonian Basin is inherited from the late-stage Miocene thermal rifting phase (Tari et al., 1999), while that in the SE Carpathians is an effect of the asthenospheric flow generated by the descending high-velocity body. However, deeper in the asthenosphere, these two sources would gradually merge (Fig. 6a and 6b) and this would explain their petrological similarities.

4.4. Superimposed effect of the latest Pliocene – Quaternary inversion

The time of eruption of ultrapotassic and K-alkalic magmas coincides with, or slightly post-dates, the onset of the latest Pliocene-Quaternary inversion in the SE Carpathians (Mațenco et al., 2007), which might be linked with the regional inversion recorded in the Pannonian-Carpathian domain during the indentation of Adria (Bada et al., 2007). The interval between 1.8 and 1.0 Ma is a time gap in activity of two adjacent adakite-like calc-alkaline volcanoes at the southern termination of the South Harghita chain, which is filled by the simultaneous generation of K- and Na-alkalic magmas south of Harghita and also the Uroi K-alkalic volcano in the Apuseni Mountains and the Gătaia lamproite volcano at the eastern edge of Pannonian Basin (Fig. 2).

Since the K-alkalic (shoshonitic) occurrences south of Harghita and in the South Apuseni Mountains (**AK source**) (Fig. 6a) are roughly contemporaneous and show the same petrological characteristics, one possible way would be to connect and activate them along the South-Transylvanian Fault (Szakacs and Seghedi, 1996) (Fig. 6b). However, there is no coeval kinematic structure in the Transylvania basin to link the two areas (Krézsek and Bally, 2006). More likely, the magmas used a local relaxation during the renewed inversion on two different crustal scale structures: (1) the South Transylvania fault, where at a regional level, the inversion changes gradually towards extension (Bada et al., 2007), and (2) the small-scale normal faults in the SE Carpathians.

5. Conclusions

The Pliocene-Quaternary evolution of the south-eastern part of the Carpathian-Pannonian area is characterized by two main geodynamic events: slab-pull, steepening and melting, and inversion tectonics. This generated various types of magma at lithospheric/asthenospheric depths in front of the Moesian plate and in the eastern part of the Pannonian basin. It also marks the end of subduction-related magmatism, generated along the CGH volcanic chain. The most plausible hypothesis for magma generation in this volcanic arc is an initial oblique collision of thick continental parts of East-European and Scythian lower plate with the Tisza-Dacia plate until 9 Ma, subsequently followed by slab break-off until 3.9 Ma (see also Mason et al., 1998). However, the continuous generation of normal calc-alkaline volcanism up to 3.9 Ma supports a differentiation in tectonic mechanisms.

Post-collisional volcanism specific to the Moesian Plate domain is characterized by adakite-like calc-alkaline, mafic Na-alkalic and shoshonitic K-alkalic compositions. Adakite-like calc-alkaline magmatism in the South Harghita area was generated as a series of overlapping composite volcanoes during two time intervals. This type of magmatism is the result of a corner-flow around the steepening and melting Moesian slab, magmas being differentiated in the lower crust. This process was coeval with the slab tearing along the Trotuş fault system, which is an inherited contact between two rheologically distinct foreland units.

Contemporaneous Na-alkalic and K-alkalic magmatic activity took place during a short interruption in adakite-like calc-alkaline magmatism. It was triggered by asthenospheric convection during slab sinking into deeper mantle levels. Furthermore, the plume-like asthenospheric upraise can also enhance the down-thrusting of the Moesian slab lithosphere, as suggested by mechanisms of plume head–lithosphere interactions near intra-continental plate boundaries (Burov et al., 2007). The ascent of magmas was facilitated by the generalized tectonic inversion event which started during the latest Pliocene.

Na-alkalic magmatism at the westernmost edge of the Braşov basin system was associated with asthenospheric uprise and decompression melting during slab steepening. Isolated occurrences of K-alkalic (shoshonitic) magmas south of the Harghita area were produced by melting at the base of a lithosphere already fertilized by the adakite-like melts, during the asthenospheric uprise that forms part of the slab-driven convective current. Isolated occurrences of lamproitic magmas at the eastern part of the Pannonian basin from Bar and Gataia and Na-alkalic mafic magmas at Lucareț have different sources (lithospheric and asthenospheric), which exploited a major fault system inherited from the transcurrent evolution of the contact between the South Carpathians and the Apuseni Mountains. Magmas were emplaced along this fault system in different locations along its strike, reflecting the progressive eastward influence of the Pliocene-Quaternary inversion of the Pannonian-Carpathians system. K-alkalic (shoshonitic) magmas in the South Apuseni Mountains have striking petrologic and age similarities to the shoshonites from South Harghita at ca. 200 km distance**.** Given the absence of a connecting structure, the magmatic ascent was favored by strain partitioning along different fault systems during inversion.

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Figure captions

Fig. 1. Sketch map of the Carpathian-Pannonian region showing the Pliocene-Quaternary magmatism (simplified after Schmid et al., 2008). The Na-alkalic volcanism in the western part (red circles) is not discussed. In the south-eastern part the volcanism under discussion (calc-alkaline, Na-alkaline, K-alkaline and ultrapotassic) is shown in red dots. Time intervals of volcanic activity are given. SH = South Harghita; STF – South Transylvania Fault

Fig. 2. Space-time distribution of Pliocene-Quaternary post-collisional magmatism in the SE Carpathians and eastern part of the Pannonian Basin, and tectonic events Local Paratethys time scale after Vasiliev et al. (2004).

Fig. 3. (a) Total alkali vs. silica classification diagram for Plio-Quaternary magmatic rocks and the symbol for each type of rock; (b) delta-Q vs. K_2O/Na_2O classification diagram for Plio-Quaternary magmatic rocks. Delta-Q is the algebraic sum of normative quartz (q), minus leucite (lc), nepheline (ne), kalsilite (kal) and olivine (ol). Silica-oversaturated rocks have delta-Q > 0, whereas silica undersaturated rocks have delta-Q < 0 (acc. Peccerillo, 2003).

Fig. 4. (a) Nb/Y vs Age (Ma); (b) Nb/Y vs.SiO_2; (c) Ba/Nb vs. La/Y and (d) $^{86}Sr/^{87}Sr$ vs. $^{206}Pb/^{204}Pb$ for the available Pliocene-Quaternary magmatic rocks in the south-eastern part of Carpathian-Pannonian region. Symbols as in Fig. 3.

Fig. 5. Simplified tectonic map of the Romanian Carpathians and magmatism during 3.0-0.03 Ma times (simplified after Săndulescu, 1984 and Schmid et al., 2008). Abbreviation: BDVF880 Bogdan- Dragoş Vodă fault; PCF- Peceneaga - Camena fault;

Fig. 6 (a) Crustal-scale cross-section and lithospheric configuration across the Apuseni Mountains, Transylvania basin, the SE Carpathians and their foreland (location in Fig. 5). Note the corrected lithospheric configuration which follows the velocity anomalies detected by local tomography studies. The calc-alkaline adakite-like magmas are generated by horizontal astenospheric flow during slab steepening, around the Trotus fault slab-tear (i.e. out of the plane of the section, in map view, see Fig. 5). The Na- and K-alkalic magmas are generated by astenospheric upraise and decompressional melting on a vertical convection circuit linked with the slab sinking into the deeper mantle (i.e. in the plane of the section);
(b) Crustal-scale cross-section and lithospheric configuration across the Apuseni Mountains, South Carpathians and their foreland (location in Fig. 5). Note the major transcurrent contact along which the magmas were emplaced (the South Transylvania Fault).

Figure

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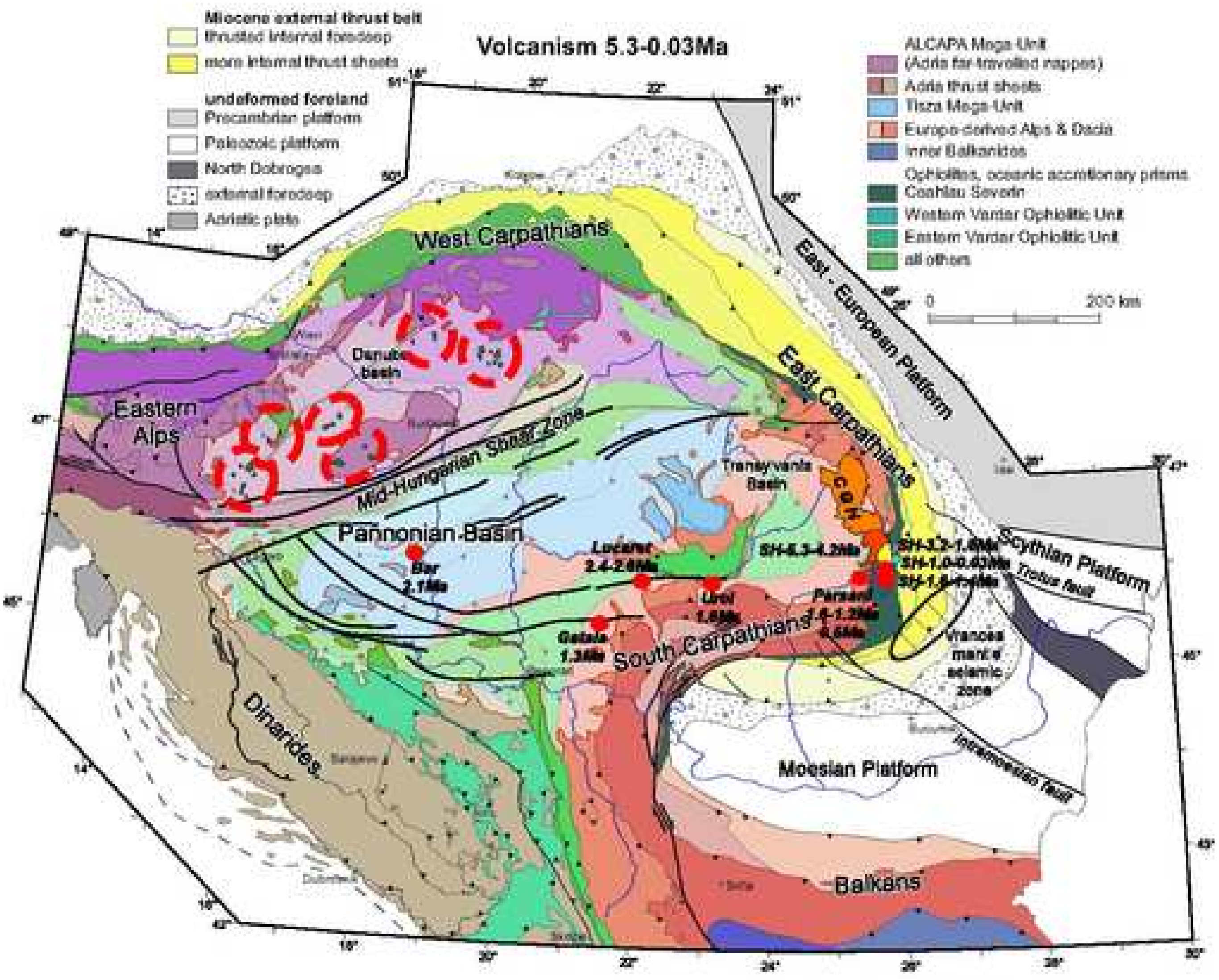

Figure 1 - Seghedi et al.

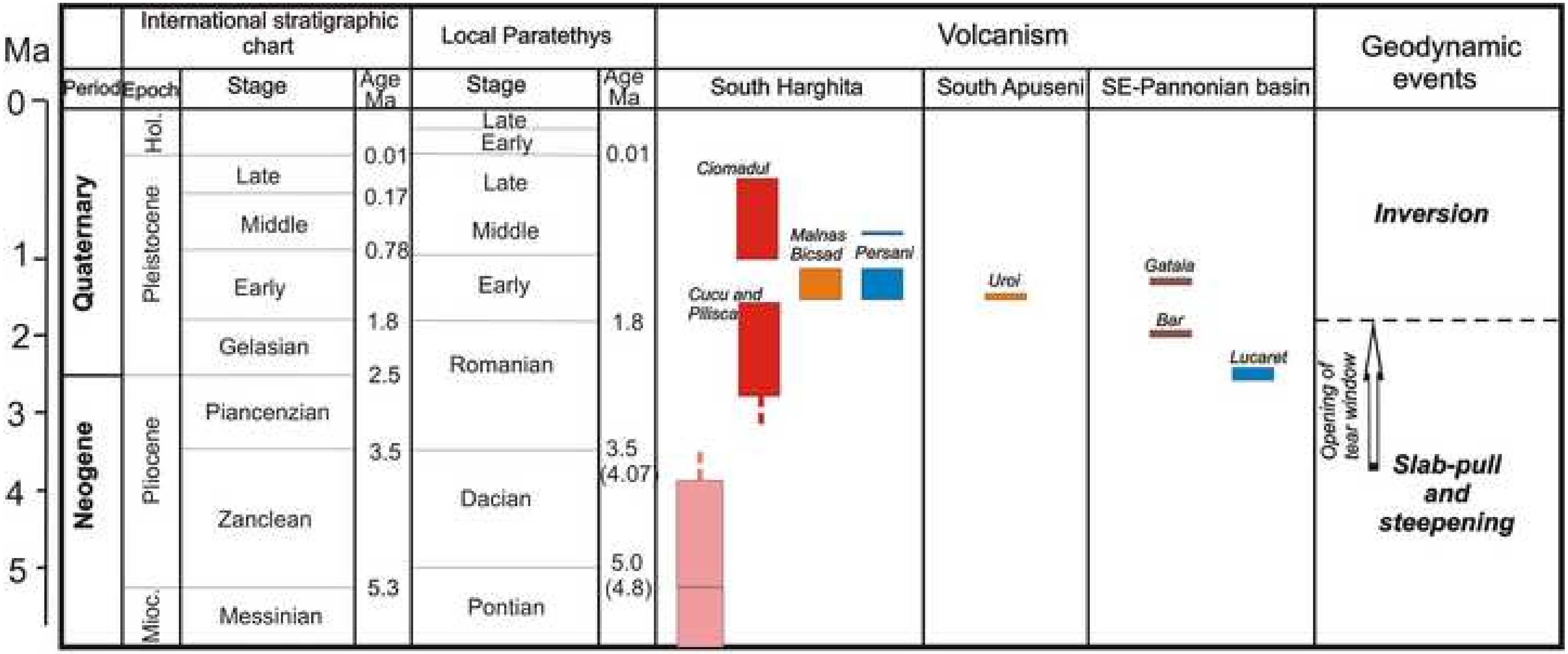
Ma
0
1
2
3
4
5
International stratigraphic chart
Local Paratethys
Volcanism
Geodynamic events
Period
Epoch
Stage
Age Ma
Stage
Age Ma
South Harghita
South Apuseni
SE-Pannonian basin
Quaternary
Neogene
Hol.
Pleistocene
Pliocene
Mioc.
Late
Middle
Early
Gelasian
Piancenzian
Zanclean
Messinian
0.01
0.17
0.78
1.8
2.5
3.5
5.3
Late
Early
Late
Middle
Early
Romanian
Dacian
Pontian
0.01
1.8
3.5
(4.07)
5.0
(4.8)
Ciomadul
Malnas
Bicsad
Persani
Cucu and
Pilisca
Uroi
Gataia
Bar
Lucaret
Inversion
Opening of tear window
Slab-pull and steepening

Fig. 2

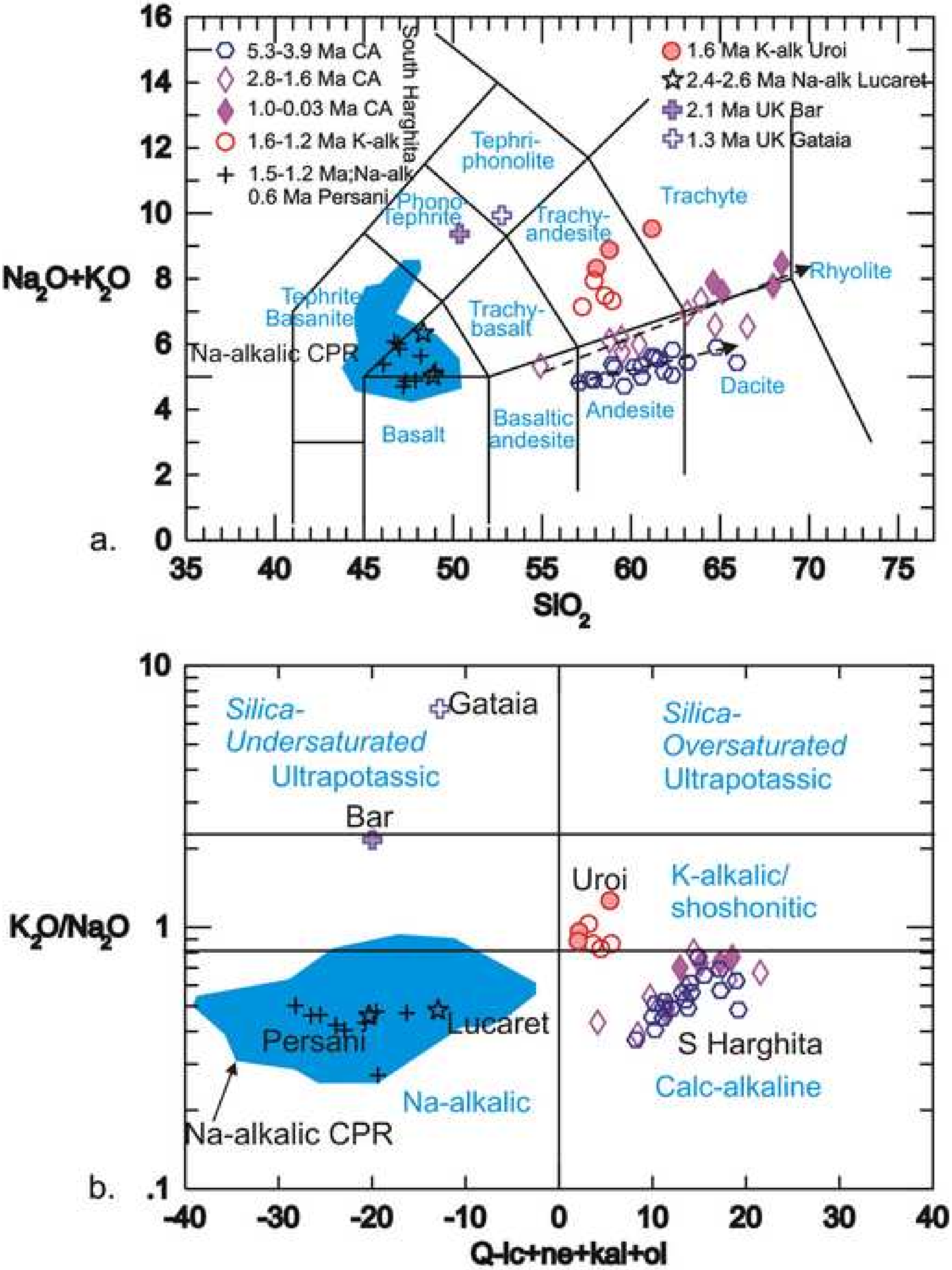
16
14
12
10
8
6
4
2
0
Na$_2$O+K$_2$O
a.
35
40
45
50
55
60
65
70
75
SiO$_2$
5.3-3.9 Ma CA
2.8-1.6 Ma CA
1.0-0.03 Ma CA
1.6-1.2 Ma K-alk
1.5-1.2 Ma;Na-alk
0.6 Ma Persani
South Harghita
1.6 Ma K-alk Uroi
2.4-2.6 Ma Na-alk Lucaret
2.1 Ma UK Bar
1.3 Ma UK Gataia
Tephri-
phonolite
Phono-
Tephrite
Trachy-
andesite
Trachyte
Rhyolite
Tephrite
Basanite
Trachy-
basalt
Na-alkalic CPR
Basalt
Basaltic
andesite
Andesite
Dacite
10
1
.1
K$_2$O/Na$_2$O
b.
-40
-30
-20
-10
0
10
20
30
40
Q-lc+ne+kal+ol
Silica-
Undersaturated
Ultrapotassic
Gataia
Silica-
Oversaturated
Ultrapotassic
Bar
Uroi
K-alkalic/
shoshonitic
Persani
Lucaret
S Harghita
Calc-alkaline
Na-alkalic
Na-alkalic CPR

Fig. 3

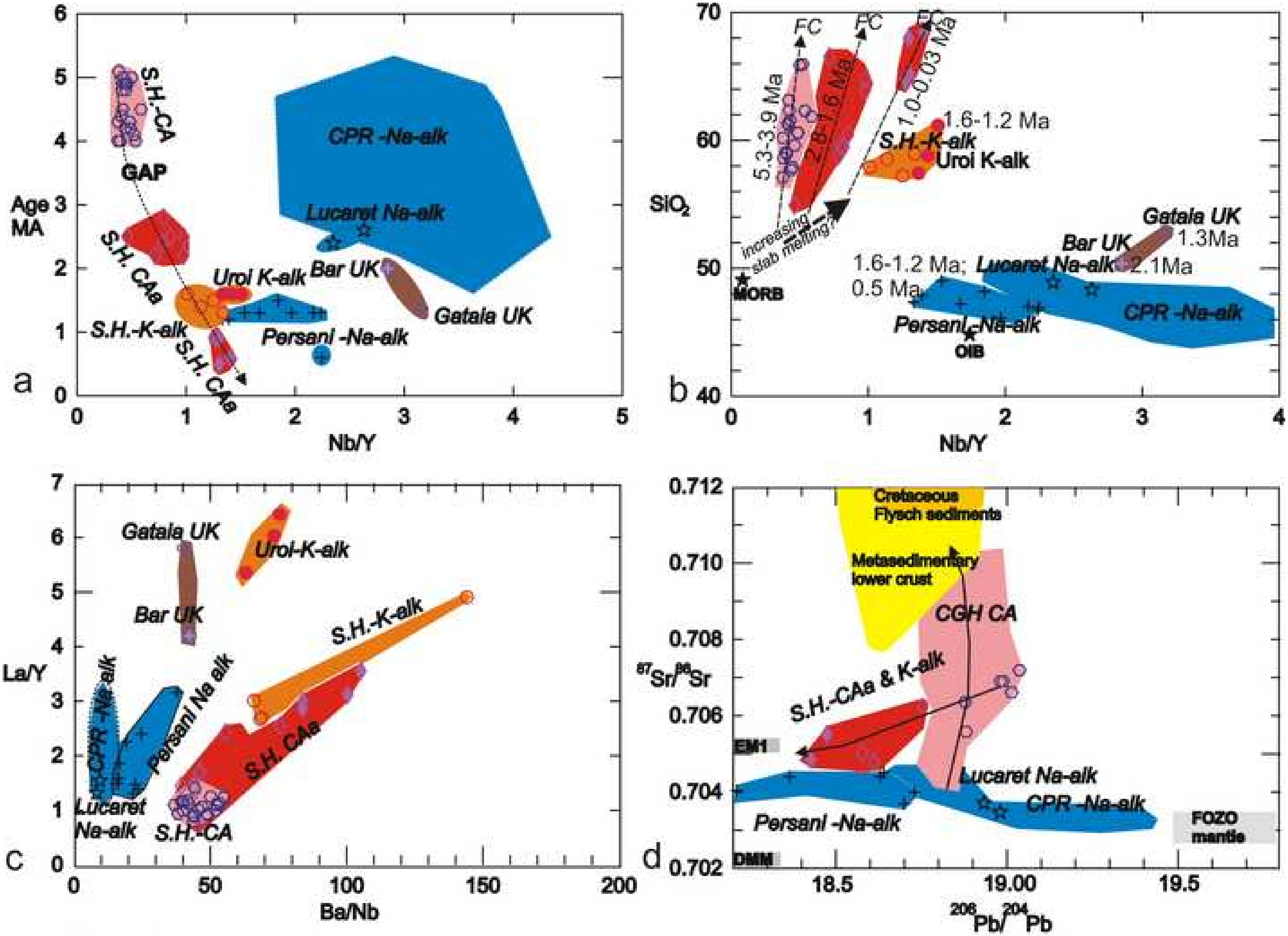
a
Age MA
Nb/Y
0
1
2
3
4
5
6
S.H.-CA
GAP
S.H. CAs
S.H.-K-alk
Uroi K-alk
Bar UK
Gatala UK
CPR -Na-alk
Lucaret Na-alk
Persani -Na-alk
b
SiO2
Nb/Y
40
50
60
70
FC
FC
FC
5.3-3.9 Ma
2.8-1.6 Ma
1.0-0.03 Ma
1.6-1.2 Ma
S.H.-K-alk
Uroi K-alk
increasing slab melting?
MORB
OIB
Gatala UK
1.3Ma
Bar UK
2.1Ma
1.6-1.2 Ma;
0.5 Ma
Lucaret Na-alk
CPR -Na-alk
Persani -Na-alk
c
La/Y
Ba/Nb
0
50
100
150
200
Gatala UK
Uroi-K-alk
Bar UK
S.H.-K-alk
CPR -Na-alk
Persani Na alk
S.H. CAs
Lucaret Na-alk
S.H.-CA
d
87Sr/86Sr
206Pb/204Pb
0.702
0.704
0.706
0.708
0.710
0.712
18.5
19.00
19.5
Cretaceous Flysch sediments
Metasedimentary lower crust
CGH CA
S.H.-CAs & K-alk
EM1
Lucaret Na-alk
CPR -Na-alk
Persani -Na-alk
FOZO mantle
DMM

Fig. 4

Figure

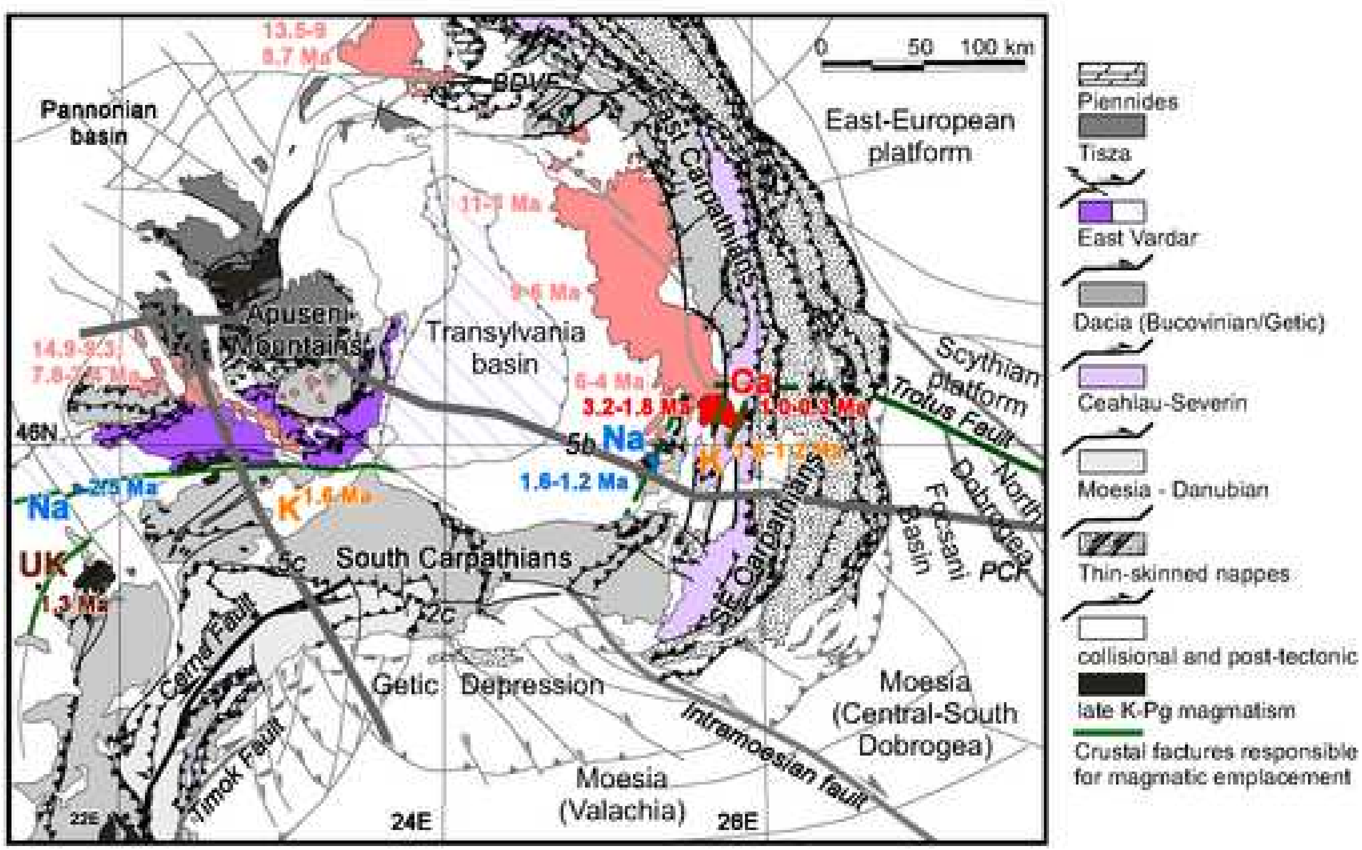

Figure 5 - Seghedi et al.

Figure

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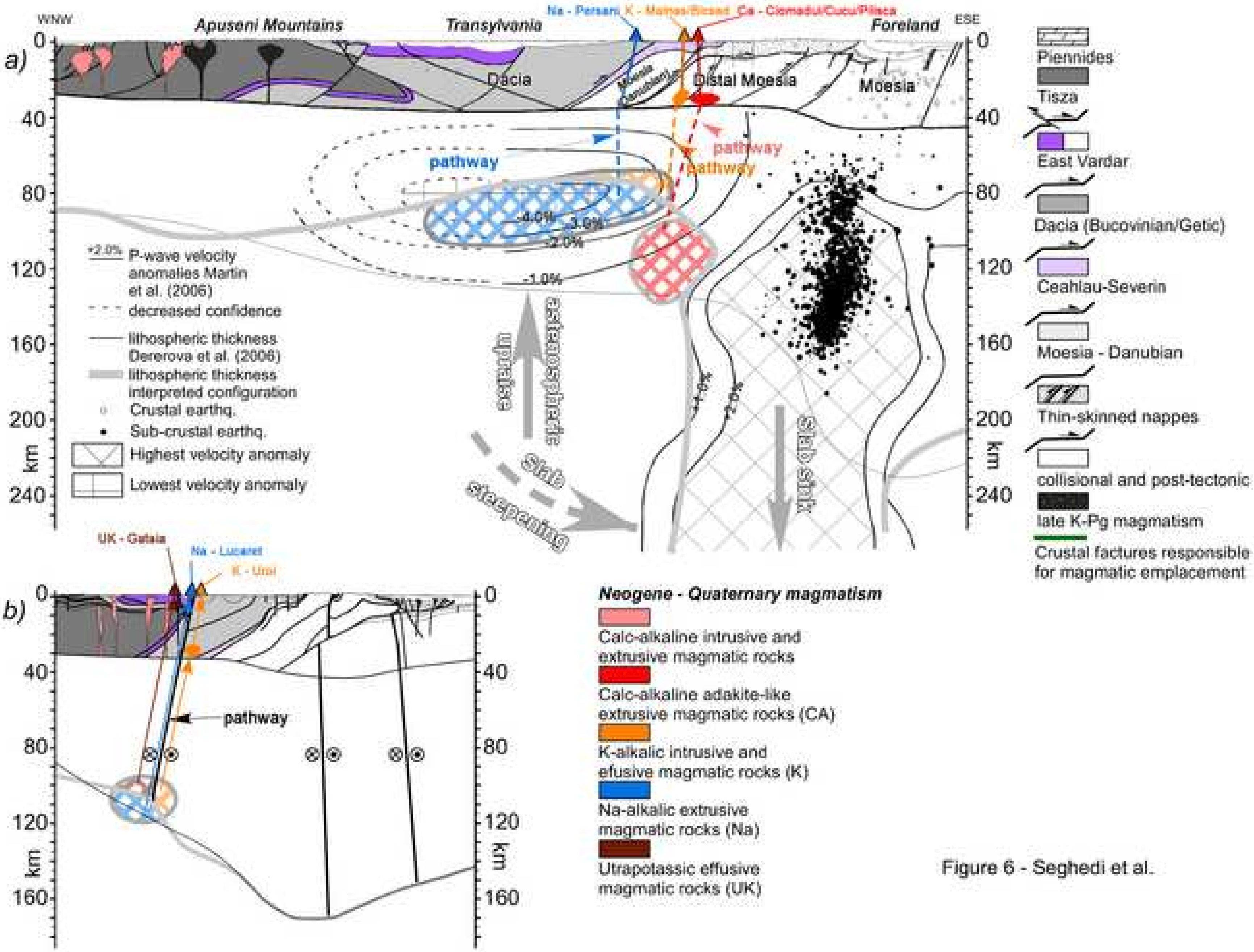

Figure 6 - Seghedi et al.